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HURRICANES AND TROPICAL REVOLVING STORMS.

A Memoir prepared in the Meteorological Office

BY

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With an Introduction on

THE BIRTH AND DEATH OF CYCLONES.

A lecture given at a Conference of Meteorologists at Bergen on 22nd July, 1920,

BY

SIR NAPIER SHAW, F.R.S.

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PREFACE.

IN NOVEMBER, 1917, Mr. Walter Long, Secretary of State for the Colonies, sent to the Meteorological Office a report upon a storm which passed from Dominica to Jamaica on September 20-21 of that year, and offered further particulars as they came in, and in reply it was suggested that the visitation of the various dominions beyond the seas by tropical storms was a subject of study which required and deserved an appropriate organisation.

The Meteorological Office was in consequence invited by the Colonial Secretary, after consultation with the Admiralty and the Board of Trade, to specify the nature and scope of a suitable organisation for conducting the inquiry. A memorandum on the subject was presented to the Meteorological Committee and approved by that body on August 21, 1918. Its recommendations were based upon the idea that the next stage in the programme of scientific inquiry ought to be a critical analysis of the dynamical and physical aspects of the phenomena of tropical storms, in relation to the normal structure of the atmosphere of the regions where hurricanes are experienced, in order that attention might be directed to the causes which are operative in determining the paths which the individual storms take. For this purpose the organisation of the inquiry resolves itself into two parts, first, the collection of suitable information as to the progress of the storms experienced, and secondly, the examination of the data in relation to the dynamics and physics of the atmosphere.

It was acknowledged that the dynamical problem of tropical revolving storms was one of great complexity, and that the ideas which had been evolved by the study of the surface conditions from before the beginning of the nineteenth century onwards, upon which the practical rules for the guidance of seamen have been based, as set out in the *Barometer Manual for the Use of Seamen* and other meteorological text-books, had apparently reached the limit of advance. The subject required to be reconsidered in the light of modern knowledge of the upper air, and therefore, so far as the Office was concerned, it should be treated from the point of view of dynamical meteorology, which is the special province of the Forecast Division, and not simply from the point of view of the compilation of statistics: in fact that it was time that we came to a better understanding of the physical processes exemplified by what goes on within the region of the individual cyclone.

It was agreed with the Colonial Office that the first step in the inquiry should be the collection, in the form of a memoir, of the information about the occurrence and characteristics of tropical revolving storms in different parts of the world which is already available in meteorological literature, and that duty was accordingly assigned as an occupation for the professional staff of the Dynamical or Forecast Division during the periods when they were free from the immediate duty of dealing with the weather-maps of the British Isles.

The professional staff of the Forecast Division at that time consisted of a number of men and women with suitable training in mathematics and physics for the purpose indicated. But the circumstances in which the Office found itself in the autumn of 1918, and the months which followed, were not at all conducive to the quiet study of meteorological literature in occasional periods of comparative leisure, or the sedentary contemplation of the physical processes of recorded hurricanes; as a joint duty of the otherwise unallotted time of a number of persons the project made little progress.

It was therefore decided to assign the duty of compiling the Memoir to Mrs. E. V. Newnham, M.Sc., one of the members of the professional staff, and to set her free from the routine of duty in the Forecast Division, so that she might devote her whole time to the subject.

The result is the Memoir which is now presented. Considering the enormous amount and complexity of the material which is available in various forms and the mixture of theory and fact which can hardly be disentangled in the original papers, the presentation of the salient features of the history of the tropical revolving storms

of the globe is not by any means an easy matter. The curious invasion of theory upon the domain of fact, which is characteristic of the subject, is well illustrated by the description of so many paths of hurricane centres as "parabolic." The properties of the parabola do not really come into the consideration of the question; the name is only shorthand notation or perhaps a "swagger" title for a shape for which the name gives a more or less approximate description. It is not easy to find a substitute, though it would certainly be better either to demonstrate that the motion of a cyclone can be related to a parabolic path, or to use some word with less technical connotation.

So also in the description of the phenomena of hurricanes Mrs. Newnham sometimes uses the descriptions of the original authors, which evidently have behind them the idea of the theory of convection of warm air. It is a theory of great antiquity, which figures very largely in meteorological literature, and about which it is very difficult to be physically precise. Most of us have given up the ideas of the operation of thermal convection, in the form in which we believe it to have been understood by the authors of the original memoirs referred to, and yet we have no other brief connotation of the conditions which we can offer as a substitute when we want to include an author's results in a general summary. It must, however, be understood here that any reference in the Memoir to convection as an operative cause in tropical revolving storms must be taken with the understanding that the process may be of the nature which I have endeavoured to explain in the Introduction to which I now refer.

The life-history of the tropical revolving storm from its birth to its dissolution, in a form which discloses the true nature of the physical processes, is certainly not yet a common possession of meteorological readers, and till we have a reasonably exact representation of the life-history we cannot adequately deal with the subject. Quite recently we have been introduced by Norwegian meteorologists to some interesting ideas of the origin and development of "cyclones" at the boundary between equatorial and polar air in middle latitudes. They are in any case quite different from the ideas of the origin and development of a column of revolving fluid in a region of uniformly flowing air, which many of us still understand a tropical revolving storm to be.

As the result of correspondence with the late Lord Rayleigh in 1917, I have devoted a good deal of attention to the study of the travel of columns of revolving fluid in the larger currents of the atmosphere. It forms the subjects of *Geophysical Memoir No. 12* (21), and is also treated in the concluding chapters of Part IV of a *Manual of Meteorology* (17). More recently I have turned my attention to thermal convection, as an original cause of the development of revolving fluid, from a new point of view. I believe this to be free from the objections which can be urged against the traditional descriptions of the process. This point of view suggests a new and rational reading of the life-history of tropical revolving storms. I had occasion to set out what I had to say on these subjects, as a contribution to the discussion of the general meteorological questions raised by the introduction of the polar front into the sphere of practical meteorology, for a lecture to a Conference of Scandinavian and British Meteorologists at Bergen in July, 1920. The lecture treats of the mutual relation between the polar front, in its most general sense, and the birth and death of tropical revolving storms. I have accordingly brought the text of the lecture into a form suitable for publication as an introduction to Mrs. Newnham's Memoir.

I am sanguine enough to think that if the original authors of some of the memoirs to which I have referred could become acquainted with the point of view which is therein presented, they would claim that it was of course what they really meant, and, therefore, that what they have written stands as a reasonable explanation of the facts for those who view it from the proper point. I have no wish that the reader should take a different view.

The Memoir which is now presented is the last of the series for which I have to carry the official editorial responsibility, and it is with peculiar pleasure that I round off the task of twenty years of responsibility for the direction of the scientific studies of the Meteorological Office by rearranging my ideas on the subject of cyclones.

The conventional view of the subject was seriously disturbed by the facts given in the *Life-History of Surface Air Currents* by Mr. Lempfert and myself, published in 1906, which presents the work of my earliest years at the Office. I consider myself fortunate in being able to present in the concluding Memoir of my series a grouping of the facts that may open the way to a reconciliation of the processes of tropical revolving storms (and of the cyclonic depressions of middle latitudes into which those storms sometimes degenerate) with the requirements of the laws of experimental physics. The satisfaction is not diminished by the possibility of the effort being regarded as merely clothing the ideas of classical authors in language that avoids the appearance of contradiction which the original descriptions suggest.

On the other hand I do not wish to claim that what I have written completes the reconciliation or that the processes which I have ventured to suggest are sufficiently verified to carry conviction with those who are satisfied that cyclones are formed without the agency of convection. Two points, however, are I think clear: one is that convection is an atmospheric agency of great potency which deserves more careful study than it has yet received; the other is that in atmospheric processes the time-scale of events varies from the second for wind velocity or the occasional cloud-burst to perhaps the year in the exchange of air between the equator and the pole, and to deal with any meteorological question without considering the time-scale invites misunderstanding. These are two steps in the reconciliation from which there need be no going back.

From the nature of the case the Memoir on *Hurricanes and Tropical Revolving Storms* is very largely dependent upon the contributions of other authors to meteorological literature, and among those to whom we are under special obligations we will name Prof. O. L. Fassig, E. H. Bowie and R. H. Weightman for the West Indian region; Mons. H. Hubert for the West African region; Father Algué for the region of the China Seas; the late Sir J. Eliot for the Bay of Bengal and W. L. Dallas for the Arabian Sea; Dr. Griffith Taylor for the region of the South Pacific, and the late Charles Meldrum, T. F. Claxton and A. Walter for the region of the South Indian Ocean. To these we are indebted for the originals of many charts and diagrams.

NAPIER SHAW.

Meteorological Office,

Air Ministry.

September 4, 1920.

NOTE. A bibliography of works consulted is included at the end of the Memoir. Numbers printed in heavy type refer to the publications listed in the bibliography.

As a rule measurements of meteorological elements and times are recorded in the same systems as are used in the original authorities. In the West African Section longitudes are referred to Greenwich, whereas in the original they were referred to Paris.

TABLE OF CONTENTS.

INTRODUCTORY NOTE.—THE BIRTH AND DEATH OF CYCLONES, By Sir Napier Shaw.

SECT.	PAGE
1. The Maintenance of a Cyclonic Depression	213
2. The Structure of a Cyclonic Depression	213
3. Revolving Fluid in the Atmosphere	213
4. The Case for Revolving Fluid in General Terms	215
5. Examples of Cyclonic Circulation	216
6. Localities of Cyclonic Depressions and Tropical Revolving Storms in relation to the Polar Front	217
7. The Extension of the Polar Front to the Equatorial Zone	217
8. The Tropical Anticyclones	218
9. The Places of Origin of Tropical Revolving Storms	219
10. The Thermal Convection of Hot Moist Air	219
11. The Birth of a Tropical Cyclone	221
12. Precipitation	222
13. The Death of Cyclones	223
14. The Height of Cyclones	224
15. Thermal Convection in the Atmosphere	225
16. Descending and Ascending Air	225

HURRICANES AND TROPICAL REVOLVING STORMS.

SECTION I.—GENERAL INTRODUCTION.

1. Regions and Times of Occurrence of Tropical Cyclones	229
2. Tracks	230
3. Some Features of the Central Calm Area	230
4. Height of Tropical Cyclones	232
5. Location of the Storm Centre	232
6. Theories on the Origin of Tropical Cyclones	234
7. Frequency of Tropical Storms... ..	235
8. Storm Warnings	236

SECTION II.—NORTH ATLANTIC OCEAN.

A.—WEST INDIAN HURRICANES—

1. Frequency of Hurricanes	238
2. Tracks of Hurricanes	239
3. The Recurve	241
4. Velocity of Motion in the Different Regions... ..	243
5. Duration of Hurricanes	244
6. Rainfall	245
7. Typical June and July Storm	247
8. Typical August Storm	248
9. Typical September Storm	251
9A. Storm of September 8-22, 1921	253
10. Typical October Storm	253
11. Exceptionally Severe Hurricane	254

B.—SQUALLS AND TORNADOES OF WEST AFRICA—

12. The Prevailing Winds	258
13. Conditions for the Formation of Storms	259
14. Description of Typical Storms	262
15. Some Characteristic Storms observed by Hubert	263
16. Mechanical Effects produced by the Conflict of Two Winds	266
17. Rain	267
18. Electric Discharges	267
19. Dimensions of Storms	268
20. Trajectories and Velocities of Storms	268

SECTION III.—INDIAN OCEAN.

A.—CYCLONES IN THE BAY OF BENGAL AND THE ARABIAN SEA—

SECT.		PAGE
	1. The Bay of Bengal.	
1.	The Cyclone Season	270
2.	Storm Frequency	271
3.	Origins and Tracks of Cyclones	273
4.	The Rate of Advance of Cyclones	277
5.	The Smaller Storms of the Rainy Season	277
6.	Storms of the Transition Periods	279
7.	Indications of Storms	282
	2. Storms in the Arabian Sea.	
8.	Monthly Distribution of Storms	285

B.—CYCLONES IN THE SOUTH INDIAN OCEAN—

9.	Frequency of Cyclones	296
10.	Variation of Yearly Frequency	297
11.	Tracks of Cyclones	298
12.	Rate of Progression	301
13.	Rainfall	302
14.	Some Precursory Signs of Cyclones	303
15.	The Hurricane of April 29, 1892	303
16.	Storm in the Mozambique Channel, March 20–24, 1910	304
17.	Cyclone at Cocos Islands (Keeling Group), November, 1909	305

SECTION IV.—PACIFIC OCEAN.

A.—TYPHOONS IN THE NORTH PACIFIC OCEAN—

1.	Frequency of Typhoons	307
2.	Zones of Origin of Tropical Cyclones in the Far East	309
3.	Tracks of the Pacific Cyclones	309
4.	Tracks and Velocity of Translation of the China Sea Cyclones	310
5.	The Classification of Cyclones	311
6.	Rain and Cloud Areas in Typhoons	312
7.	Precursory Signs of Typhoons	313
8.	The "Capiz" Typhoon	314
9.	The Typhoon of April 20–30, 1905	315
10.	The Typhoon of December 15–18, 1905	317
11.	The Typhoon of January 9–11, 1907	318
12.	The Typhoon of North-Western Luzon, August 19–28, 1907	318

B.—REVOLVING STORMS OF THE SOUTH PACIFIC OCEAN—

13.	The New Hebrides	320
14.	The Fiji Group	321
15.	General Remarks on Fiji Hurricanes	326
16.	New Caledonia	327
17.	Banks Group of Islands	327
18.	Tonga or Friendly Islands	327
19.	Samoa Islands	328
20.	Australian Hurricanes	328

BIBLIOGRAPHY—

General Works	331
North America and West Indies	331
North Indian Ocean	332
South Indian Ocean	332
North Pacific Ocean	332
South Pacific Ocean	333
West Africa	333

LIST OF PLATES.

INTRODUCTORY NOTE.

	<i>To face page</i>
Section of the atmosphere along the meridian of 30° W long. showing average conditions of temperature pressure at the surface and at the level of 4000 metres, and the prevailing winds in January	217

SECTION II.—NORTH ATLANTIC OCEAN.

PLATE	FIG		
I.	1.	Variation of yearly frequency of West Indian hurricanes	238
	2.	Chart showing the points of origin of 150 hurricanes	
II.	1.	Paths of West Indian hurricanes during June and July, 1876-1919	239
	2.	Paths of West Indian hurricanes during August, 1876-1919	
III.	1.	Paths of West Indian hurricanes during September, 1876-1919	240
	2.	Paths of West Indian hurricanes during October, 1876-1919	
IV.	1.	Abnormal tracks of West Indian hurricanes	241
	2.	Hurricane paths of August 14-31, 1873 and August 7-20, 1899 and the distribution of atmospheric pressure over the N. Atlantic	
V.	1.	Rainfall over Porto Rico during the passage of the hurricane of August 5-9, 1899	248
	2.	Tracks of typical hurricanes for July to October respectively and of the severe hurricane of September, 1919	
VI.	1, 2 and 3.	Barograms for a portion of the Middle Gulf Storm of July 1-10, 1916	249
	4.	Plot of corrected aneroid readings at Velasco, Texas, August 16-17, 1915	
	5.	Barogram at Galveston, Texas, August 16-17, 1915	
	6.	Barogram at Houston, Texas, August 16-17, 1915	
VII.	1.	Pressure variation at Pensacola, September 28th, 1917	254
	2.	Graphs of pressure, wind direction and wind velocity at Pensacola, Florida, during passage of hurricane of October 18th, 1916.	
	3.	Pressure variation at Key West, September 9-10, 1919	
VIII.		Map of West Africa	255
IX.	1.	Two examples of "Crochet de Grain" observed in West Africa	264
	2.	Distribution of cumulus and cumulo-nimbus at Ségu during the storm of May 28th, 1910	
X.	1 and 2.	Diagrams showing position of cloud and rain in storm of September 28th, 1913, at Dakar	265
	3.	Diagrams illustrating cloud and rain at Oronkua during the storm of August 13th, 1909	

SECTION III.—INDIAN OCEAN.

XI.		Map of the Bay of Bengal and the Arabian Sea	268
XII.	1.	Chart showing the variation in yearly frequency of storms in the Bay of Bengal	269
	2.	Tracks of two remarkable cyclones	
XIII.		Chart showing the points of origin of storms in the different months of the cyclone season for the years 1900-12 in the Bay of Bengal	270
XIV.		Tracks of cyclonic storms in the Bay of Bengal and the Arabian Sea for the years 1900-12 during March, April, May and June	271
XV.		Tracks of cyclonic storms in the Bay of Bengal and the Arabian Sea for the years 1900-12 during July and August	270
XVI.		Tracks of cyclonic storms in the Bay of Bengal and the Arabian sea for the years 1900-12 during September and October	271
XVII.		Tracks of cyclonic storms in the Bay of Bengal and the Arabian Sea for the years 1900-12 during November and December	270
XVIII.		Barograms during the passages of the Calcutta cyclone of October, 1864, the Midnapore cyclone of October, 1874 and the False Point cyclone of September, 1885	271
XIX.	1.	Variation in annual frequency of storms in the South Indian Ocean during the period 1886-1917	298
	2.	Chart showing the distribution of points of origin of cyclones during the years 1886-1917	
XX.		Tracks of cyclones in the South Indian Ocean during the months of November and December, 1886-1917	299

PLATE	FIG		To face page
XXI.		Tracks of cyclones in the South Indian Ocean during the month of January, 1886-1917	300
XXII.		Tracks of cyclones in the South Indian Ocean during the month of February, 1886-1917	301
XXIII.		Tracks of cyclones in the South Indian Ocean during the months of March, April and May, 1886-1917	302
XXIV.	1 and 2.	Records of barometric pressure and wind direction and velocity at the Royal Alfred Observatory during the passages of the cyclones of April 29th, 1892, and February 9th-10th, 1902	303
	3.	Record of barometric pressure, wind and weather during the storm in the Mozambique Channel, March 1910, compiled from the report from ss. <i>Delhi</i>	
	4.	Barogram during the passage of a cyclone over Cocos (Keeling Island), November 1909	

SECTION IV.—PACIFIC OCEAN.

XXV.		Variation in yearly frequency of typhoons in the North Pacific Ocean	308
XXVI.		Tracks of typhoons during recent years for the months of January, February, March, April and May	309
XXVII.		Tracks of typhoons during recent years for the months of June, July, and August	310
XXVIII.		Tracks of typhoons during recent years for the months of September, October, November and December	311
XXIX.		Isobars for January 9th-11th, 1907	318
XXX.		Isobars for August 21st-23rd, 1907	319
XXXI.		Charts showing the number of cyclones reported from each 5° square in the South Pacific Ocean and the tracks followed by these cyclones in the different months	320
XXXII.		Tracks of the hurricane of March 23rd-25th, 1910, and of the storm of January 28th-29th, 1912	321
XXXIII.	1.	Tracks of some Australian hurricanes	330
	2.	Heavy rain associated with the <i>Koombana</i> hurricane of March, 1912	
	3.	Weather Charts for the <i>Koombana</i> hurricane of March, 1912	

INTRODUCTORY NOTE

ON

THE BIRTH AND DEATH OF CYCLONES.

A Lecture given at a Conference of Meteorologists at Bergen on July 22, 1920, by Sir Napier Shaw, F.R.S.

1. THE MAINTENANCE OF A CYCLONIC DEPRESSION.

In the course of his communication to *Nature*, June 24, 1920, on the subject of the Polar Front, Professor V. Bjerknes has suggested that the death of a cyclone results from the cutting off of the supply of warm air by the protrusion of two branches of the polar current, until they overlap on the south side of the cyclonic centre and completely surround it with air derived from a polar source.

If that be a correct representation, then we must regard a continual supply of warm equatorial air along the surface to the central region, with the accompanying convection, as necessary for the maintenance of the cyclone, which is, for the rest, composed of "polar" air. It is quite possible that the conclusion is correct, whatever view may be taken of the nature and origin of depressions, which are thus starved out of existence when the supply of equatorial or warm air is cut off. No specific view is expressed by Bjerknes as to the origin of the depression except that it is associated with the juxtaposition of air from equatorial and polar sources along the line of discontinuity that marks the intersection of the polar front with the surface. For the cyclonic depressions of middle latitudes warm and cold air in juxtaposition, combined with the rotation of the earth, are regarded as sufficient causes.

2. THE STRUCTURE OF A CYCLONIC DEPRESSION.

The cyclone as pictured and modelled by J. Bjerknes consists of warm air ascending obliquely from the "steering line" over cold air moving from the East, which forms the "anaphalanx" of the polar front. The same cold air curves round to the south and, as the "kataphalanx," undercuts the flank of the warm air along the "squall line." The whole process takes place under a current at the cirrus level, which would be generally from west to east in England, and perhaps from south-south-west to north-north-east in Western Norway, following roughly the lines of the average isobars of the four-kilometre level for July, as computed by Teisserenc de Bort. The system thus indicated has a "centre," but its properties are not generally arranged symmetrically with regard to it, so that the word "centre" is perhaps not quite appropriate. The pressure lines may, indeed, be disposed in closed curves more or less concentric; but the temperature, the wind velocity, and the humidity show no sign of symmetrical arrangement with regard to the point of minimum pressure which is called the centre.

Professor Bjerknes, in introducing the subject in a lecture on July 20, began by exhibiting a diagram of my own from *Forecasting Weather*, p. 212, which was intended to call attention to this lack of symmetry in the winds at the surface. It seemed to me to be conclusive evidence that the practice then common of regarding a cyclone as a travelling vortex of which the centre marked the foot of an axis (vertical or inclined) was erroneous and misleading so far as the surface was concerned. Mr. Bjerknes' model does not suggest the idea of air circulating round a vertical axis at any level: the want of symmetry appears, not as a local accident expressing conditions near the surface, but as an essential characteristic of the whole dynamical system. The forward motion of the meteor appears to be dependent simply upon the rate at which the westerly current undercuts the equatorial air, or the rate at which the squall line or kataphalanx travels along the steering line of the polar front. It is therefore dependent on the properties of the two sources of air-supply in the immediate neighbourhood of the centre or minimum of pressure.

3. REVOLVING FLUID IN THE ATMOSPHERE.

By the diagram referred to the idea of travelling columns of revolving air was removed from my own conception of the meteorological process, and I supposed that the mode of propagation must be something different from that of a vortex

of revolving fluid formed and carried along in a current of air. Then the late Lord Rayleigh wrote a paper for the Royal Society of London (14) in which he set out the properties of revolving fluid because, he said, it was so important in meteorology. The practical conclusion of the paper was that, if fluid had any vorticity to start with, the removal of fluid along a central axis would result in the superposition of a simple vortex, $vr = \text{constant}$, upon the original rotation ζ , so that the motion would be a combination of the velocities represented by the two curves of figure 1. I wrote

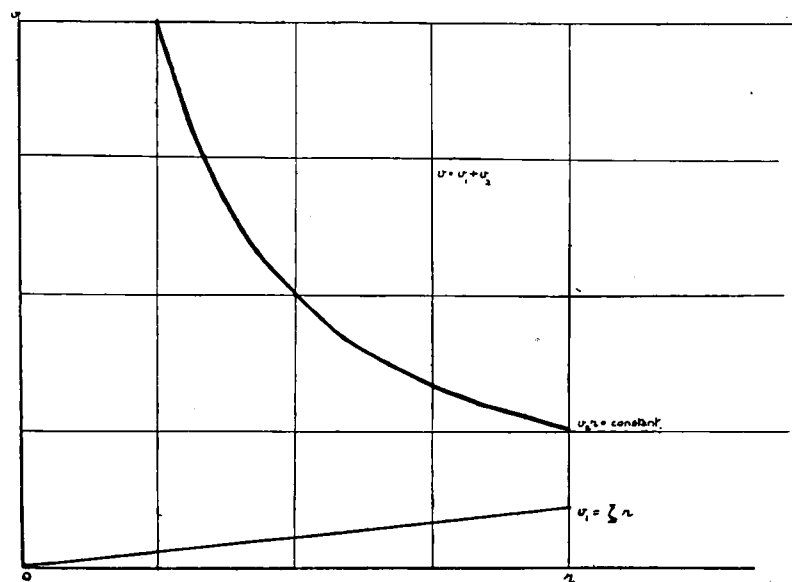


FIGURE 1.

to Lord Rayleigh to explain that, although it might be exemplified in tornadoes and tropical revolving storms, and in spite of the fact that tropical revolving storms sometimes passed continuously from their original condition to cyclonic depressions in our areas, I had been unable to find any evidence of the existence of revolving fluid, such as he described, in the winds of the cyclonic depressions of our latitude. He was unconvinced; and on further consideration I recognised that in looking for pictorial evidence of revolving fluid I had not taken proper account of the fact (which ought to have been obvious to anyone during the last fifty years) that if the revolving fluid were carried along by a current the winds would represent, not simply the rotation, but the combination of translation with rotation and present a horizontal diagram of the type of figure 2, wherein are represented the winds of a current of 10 m/s carrying a vortex with its core 100 k. wide at the point marked A. And

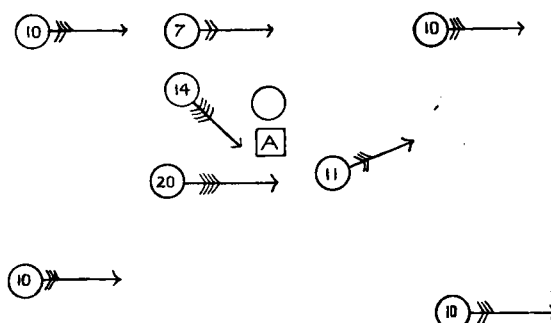


FIGURE 2.—Chart of winds in a whirl with a maximum of 20 m/s in a ring 100 k. wide in a current of 10 m/s. [On the scale of the International Map of the Daily Weather Report (1: 2×10^7)].

further, as the resulting map of winds might be considerably modified by incurvature at the surface, due to friction, the system of winds on a weather map representing revolving fluid would be very different from the symmetrical distribution round a centre which one has in mind all the time. With this enlightenment I found

two examples of small secondaries over England and Wales, which could fairly be regarded as revolving fluid travelling with the speed indicated by the isobars in which they were embedded; and a further search showed that after correction for surface-friction the most violent cyclonic depression within my personal recollection, the British Association storm of September 10, 1903, could also be classed as a rotating column contained within the current indicated by a field of isobars.

4. THE CASE FOR REVOLVING FLUID, IN GENERAL TERMS.

The conclusion that the phenomena might be ascribed to a circular vortex carried along in a current represented by isobars is further supported by a consideration of the travel of tropical revolving storms. Those of the West Indies travel round the tropical high pressure in a manner which is very well described as the path indicated by the normal isobars; and the velocity of travel of 10 or 12 miles per hour is quite appropriate. The summer cyclones of the Bay of Bengal pass to the north and west along the line of the Himalaya as the normal winds do, following a peculiar run of the normal isobars there; and again the velocity of travel is apparently appropriate to the normal velocity of the wind.*

The bagnios of the China Seas and the hurricanes of Mauritius are also suggestive of motion along isobars on the margins of areas of high pressure; though it is easy enough to find hard cases, and not at all easy on any given occasion to make out exactly what the distribution of pressure would be if the cyclone were not there. The association of the travel of a cyclone with the motion of the normal wind is hampered by the fact of the apparent outflow of wind from an anticyclone at the surface across the path of the cyclone, but that outflow is probably a phenomenon confined to the surface. It may be added, in support of the general idea of the representation of certain examples of depression as revolving fluid in a main current, that the tornadoes of the United States are formed in the south-eastern sectors of large depressions, and apparently travel along the general isobars; and, moreover, the average rate of travel of centres of depressions across the British Isles is of the same order as the velocity of travel computed from the normal isobars of Teisserenc de Bort's charts for 4,000 metres, and has a seasonal variation more or less corresponding therewith.

None of these reasons can be urged as conclusive evidence of a persistent column of rotating fluid, but they are sufficient to justify further inquiry into the evidence for the formation and persistence of examples of revolving fluid as stable dynamical systems carried along in the wider currents of the atmosphere.

The existence and persistence of columns of revolving fluid in the atmosphere are also attractive as a working hypothesis, on account of the high coefficients of correlation between changes of pressure and corresponding changes of temperature in the levels between four and eight kilometres of height, which Mr. W. H. Dines (5) has demonstrated. Those coefficients, when allowance is made for the probable effect of casual errors of observation, reach the astonishing figures of .98 and .99 for two quarters of the year at one or other of the levels (3); and as the numbers are correlated in a random assortment and include all deviations of pressure and corresponding temperature from their own mean values—that is to say they include the changes from every high pressure to every low irrespective of sequence, or from low to high just as they happen to come—it follows therefrom that there is at least a presumption that, at a height of four kilometres from the surface within each well-marked cyclonic system, there is symmetry in the distribution of pressure and temperature such as we might expect in the case of the tropical revolving storm. If, then, the lack of symmetry of the winds is explained by the surface friction and the superposition of the velocity of translation upon that of rotation, and the lack of symmetry of temperature by irregularities of the surface-temperatures which do not extend beyond four kilometres, we reach the conclusion that, so far as any horizontal section between four and eight kilometres is concerned, our cyclones may be examples of

* See Climatological Atlas of India by Sir John Eliot (41).

revolving fluid carried along in the main current, which have the portion nearer to the surface distorted and made unrecognisable by differences of temperature peculiar to the lower layers and by the friction of the surface.

Considering, then, cyclones to be dynamical systems of revolving air formed in a flowing current, it seems hardly possible to find any source except convection, reinforced by the latent heat of condensation, for the vast amount of energy which they develop. The velocities are so much greater than anything which occurs outside their spheres of action that the attempt to derive their energy from pre-existing air currents is not encouraging. But there is a difficulty: it has now been generally agreed that in the troposphere the core of a permanent cyclone is cold relatively to its environment and the interior region of an anticyclone relatively warm. For that reason the birth of a cyclone by convection seemed to be ruled out, and I concentrated my attention on the maintenance of its motion and left the consideration of its birth for a future occasion. The chief difficulty about its maintenance was the possible filling up at the top, which has not the same protection as the bottom. I got over that by considering that in the stratosphere the core was ascertained to be warmer than the environment, and, therefore, the pressure-difference and the wind velocity would gradually diminish with height to zero, so that the "free" end of the vortex would find its protection in the gradual diminution of its intensity (19). The next difficulty was the difference of velocity of winds at different levels in the carrying current, which might shear the meteor out of existence, and for that there is a glimmer of suggestion in a further conclusion to be drawn from the symmetry of pressure and temperature. If isobaric surfaces are also isothermal surfaces there is no change of wind-velocity with height (17). In any case one would have to assume approximate uniformity of direction and speed for a thickness of several kilometres, in order to get a definite connected body of air in stable motion. Perhaps for the levels between four and eight kilometres there are enough occasions of little change of wind velocity between those levels to furnish convenient circumstances for the persistence of a sufficient number of cyclones or cyclonic depressions. When we remember that cyclonic depressions are nearly always suffering changes, we need not expect the structure of the upper atmosphere always to be consistent with what we recognise as the conditions for no change. And, further, it is a matter for careful consideration what is actually presented to us by the motion of a pilot balloon in a cyclonic depression. The irregularities due to local turbulence, or the changes incidental to an inclined axis, appear in the results with as much weight as the examples of fundamental structure.

5. EXAMPLES OF CYCLONIC CIRCULATION.

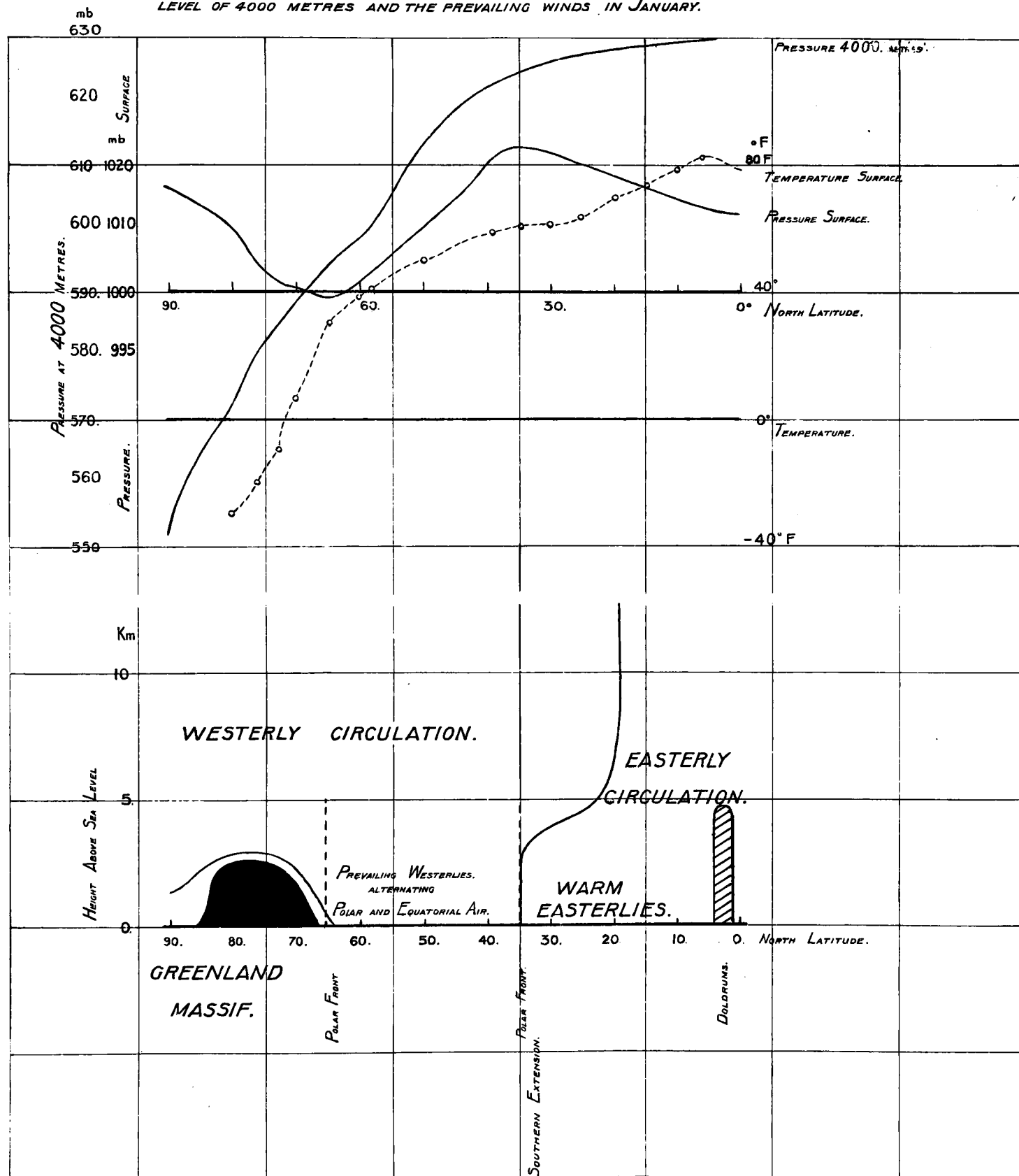
Let us put together the various cyclonic circulations for the existence of which claims have been made. They are as follows:—

(1) The normal circulation of the upper air round the pole of each hemisphere, represented by Teisserenc de Bort's isobars, the persistence of which for the northern hemisphere, together with its winter intensity, may be attributed chiefly to the drainage of cold air from the Greenland plateau at about the level of three kilometres, which must give rise to convergence, and, therefore, to cyclonic circulation in the four kilometre level (20). The explanation is borne out by the difference between the charts for summer and winter (July and January). For the southern hemisphere the loss of heat from the high Antarctic Continent must be equally effective.

(2) Tornadoes and tropical revolving storms, which are undoubtedly circular and dynamically persistent, the former for minutes or hours, the latter for days or even weeks. They begin by travelling with the velocity of the normal current in the region of their origin, about 10 miles per hour, from the east, and pass round the anticyclones of the tropics into the westerly currents of middle latitudes, where their velocity of travel is increased and their intensity is diminished.

(3) The cyclonic depressions of middle latitudes, which on the average travel over England with a speed of the same order as that indicated by Teisserenc de Bort's isobars. Some of them have a north side so cold that the distributions of pressure

FIGURE 3. SECTION OF THE ATMOSPHERE ALONG THE MERIDIAN OF 30° W LONG
SHOWING AVERAGE CONDITIONS OF TEMPERATURE PRESSURE AT THE SURFACE AND AT THE
LEVEL OF 4000 METRES AND THE PREVAILING WINDS IN JANUARY.



and consequent winds at the surface are modified at a considerable elevation, the disturbance becoming merely a deviation of isobars, which may, however, indicate a feeble cyclonic circulation travelling with the upper current (22).

Some of them, however, by the motion of cirrus cloud from an easterly or north-easterly point give indications of extending to great heights and do not suffer much in intensity when correction is made for the temperature of the lower layers. The extension of systems of low pressure to very high levels is borne out by observation of cirrus cloud (9), and by the values of the standard deviations of pressure at the different levels which show no diminution at heights below the stratosphere (5).

Some cyclonic depressions are very large, covering regions 1,000 or 2,000 miles in diameter; some are smaller, and some are merely indicated by slight deviations of the isobars, which may still indicate revolving fluid with a ring of maximum velocity having a very limited diameter.

The whole system of the northern hemisphere may therefore be supposed to consist of:—

- (1) The general circulation round the pole in the upper air.
- (2) Large areas of revolving fluid travelling along the lines of the general system of the upper air.
- (3) Still smaller areas or secondaries travelling along the isobars of the primaries.
- (4) Very small revolving columns indicated by sinuosities in the isobars.

6. LOCALITIES OF CYCLONIC DEPRESSIONS AND TROPICAL REVOLVING STORMS IN RELATION TO THE POLAR FRONT.

Let us first consider the transition of the tropical revolving storms into travelling cyclonic depressions of our latitudes. The consideration will raise a point of some importance in relation to the investigation of the polar front. Let us take a vertical section from the pole to the equator (Fig. 3) drawn near Iceland along the meridian of longitude 30° W., across the map of average surface pressure during January, chosen because it represents the conditions in a more typical manner than July, the month in which we happen to find ourselves assembled. We may remember that the pressure distribution at 4,000 metres is indicated by Teisserenc de Bort's isobars, which will certainly control the motion in polar regions, but will have very little influence in the equatorial region.

We see in the polar region north of latitude 65° a region of easterly winds at and near the surface, probably fed by air from the massif of Greenland, with the westerly circulation overhead. Between 65° and 35° we have the region of prevailing westerlies which extends throughout the troposphere and beyond, better described perhaps, so far as the lower layers are concerned, as the region of alternation of polar and equatorial air. Between 35° and the equator there is a region of easterly winds of the surface and upper air, which displace the westerlies over a belt extending north and south of the equator between latitude 35° on each side, but in the upper air perhaps the westerly wind encroaches from middle latitudes as far as the tropics, judging by observations of higher clouds.

In the lower layers, with some allowance for friction, the wind conforms to the gradient which is shown on the surface; the reversal of the gradient from that of the 4,000 metre level is due to the gradual increase of mean temperature towards the equator, but in the upper layers the supply of air may be sufficient to drive a current westward, in spite of the slight gradient of the equatorial regions and of the feeble control which it exercises in very low latitudes.

7. THE EXTENSION OF THE POLAR FRONT TO THE EQUATORIAL ZONE.

It must be remarked that the easterly winds both of the polar and equatorial regions belong originally to the polar front. So far as the Atlantic is concerned, we may suppose that the cold air which forms that front advances from the polar regions. In winter the main source of supply for the surface of the Atlantic Ocean is, doubtless, due to the radiation from the high ground of Greenland. For the

eastern Atlantic and the continent of Europe it comes along the south side of the Asiatic high pressure, but in July the supply probably comes from the west of Greenland as a continuation of the equatorial air which passes Spitsbergen, or it may be the continuation of the south-west monsoon coming from the Behring Sea across the north of America. In either case, the end of the equatorial air of lower latitudes is to become polar air for the other side of the low pressure round which it circulates.

How far south the cold air of the polar front penetrates on any particular occasion depends upon the form and position of the low pressure areas, but it is fair to regard the northern part of the tropical high pressure as bounding the region of lines which mark the connexion between the kataphalanx of the cyclones gone eastward and the anaphalanx of the cyclones coming from the west.

8. THE TROPICAL ANTICYCLONES.

And here we get some new light upon the formation of the belt of anticyclones which are characteristic of all tropical oceans except the Indian Seas during the summer. We have already understood that if two extremes of a polar front unite to enclose a cyclonic centre the cyclone dies; the pressure in its interior rises; but that which is the death of the cyclone is, algebraically speaking, the birth of an anticyclone, and if a region of high pressure be surrounded by the polar front we get what is necessary for the maintenance of the anticyclone. Thus the same circumstances which kill an enclosed cyclone are salutary for an enclosed anticyclone.

We have two polar fronts, one for the northern, the other for the southern hemisphere; and the cold air belonging to them should from time to time push the line of discontinuity further and further along the surface towards the equator, having a series of cyclone-centres threaded upon the line of discontinuity which marks its boundary. And always the centre of a cyclone travelling east is the most northerly point of the front in its own region. We could only suppose the end of the process to be that the push of the polar front on either side of the equator would bank up a belt of high pressure there between the two advancing phalanxes; but there is no uniformly adjusted balance all round the world, the front is cold and the equatorial air is warm and consequently the polar fronts of either side penetrate the warmer air and go on until they converge to form a great equatorial current of air passing westward and imprison a section of the high pressure which thereafter they maintain for ever over certain oceans. The air, originally colder than the belt which it has penetrated, gets warmer as it travels to the west and becomes the source of equatorial air for the temperate regions later on. This process finds permanent expression in the maintenance of the great feeding currents of the trade winds on the eastern sides of the great oceans in both hemispheres.

Thus we may regard the tropical highs as a natural consequence of the conditions which find expression in the polar front, and we may regard the equatorial region as a region of comparatively low pressure where there is a belt of air moving westward and fed continually by gigantic streams from north and south.* In studying the geography and meteorology of the equatorial region, attention is generally directed to the convergence of the approach of the surface air from each side of the equator; that may be merely a characteristic of the surface, comparatively unimportant compared with the convergence of the easterly components to form a gigantic stream of air to the westward; its importance will be apparent if we consider that the area of the belt between 30° N. and 30° S. is just one half of the area of the whole globe, consequently we may look upon the belt of equatorial east winds as a belt comprising nearly one half of the atmosphere rotating slowly in the lower layers, more rapidly in the upper layers, against the earth's spin.

Among the consequences of the movement westward round the globe of this vast equatorial belt of air, not perhaps uniform nor homogeneous in structure, we

* Information bearing upon the structure of the great equatorial current is given by Hildebrandsson and Teisserenc de Bort in their work (9), by Berson (2), A. L. Rotch and L. Teisserenc de Bort (16), and by W. van Bemmelen, *The Atmospheric Circulation above Australasia according to the Pilot Balloon Observations made at Batavia*. Amsterdam, Proc. K. Acad. Wet., vol. xx., Nos. 9, 10.

must recognise one of the great permanent elements of the general circulation of the atmosphere to which we owe amongst other things perhaps the rainfall of the Amazon basin. We note that at the equator itself no controlling or deviating force arises from the earth's rotation. The current once established has only to reckon with surface friction and internal friction. But on its northern and southern margins the rotation of the earth should become effective in deviating the westward movement to the north and south respectively, unless its motion is constrained by a suitable distribution of pressure. We must therefore expect the great body of easterly wind to direct a portion of its supply to higher latitudes wherever the guiding distribution of pressure is weakened.

[NOTE.—December 1921. The lower part of Figure 3 shows the westerly circulation extending southward from lat. 35°N over part of the surface-layer of the easterly circulation. When the diagram was drawn the immediate reason for this extension was found in the run of Teisserenc de Bort's isobars at 4000m, which showed a gradual increase of pressure up to the Equator and suggested that the polar circulation spread itself in that region over the tropical anticyclone of the North Atlantic Ocean. The reversal of the direction of the wind over the north-east trade might be accounted for in that way. In that case the remaining part of the easterly current would represent a flow independent of the distribution of pressure. More recently, maps of the distribution of pressure at a succession of levels have been computed and the available information about winds in the upper air over the equatorial region has been brought into relation therewith. The results obtained do not lend themselves to simple generalisation and require more elaborate discussion than can be included here. The section along the meridian of 30°W appears indeed to be exceptional; the westerly circulation apparently extends there further south than elsewhere. Some further information is given in a work entitled *The Air and its Ways* which is now in course of publication by the Cambridge University Press.]

9. THE PLACES OF ORIGIN OF TROPICAL REVOLVING STORMS.

On referring to the section of the atmosphere over the Atlantic, we see that there are two lines of no east or west velocity which indicate surfaces of demarcation between the currents. One cuts the ground at the minimum of pressure, the other at the maximum. The line of discontinuity which marks the position of the northern polar front will be somewhere between those two limits and may be regarded as oscillating between them. There must be another line of discontinuity on the southern side of the tropical high pressure which marks the boundary of polar air newly supplied from higher latitudes. If the cyclones of temperate latitudes are to be regarded as being generated at the northern surface of discontinuity, the tropical revolving storms may certainly be regarded as finding their origin about the latitude of the discontinuity near the equator.

But they do not take their rise or reach their full development in those parts of the ocean where the air has just arrived from higher latitudes, where it may fairly be regarded as being still part of the polar front and relatively cold. The regions of origin of tropical hurricanes are reached when the wind, turning westward, has passed over a long stretch of equatorial or intertropical ocean. For the West Indian hurricanes, which originate near the lesser Antilles, the air will have travelled over hot sea for 30° of longitude from its break through the belt of high pressure; for the Baguios of the Philippines, over 50° ; for the hurricanes of the Mauritius over 40° ; and for those of northern Australia, perhaps over 120° . These regions are sometimes identified as being waters off the eastern shores of continents which are studded with many small islands, which may have some thermal significance; this is certainly true, but they are also regions of conspicuously high temperature of sea water (23, Plates XIII–XVI), and that fact is of more importance because it brings into association with them other regions of tropical revolving storms, namely those of the open waters of the Bay of Bengal and the Arabian Sea, which are only related in an indirect manner to the great belt of easterly wind. They certainly develop in the Bay of Bengal in October, when the surface water is very hot and the air relatively calm.

10. THE THERMAL CONVECTION OF HOT MOIST AIR.

The selection by tropical cyclones of the localities of hottest sea water for their place of birth or nurture is certainly suggestive of convection from the surface as their cause; and the recent investigation of the upper air enables us to say that conditions have been ascertained which, if brought into juxtaposition, could produce

certain results of the proper order of magnitude for tropical cyclones. For example, from the soundings of air at Batavia on the island of Java, we obtain an average or normal representation of the lapse of temperature with height in the equatorial region (24, p. 54), and we know also from Neuhoﬀ's diagram (24, p. 16) and equation the effect upon temperature of adiabatic changes of pressure in the case of air saturated with water vapour at, for example, 300a. (about 80° F.). We can set out these side by side, and we see at once that air saturated with water vapour at 300a would be in unstable equilibrium at the surface at Batavia. If it began to rise it would not find itself at the same temperature with its surroundings, and therefore not permanently in equilibrium, until the level of 15 kilometres had been reached, and only then if we suppose it to be loaded with its condensed water as drops. After they had fallen out, further height would be required to bring the density of the rising air to that of its environment. There is nothing to excite surprise in this result, because we know from the results for temperature for equatorial regions that convection does go on there up to a level of 17 kilometres before the stratosphere is reached.

We can go further and consider what would be the pressure at the surface if a column of air some 10 or 20 miles in diameter, for example, were replaced by the air which was saturated at the surface and thrust up into the heights. We can compute the pressure-difference between an interior column of air so defined and its environment, neglecting the humidity of the air, in the computation of the density, but allowing for it in the change of temperature. It appears that in these circumstances the difference of pressure between the exterior column and the environment would be as much as 81mb. at the surface and gradually diminish from that to 8mb. at the level of 10 kilometres and to nothing at the level of 15 kilometres. We can set out all these facts respecting saturated air and its possible relation to its environment in a table as follows:—

TABLE I.—NORMAL PRESSURES AND TEMPERATURES in equatorial air (Batavia) with the temperatures of air saturated with water vapour at 300a and reduced without any supply of heat to the pressure at the uppermost level, with the differences of pressure at different levels between the normal air and the column of saturated air.

Height.	Normal Air. Batavia.		Saturated Air changed adiabatically to same Pressure at 15k.		Pressure differences between the two columns.
	Pressure.	Temperature.	Temperature.	Pressure.	
k.	mb.	a.	a.	mb.	mb.
15	128	198	199	128	0
14	152	203	209	151	1
12	209	219	229	207	2
10	283	235	248	275	8
8	376	251	263	360	16
6	491	265	275	464	27
4	632	279	284	591	41
2	803	290	292	745	58
1	903	295	296	835	68
0	1,012	300	300	931	81

It may be noted that this form of instability is very much dependent upon the temperature of saturation of the air, and it is therefore limited to regions where the air is not only very hot, but also very moist. It should also be noted that the difference of temperature between the rising air and its environment reaches a maximum of 13a at ten kilometres.

We can see from this table that under suitable conditions the air of the surface is capable of rising to the heights which are actually characterised by convection in the equatorial regions, and that, if a hollow column could be filled with it and protected by a rigid wall from its environment it would give rise to a difference of pressure at the surface of the same order as those found between the centres and margins of tropical cyclones, and rather larger than is generally recorded.

The question remains as to how a hollow column can be provided automatically which will fill itself with air of suitable composition and temperature without bulging or collapsing. In the atmosphere there is certainly no rigid wall to protect it; we can only suppose that the interior column is protected dynamically by the spin of the surrounding air, and we must also suppose that the necessary velocity of rotation has been acquired by carrying away the air which originally filled the space now occupied by the interior column (and much more besides) in order that the convergence of the environment towards the region from which the air has been removed may develop the angular velocity of rotation necessary to provide a stable system with a core of very low pressure.

11. THE BIRTH OF A TROPICAL CYCLONE.

If we agree that the situation which is thus disclosed is strongly in favour of convection from the surface as the real agency in the formation of a tropical cyclone we have still to consider the manner in which convection could produce the result. We have to recognise that *the first stage* is the removal of a very large volume of air *at all heights* so that the air at all levels may converge towards the axis and cause the superposition of a simple vortex upon the original rotational condition of the air.

It may here be remarked that, if there is no general tendency towards rotation which can be developed by convergence, the instability of the air will only be attended by a local shower and local disturbances of wind, such perhaps as those of the doldrums, which are too near the equator for the earth's rotation to be effective in originating a vortex.

The traditional view of the process of convection in meteorology may be described as the formation of a continuous local circulation, with a vertical portion caused by the continuous ascent of air in a particular locality in consequence of its relatively high temperature, and a horizontal portion for the continuous replacement of the rising air by the pressing forward of colder air, which approaches from a considerable distance and itself becomes warm enough for ascent by the time it comes to the proper locality. The process is pictured in imitation of the continuous circulation which is set up in a vessel of water when one part of the bottom of the vessel is heated or in a system of heating by hot-water pipes; but in the atmosphere conditions are different; dynamical cooling introduces modifications which make the establishment of a continuous circulation, on the model of the laboratory or of the hot water-engineer, very difficult to trace or to imagine. The ascent of air becomes a question not merely of local warming but of environment as well.

And apart from this fundamental difficulty, the continuous pushing upwards of a supply of air by distant pressure, acting like a continuous piston moving inwards, would not provide for the necessary abstraction of air at all levels. On the contrary, it would seem to suggest the bulging of the sides of the column outwards by the intrusive air. The traditional explanation does not take proper account of the fact that air only goes upward when it is pushed up.

Let us therefore consider more closely the process of convection. In the atmosphere convection may apparently proceed either by threads or bubbles. By the thread process, which may be operative on a sunny day when the surface is solarised, a thick layer covering an enormous area may be gradually brought into the condition of convective equilibrium for dry air. This is probably the case with the air over the Sahara or any other hot desert. The process is different from the formation of a huge bubble separated from the mass below through undercutting by the inflow of cooler air in the neighbourhood. What conditions are necessary for the formation of bubbles on a very huge scale are not known, but it seems certain that when condensation begins bubble formation must be set up.

When a large bubble forms, it is pushed upwards by the convergence of the air beneath it, and it pushes aside the air above it, the final result of the ascent of a single bubble being the convergence of the surrounding air at the level where the bubble was first formed. But as it passes upward eddies will be formed on its exterior, and some of the original column will be dragged up with it at the expense of some

ascensional force. If we conceive the process of convection as the passage upwards of a succession of innumerable large bubbles somewhat in the same manner as the escape of air from the neck of a bottle completely submerged, until many cubic miles of air have been lifted, the air originally over the area will have been gradually removed; the external air will have converged towards an axis and the beginnings of revolving fluid will have been set up by the dynamical consequences of the original thermal process. Continued further, the same process will continue to remove the internal portion of the revolving column until the rotation has become sufficiently developed to resist further convergence towards the centre. By that time, with the aid of the original vorticity of the earth's rotation, we shall have reached at all levels the condition of a simple vortex with a ring of maximum velocity, within which the pressure is kept low through the continual removal of air by what may be called the scouring action of the ascending bubbles. The axis then becomes practically unapproachable because the air that aims towards it is always deviated from its course. It takes part in the circulation and misses the convergence. So we get a dynamical system of great stability which admits air to the region of the axis only along the immediate surface, where the motion cannot reach the limit of protection, because it is retarded by friction.

So far we have a warm core with an environment the temperature of which, except at the very bottom, is governed by the dynamical cooling due to the convergence towards the axis. If the air of the environment contains sufficient moisture, cloud will form; and with the formation of cloud instability is probable, which will cause further condensation and possibly abundant rainfall outside the original column. All this can occur while the whole system is being developed in the easterly wind, and it moves with the wind towards the region where the surface water is still warmer, and, consequently, the surface air also becomes warmer; the dynamical process of scouring the central column is continued. But there will come a time when the supply of hot moist air at the surface is exhausted and then the passage of the air through the column by ascent from the bottom must cease; the air can only rise until its temperature is the same as that of the cooled environment. When that stage has been reached, any hot air remaining in the column will be ejected at the top by the convergence from the sides, and we shall have obtained a dynamical system consisting of a vortex with a ring of maximum velocity of finite diameter and its interior protected from further invasion, except at the bottom, by the velocity of rotation, so that it can only be affected by the creeping of air or other material into the interior along the bottom. The temperature distribution will be that produced by convergence of the environment towards the axis; the whole effect of the convection, originally due to the heated and saturated surface air, will have been to cause the removal of the air from along the axis, which Lord Rayleigh's exposition requires for the formation of a vortex of revolving fluid. Thus the high temperature of the interior is merely a temporary incident in the formation of a cyclonic vortex: by the time the vortex is developed as a dynamical system the core is cold; there is no longer any convection in it; it becomes a comparatively small area, protected from the ordinary vicissitudes of weather by the enormous momentum of a vortex with a high rate of spin, represented by the very violent winds of a certain ring, but extending in less violent form over a vast area.

It may be noticed that the ultimate violence of the winds of the maximum ring depends on the limitation of the area of convection. Since the velocity in the vortex varies inversely as the distance from the axis, if convection can be effective in removing the necessary amount of air without using an area greater than a half kilometre in diameter, the wind at a distance of one kilometre from the axis will be only one quarter of the maximum. The shape of the curve $v_2 r = \text{constant}$, in Figure 1, will approach much more nearly to the two axes.

12. PRECIPITATION.

In such a case there may have been enormous precipitation from the convection, which was operative while the system was in process of formation. That in itself involves a loss of mass from the interior, and as the reduction of pressure to the

minimum near the centre is operative in more or less diminished degree in the whole of the surrounding region, and may be of any magnitude from an infinitesimal amount to as much as 80 mb., we may expect cloud over a large area; and, as already mentioned, the formation of cloud may lead to instability, and, therefore, to precipitation at a great distance from the centre. Moreover, when the system of rotation is once established, the further supply of warm air along the surface cannot reach the centre, and must take the form of a spiral movement upward to the region of great velocity; so that its contribution of precipitation is not to the central region but to the environment.

This exposition of the probable course of events in the birth and nurture of a tropical cyclone depends upon the removal of a vast mass of air from the upper and lower regions of the troposphere by the operation of frictional forces, in association with the original convection to a level which we have indicated provisionally as that of 15 kilometres. Arrived at that level, it has to accommodate itself to such conditions as may be found there. It will be noticed that the contribution of the uppermost 4 kilometres to the pressure-difference is very small, so that no great harm will happen to the cyclone if the top is removed by a wind which travels faster than the cyclone or in the opposite direction. It may indeed be a fortunate circumstance if the first delivery of the rising "smoke" of the vortex, while forming in the easterly drift, passes upward into a westerly drift in the upper levels, provided that, when the time comes for it to stand upon a dynamical rather than a thermal footing, it has reached a region where the easterly current extends to the highest levels.

When once the dynamical system is established it becomes a separate entity and is subject to the laws of gyrostatic phenomena. So far we have regarded it as developed in the easterly drift and moving with it; but nearly all of the tropical cyclones turn out of the easterly drift and recurve into the prevailing westerlies. We have seen that the air of the polar margins of the easterly drift is subject to the earth's rotation and tends to turn poleward. It certainly does so on the surface round an area of high pressure; but whether the easterly current throughout its whole thickness comes that way, or whether the cyclone can move as a mass across a current in consequence of gyrostatic action, we are at present unable to say.

If this be the true account of the birth of cyclones, then convection is the operative force in their creation, but not in the simple way which has hitherto been assumed. Perhaps we may accept convection as the beginning of cyclones, as our predecessors have done, but with a difference as to the mode of operation. We have seen that it is able to explain not only the formation of the vortex, but also the cold of low pressure in the upper layers. It would appear, indeed, that, apart from the local convection of air masses forming part of the system, the changes of temperature will be conditioned entirely by changes of pressure. There can, therefore, be no difficulty in accepting the conclusion, suggested by Mr. Dines' coefficients of correlation, that pressure changes and temperature changes at the same level are expressions of the same physical process, except in so far as temperatures are affected by radiation, including solar or terrestrial radiation, or by the conveyance of heat by conduction from extraneous bodies, either on the ground or possibly in the air. The conclusion at which we arrive is that these causes of interference with the relation of pressure and temperature are not operative between the levels of 4 and 8 kilometres.

13. THE DEATH OF CYCLONES.

With the conception of the structure of a tropical cyclone which is indicated herein, the process of its death is easily explained, and is quite in accord with Professor Bjerknes' explanation of the strangulation or starvation of cyclonic depressions by the grip of the polar front. If we regard a tropical cyclone as a dynamical system carried along by the easterly drift, or in the prevailing westerlies, it is protected by the inertia of its rotary motion from attacks from the outside except at the bottom. As it passes over the surface of land or sea it sweeps into its inner rings whatever it may find close to the surface; birds, butterflies and other living creatures are often included. It acts very much like a vacuum-cleaner on a very large scale. But it cannot lift the included material throughout the whole length of its own column.

So long as the surface air which is dragged into its interior in this way is warm enough to cause local convection in the region to which it is carried, additional energy is conveyed to the dynamical system ; but when a layer of cold air is attacked the convection only extends until the temperature is reduced sufficiently for the air to remain in dynamical equilibrium with its surroundings, and the addition of mass to the interior, instead of helping to scour the column, increases the pressure there. The ring of maximum velocity is, therefore, enlarged, but its velocity is diminished. The reverse of the process of formation is followed. As this process is continued, the central pressure continually increases and the ring of maximum velocity is widened and depressed. This apparently happens as the cyclone passes into the region of the prevailing westerlies, and is continued as the journey proceeds. If, in the course of its travels, the cyclone should find its base supplied with polar air, its energy is necessarily paralysed. Though the death is a lingering one, it must die when the velocity of the vast mass is sufficiently reduced and its area correspondingly extended. Its existence might be prolonged somewhat if it could make use of the convective properties of the equatorial air in juxtaposition with the polar front, but it would certainly be starved out of existence if it had to feed exclusively upon polar air.

There are other ways in which its existence might be brought to an end, as by the shearing of its head with reference to its foot by difference of velocity at different levels in the air which carries it ; but the slow starvation with cold air is enough.

14. THE HEIGHT OF CYCLONES.

We have regarded the cyclone as extending up to the tropopause and sufficiently far beyond it to enable the cyclone to cover itself with gradually diminishing rotation and corresponding pressure-difference. Otherwise one cannot understand its persistence except perhaps temporarily in the case when the air rising in an easterly current is delivered into a westerly current and carried away thereby. The height of a range of mountains is sometimes assigned as the limit of the height of a cyclonic storm because it was found to have died when it passed over the range. The conclusion seems scarcely justified. No doubt a mountain range, 2 kilometres high for example, would cut off the bottom 2 kilometres of the cyclone, and, unless it could rapidly extend itself to the surface on the other side of the range, it would fill up. In any case it would have to take a great deal of air from the other side into its interior in order to remove a core from the lowest 2 kilometres. It has the machinery for beginning the process (21), namely a suitable distribution of pressure which it can superpose upon the lower strata ; but whether the air which it thus takes into its interior can be thrown out at the top, and used to scour the column and maintain the cyclone, depends upon its temperature and humidity. If the travelling revolving mass happens upon a suitable sample of surface air, well and good ; but if not it perishes by being filled up. Hence the annihilation of a cyclone by a range of mountains is not a real index of its height, and the fact that cyclonic depressions sometimes cross mountain ranges and re-establish themselves on the other side, though many perish, suggests that the dynamical conditions do extend to great heights.

It thus seems possible to suppose that revolving fluid, with convection as its primary cause, may be a correct description of some types of cyclone and the cyclonic depressions of middle latitudes which represent the final stages of cyclones. It is not suggested that all the cyclonic visitations of middle latitudes are necessarily of that nature. If the hypothesis of their representation by wave motion on the two sides of the polar front be an alternative, and the polar front be regarded as the visible expression of Helmholtz's surface of discontinuity between easterly air and westerly air, which tends towards parallelism to the polar axis, we may look for the development of that theory for middle latitudes ; but for the equatorial regions the discontinuity would become in the limiting case the separation between two horizontal layers and would have little or nothing to do with cyclones that have a vertical axis.

15. THERMAL CONVECTION IN THE ATMOSPHERE.

Of the four different kinds of cyclonic circulation which we enumerated, we have attributed the two most important to convection, that is to say the general circulation of the upper air round the poles has been attributed to the downward convection of cold air off Greenland or off the Antarctic continent, and that of tropical revolving storms has been attributed to the upward convection of warm air in the neighbourhood of the tropics. We do not pursue the subject at present to the explanation of the smaller circulations to which Professor Bjerknes is devoting his attention.

If, then, convection is of such great importance in the atmosphere we ought to know something more about it than we do. In some conditions it must be very intense, because it is certain that air moving upward carries up with it hailstones of great size and occasionally other bodies. Major H. E. Wimperis, from his experience of bodies falling in air has given an estimate by extrapolation of about 23 m/s as a somewhat improbable limiting velocity of a hailstone of 2 cm. diameter. Accepting it for the time being, the velocity of rising air must be regarded as reaching that limit occasionally. The question arises how such great velocities can be evoked by the juxtaposition of warm and cold air. We know of no estimates of the velocity with which a bubble of warm air would ascend. If it is anything like the velocity of a small bubble of air in water it would not be fast enough to carry up large hailstones. But with a mass of air moving through air it may be different. It seems difficult to attribute these large velocities to what may be called "flue" action, that is to say, the development of convection in a long vertical channel with rigid walls. Perhaps when a vast mass of air is in convection its exterior surface may be cooled by eddies. Thus while the whole mass is being pushed upward slowly, the external portion may thrust up the inner portion and so give rise to local uprushes of great intensity. The matter seems capable of theoretical and experimental investigation.

16. DESCENDING AND ASCENDING AIR.

The appreciation of the true relation of convection to the atmospheric circulation has been much hampered by the popular acceptance of the general statement that cyclones are regions of ascending air and anticyclones regions of descending air; from which it is easy, if it is not actually common, to pass to regarding the effect of convection as being like a current of air descending in the central region of an anticyclone, passing along the surface to the central region of a cyclone or to the doldrums of the Equator and ascending there, to complete the circuit by a passage from above the low pressure to the region, where, by recommencing the descent, it forms an anticyclone. That is in fact the received explanation of the anticyclones of the tropics. That such language must be applicable in a very general sense for the description of the integrated process which is involved in convection of any sort is evidently true; the flow of air along the surface across the isobars from high pressure to low pressure, which is one of the most obvious features of weather-charts, cannot be denied as evidence. The only question is whether the idea has any practical importance from the point of view of the dynamics and physics of cyclones and cyclonic depressions. I propose to show that in the case of the anticyclone the time scale is so large that the general description is quite inadequate as an explanation of the current dynamical conditions.

It is fortunate that that is the case, for if a real current of air were established, flowing downward to the surface, from an unlimited supply at a level of about eight kilometres, for example, with a motion sufficiently rapid to be of dynamical or thermal importance for the air at the surface, the area covered by the descending air would show the condition of convective equilibrium for dry air with the corresponding instability that is inseparable from convective equilibrium. The air of the central regions of anticyclones would certainly be extraordinarily warm* and very dry; but instead of being regions of marked stability, as they are in fact, they

*The potential temperature at 7k. of equatorial air which was saturated at 300a. is about 340a.; that is to say, if it were brought down directly without loss of heat, its temperature would be 67° C. at the ground. We find no temperature like this anywhere on the earth's surface.

would be just as unstable as the regions of rising air, or indeed more so, because the lapse-rate in the descending air would be that of the dry adiabatic which represents the maximum possible instability for atmospheric air. What would happen within an Atlantic high pressure if it derived its characteristics from the descent of air from above would require the pen of a romantic novelist to describe. But there is not much danger of his being called upon ; the antecedents postulated for a continuous descending current are quite outside the range of possibility.

To get the air to flow downward its potential temperature has to be reduced by a supposed loss of heat by radiation ; sufficient to get rid of the latent heat of condensation of equatorial rain ; but if that be a true explanation the skies ought simply to fall everywhere, because the loss of heat by radiation cannot be supposed to be located simply above the central regions of anticyclones ; it must be equally operative all over the world, and the air of highest potential temperature would be the last rather than the first to fall.

We may therefore with advantage consider more closely what the surface flow across the isobars really implies if it does not entitle us to use it as an index of a descending stream.

There is a proposition which I have never seen in print, though it is very easily proved, to the effect that if air flows across a series of concentric circles towards the centre with a constant angle of incurvature α , the amount of convection associated with the flow will be different for different laws of variation of the velocity of the air with distance from the centre of circulation. The integrated flow inward across a belt of unit height for air-velocity v and a circle of radius r will be $2\pi r v \sin \alpha$. If the law of variation of velocity be that of the simple vortex, $vr = \text{constant}$, the flow will be $2\pi \sin \alpha$ multiplied by the same constant ; and therefore will be the same across every successive circle. There will, therefore, be nothing available for convection either up or down within that region of a cyclonic vortex. But if the law of variation of velocity be that of proportionality to the radius, $v = kr$, then the integrated flow per unit of height across the circle of radius r is $2\pi k \sin \alpha \times r^2$. This is proportional to the area of the circle, over the circumference of which the air is advancing ; and the same will be true of successive inner circles. Consequently as each ring is passed a quantity of air proportional to the area of the ring will be left behind to be disposed of by convection. Air for convection will, therefore, be uniformly distributed over the whole circle, and the proper consequence of the state of things described is a uniform flow upward over the area. Reversing the signs, if air is flowing out from the circular boundary of a region with uniform deviation of the flow from the circular path and velocity proportional to the radius, uniform descent of air over the area will feed the outflow.

We can now make an approximate calculation of the descent of air over a region like the high pressure of the North Atlantic Ocean in summer, regarding it modestly as a circular area with a radius r of about 10° of arc, or 1,000 kilometres. We take the angle of deviation of flow from the isobar to be α , V_H to be the horizontal surface velocity, and V_z to be the downward velocity of convection. We may take convection to be uniform over the area, because the surface wind certainly increases with the distance from the centre, perhaps not in strict proportion but not very differently therefrom.

Further, we require an estimate of the height to which the outflow extends, and for that purpose we shall suppose that by uniform stages agreement with the gradient is reached at a height of 500 m, and that the mean velocity of outflow over the vertical distance of 500 m. is one-half of the outflow at the bottom. That being $V_H \sin \alpha$ the average velocity of outflow may be taken as $\frac{1}{2} V_H \sin \alpha$.

Whence we obtain for the outward flow $\pi r h \sin \alpha V_H$, and for the downward convection necessary to supply this flow $\pi r^2 V_z$. These are equal ; hence

$$\pi r^2 V_z = \pi r h \sin \alpha V_H$$

or

$$V_z = \frac{h \sin \alpha}{r} V_H$$

If we insert the numerical values (taking 1 m. as the unit of length) we get

$$\begin{aligned} l_z &= \frac{500}{1,000,000} \sin \alpha l_H \\ &= 5 \times 10^{-4} \sin \alpha l_H \end{aligned}$$

If the angle of deviation α be 30° , and the horizontal wind 4 m/s (about 10 miles per hour) the vertical velocity works out at 10^{-3} m/s, or one millimetre per second. This means a descent over the whole area at the rate of 3.6 metres in an hour, or 86 metres in a day. At that rate it would take a hundred days (more than fourteen weeks) to bring the air down from 8,600 metres to the surface, and in fourteen weeks many things may happen in the atmosphere. Dynamical processes in the open air cannot wait for so long. Their time unit is the minute or the hour. The easterly current of the equator would complete the circuit of the earth, some of it three times over, in less time than that required for the air to reach the surface.

The result is not much affected if we increase the numerical value of the wind velocity or the angle of deviation. In any case the rate of descent is so slow that the dynamical consequences of the descent may be entirely masked by other changes which do not use so large a time-scale. The descent of air in anticyclones is related to current weather very much in the same way as the semidiurnal variation of pressure is related to cyclonic depressions; it is, of course, there all the time, but can be neglected in comparison with more stirring events. The outflow is there, of course, and it entails *subsidence* of the column to the extent of a millimetre per second. It is so slow that the characteristics of an anticyclone are not those of air which has just accomplished a journey from the upper layers, but of air which has time to take up the local colour imposed by the surface and other conditions; and that is indeed the anticyclone which we know.

So the flow across isobars at the bottom is not properly regarded as a great drift fed by a local stream flowing downward; it is simply a matter of quarrying away the bottom of a mass of atmosphere and letting the superstructure subside, bringing with it all the characteristics that comparative repose can produce. The essential features of an anticyclone are repose and permanence, not instability, which is the essential feature of "descending air."

In the case of cyclones the ascending air has no such quiet time. Convection seems to be necessary either on Bjerknes' hypothesis or on that which we have set out. But the ascent is very much localised, and the more localised the convection, the more violent is the cyclone over a limited area. In the case of the cyclonic depressions of middle latitudes, the Norwegian meteorologists assign precipitation, due to convection, to the neighbourhood of the anaphalanx, where the fall is in front of the equatorial air beyond the surface line, and to the neighbourhood of the kataphalanx where the rainfall is through the polar air behind the surface line. Showers may occur in the sector of equatorial air. We have no very satisfactory information about the distribution of precipitation in a tropical revolving storm. According to our computation, if the cyclone is of the nature of a simple vortex the surface air would pass under the external region of the vortex without convection, except in so far as the deviation of the wind from the circle was not uniform. The greater part of it would pass on to the inner region; but it cannot reach the eye of the storm because the spin becomes too great. It may form a sort of lining of the inner tube between the eye of the storm and the circle of maximum velocity.

Within the area of a cyclonic depression, convection may be of extreme violence, but is not by any means uniform. The localising of convection points apparently to the line along which additions to our knowledge might be made with advantage, and the accurate tracing of the position of rain areas must be of importance not only for the further investigation of the polar front, but for many other sides of meteorological investigation.

HURRICANES AND TROPICAL REVOLVING STORMS.

SECTION I.—GENERAL INTRODUCTION.*

Tropical cyclones have been described in detail in the various sections of this report ; and from these descriptions of the individual storms the main characteristics of the phenomena as a whole can be built up.

A tropical cyclone is a vast atmospheric whirl originating near the equator, and with a diameter between 100 and 600 miles while in tropical latitudes ; but after the thirtieth parallel north or south is reached, the diameter usually increases steadily, and at the same time the storm's intensity decreases. In temperate latitudes the diameter is often as great as 1,000 miles.

In addition to the rotary motion of the storm, clockwise in the southern hemisphere and counter clockwise in the northern, there is a definite velocity of translation along a fairly well-defined course. So long as the storm is within 30° of the equator this translatory velocity is very variable, but is, in general, comparatively slow, the average value for the storms in most parts of the tropics being from 10 to 12 miles per hour.

Certain storms seem to move very slowly during formation, at less than four miles per hour, and others show a marked decrease when moving over the recurve branch of the customary parabolic track, but numerous exceptions can be found to both these statements. In the temperate regions, however, in other words north or south of 30° N. and 30° S. respectively, the translatory velocity shows a regular increase with latitude. The whirling nature of these storms was first recognised by Varenus in his *Geographia Generalis* in 1650. The famous sea captain, Dampier, who experienced one in 1687, correctly describes it and states that a typhoon is a kind of violent whirl which occurs on the coasts of Tonkin in July, August and September. More exact and definite information, however, came later, and amongst the pioneers in research on this question the following are noteworthy :—

1828. Dove and Redfield made some researches on tropical cyclones. They advanced theories on the formation and movement of low-pressure areas, and established the opposite rotatory directions of storms in the northern and southern hemispheres.

1831. Redfield (33) formulated the first valuable idea of a cyclone in his *Remarks on the Prevailing Storms of the Atlantic Coast and of the North American States*. He continued to work on this subject, and his publications are to be found in the same journal for the years 1833, 1835, 1839 and 1842.

1846. Redfield (32) published a book *On Three Severe Hurricanes of the Atlantic*. In this he emphasises the importance of barometric irregularities as precursory signs of storms, especially in the Tropics, where the barometric changes are normally so regular. He also states that the centrifugal force, caused by the rotatory winds of the cyclone, is responsible for the low pressure at the centre. Redfield estimated the height of the whirl as one mile.

This work was taken up in England by Colonel Reid, who studied not only the storms of the Antilles, but also those of the Indian Ocean. In his book *An Attempt to Develop the Law of Storms and the Variable Winds* (15) he formulated the first rules for the guidance of sailors navigating waters where these storms occur.

1847. Reid established the first system of storm warnings. He obtained much financial help from the East India Company, with the result that he was able to establish numerous observatories in different parts of India, working under, and reporting to, a Central Office in Calcutta under the directorship of Piddington.

This increase of information concerning tropical revolving storms resulted in the publication of the famous *Sailor's Horn-Book* (13) giving the laws of storms for all parts of the world.

* N.B.—This introduction does not apply to the West African Section.

Thom's work, *An Inquiry into the Nature and Course of Storms in the Indian Ocean, South of the Equator* (49), published in London in 1845, is well known, as is also the companion volume of Keller (10), *Des ouragans, tornados, typhons et tempêtes*.

The work of Meldrum (48), referred to in detail in the section on the South Indian Ocean, first established the spiral movement of the winds inwards to the centre; this was a very important step, since this new and correct conception of the structure of the storm rendered necessary a considerable modification in the "Seaman's Rules."

Among later work on the subject, that of Mohn should be mentioned, since in his *Météorologie* (12), published in 1883, he gave reliable tables showing the frequency of these storms in different parts of the world as follows:—

- (1) North Atlantic Ocean (1493–1855).
- (2) North Indian Ocean (1493–1855).
- (3) South Indian Ocean (1809–1844).
- (4) Mauritius (1820–1844).
- (5) China Seas (1780–1845).

One of the best general descriptions of the approach and passage of a tropical cyclone is found in Milham's *Meteorology* (11, p. 277), published in 1912. It is as follows:—

"The first signs of the approach of the storm are to be found in both sea and sky. The sky is covered with a thin cirrus haze, which causes lurid red sunsets and halos or rings about the sun by day and the moon by night. The air is still, moisture-laden, sultry and oppressive. The barometer rises unduly high or remains stationary when the daily drop is expected. The wind disappears, and the long rolling swell of ominous import appears on the ocean. Soon the barometer begins to fall. A breeze springs up, but the air is still sultry and oppressive. The cirrus haze becomes true cirrus, which usually stretches in bands across the sky and begins to thicken into cirro-stratus or sometimes cirro-cumulus. The barometer begins to fall more rapidly, the wind increases, and on the horizon the dark rain cloud, shield-like, has appeared. The barometer now falls with startling rapidity; the blue black rain cloud rushes overhead; rain falls in torrents, cooling the air; the wind has increased to full hurricane strength, a hundred miles an hour or more; the sea is lashed into fury.

"This may continue many hours, when suddenly the wind ceases, the clouds break through, the temperature rises, the moisture grows less, and the barometer is at its lowest, for the calm central eye of the storm has been reached. The respite is but brief, perhaps twenty or thirty minutes, after which the wind changes to the opposite direction and increases to full hurricane strength as suddenly as it ceased. Rain again falls in torrents, and everything is as before except that the barometer is rising. After several hours the end of the storm is reached, the wind dies down, the rain ceases, the nimbus clouds break through and give place to cirrus, the temperature rises somewhat. A while later and the nimbus cloud sinks, shield-like, below the horizon, the cirrus retreats after it, the wind is a gentle breeze, the barometer has reached its accustomed height, and but for the wreckage and the ominous heaving of the ocean one would not know that a storm had passed."

I.—1. REGIONS AND TIMES OF OCCURRENCE.

There are six regions of occurrence in the tropical parts of the great oceans, and it is a significant fact that the South Atlantic is the only ocean in which these storms never occur. The regions are as follows:—

- (1) North Atlantic Ocean. The West Indies, the Gulf of Mexico, the Caribbean Sea and the Florida Coast.
- (2) North Indian Ocean. Each side of India, in the Bay of Bengal and in the Arabian Sea.
- (3) South Indian Ocean. To the east of Madagascar, near the islands of Mauritius and Réunion.

- (4) South Indian Ocean. Between the north-west coast of Australia and the Cocos or Keeling group of islands.
- (5) North Pacific Ocean. Over the China Sea, the Philippine Archipelago and Japan.
- (6) South Pacific Ocean. From the Queensland coast of Australia to the Paumotu Islands.

At least 90 per cent. of the hurricanes recorded in the last 40 years have originated in these areas.

It is seen that with the exception of region (4) these cyclones always originate in the western area of a great ocean, and many writers have stated that they never occur on the eastern side of an ocean; but the West Australian hurricanes, whose tracks lie over the extreme eastern edge of the South Indian Ocean, very effectively disprove this idea.

Tropical cyclones seldom, if ever, originate on land, and if they run ashore they weaken, lose their destructive violence and are soon transformed into extra-tropical cyclones or die out altogether.

The seasons of occurrence can be found by consulting the frequency tables given in the various sections of the report. From these it will be found that the time of maximum frequency is usually during the summer or autumn months, *i.e.*, from April to October in the northern hemisphere, and from November to April in the southern hemisphere. In the case of storms of the Bay of Bengal and the Arabian Sea there are two maxima corresponding to the two transition periods between the monsoons.

I.—2. TRACKS.

The tropical cyclones originate in the doldrums, not directly over the equator, but from 8° to 12° from it on either side. Paths over which they move are usually described as "parabolic" though "hyperbolic" would, in most cases, be a more accurate description. The directions of translation are north-west, through north to north-east in the northern hemisphere, and symmetrically, south-west through south to south-east in the southern. This is only a very generalised statement and numerous exceptions are to be found to it. Certain storms pursue most irregular tracks, but these, in general, are due to obstacles in the path, usually areas of high pressure, which cause considerable deviation of the storm.

In the case of the tropical cyclones which occur in the Bay of Bengal and in the Arabian Sea, the characteristic parabolic path is frequently lacking. The majority of the paths are approximately straight, and often much shorter than those of other regions; and in this way, the forecasting of the storm path once the point of origin is known, is much simpler for the Indian storms than for others, since in the latter the point of recurve is often a very uncertain factor.

I.—3. SOME FEATURES OF THE CENTRAL CALM AREA.

The main features of the "Eye of the Storm" are well known, and need only very brief mention. The most noticeable is the sudden drop in wind from hurricane force to complete calm, or at least to very light, unsteady breezes. Also there is usually complete absence of cloud and rain, and the sun, moon or stars are visible according to the time of day when the calm is traversed. Another striking feature is the presence of land birds, grasshoppers and butterflies, which have been sucked into the vortex and are usually in a state of complete exhaustion. If the "calm" is encountered at sea it is often more dangerous for navigators than the actual inner storm area itself, since the sea is excessively turbulent and high owing to the "churning" action still proceeding on all sides of the centre. If encountered over land, the "calm" is a distinct breathing space in which to prepare for the renewed storm violence as the rear quadrant of the whirl approaches.

In their general characteristics these phenomena are the same throughout the tropics. In the cyclones of temperate zones there is also a notable diminution in wind force as the centre is reached, and their internal conditions are in many respects analogous to those in tropical storms.

S. M. Ballou (1) has made a comprehensive report on the centres of tropical cyclones of all parts of the world. The main points of this report are the following :—

(1) Before the passage of the centre the wind blows constantly from the same direction, and its force steadily increases. It often exceeds 50 metres per second (110 miles per hour) and the maximum wind force occurs in practically every case immediately before the central calm is reached. A few exceptional cases are cited in which the force decreased gradually for some time before the centre was reached ; for example in the typhoon of July 29, 1893, in the China Sea (58).

(2) Generally the calm is complete ; on the other hand, there are several cases in which light variable breezes or squalls alternating with complete lulls have been found.

(3) The sea is always very high and dangerous. No exception to this is known.

(4) The time occupied by the passage of the central zone over a particular place is very variable, the limiting values being 10 and 480 minutes respectively. In general, however, the time is from 20 to 40 minutes and in only 10 cases (out of the 55 examined) did it exceed an hour.

(5) The mean diameter (from readings at land stations) is 14 miles (23 kilometres), but here also the variations are very wide. On the whole, however, the diameter of the “ eye ” greatly exceeds the height of the storm, which usually does not appear to exceed 3,000 feet.

(6) Around the central area the sky is completely overcast and torrential rains fall. When it is possible to observe the clouds, it is found that their movement is centrifugal and that this divergence becomes greater for the higher clouds. In the central calm the rain ceases, and the clouds disappear more or less completely. A thick bank around the horizon is sometimes noticeable, but generally there is a light mist with clearings.

(7) *Temperature, Air Pressure and Humidity during the Calm.*—Observations in such a dangerous position are very difficult to make, and also the number of cases of cyclones passing over well-equipped observatories, whose instruments have withstood the violence of the storm, is restricted, so that information on these important points is very limited. Three famous cyclones, namely the one passing directly over Manila on October 20, 1882, the False Point cyclone—with probably the lowest authentic barometric reading, 27·2 inches, ever obtained at sea level—of September 22, 1885, and the Martinique cyclone of August 18, 1891, provide some information ; also Ballou found eleven other cases in which the movements of the barometer were *continually* followed during the whole of the calm. The information obtained from a systematic investigation of these data is so contradictory that it is quite impossible to generalise from it. In some cases, the barometer was absolutely steady throughout the entire calm ; in others the barogram shows a very distinct minimum at the beginning of the calm and a continuous rise during the rest of the calm ; others showed sudden oscillations at the beginning and end of the calm, and perfectly steady pressure during the calm ; others showed continuous oscillations throughout, and others a continuous fall. The most frequent case is that in which there is a distinct minimum about the centre of the calm with a rise and fall before and after ; of this there are several well-marked examples.

Regarding variations of temperature and humidity there is even less evidence. The curves from Manila give a considerable rise of temperature and a corresponding fall of humidity, and the account spoke of a “ burning wind ” like the Italian sirocco. Similar reports have come to hand from numerous other land stations, but this excessive rise of temperature during the passage of the “ eye ” has never been noticed at sea. In the log of the steamer *Ucimar* it is expressly noted that, during the passage of the central calm of the cyclone of October 5, 1891, both the wet and dry bulb thermometers read constantly 22° C., the sky remaining overcast throughout.

(8) *The End of the Calm.*—Usually the calm ends in the same way in which it began. If the wind ceased suddenly, it will recommence suddenly, and vice-versa. The interior margin of the storm appears to be symmetrical around the calm.

Numerous theories have been advanced to explain the cause and origin of these phenomena, and it seems probable that the air above the centre of the storm has always a very slow *downward* movement. This hypothesis was first advanced by Espy in 1857. A slow descent causes a heating of the air, and in this way the dispersal of the clouds is explained; any surplus heat would then simply increase the air temperature, and this surplus is much more likely to exist over land than over sea, where the humidity is higher, so that in the latter case little or no rise of temperature would be expected, which is in accordance with practical experience. It is clear that any vertical movement must be both slight and gradual, since the horizontal diameter of the calm undoubtedly exceeds its vertical height.

I.—4. HEIGHT OF TROPICAL CYCLONES.

All investigations have led to the conclusion that the height is small. Eliot (40) estimates the height of a violent cyclone as less than 6,000 ft. Most of the cyclones of the Bay of Bengal originate in the Bay itself. There are, however, several cases in which cyclones have crossed over from the Gulf of Siam to the Bay, and on the way these have always crossed over the Isthmus of Kra, where there is no ground above 1,000 ft. in height. The range of mountains to the north in Tenasserim, and that to the south running along the Malay Peninsula, seem to provide impassable barriers to the storms.

According to Dallas (39), the cyclones of the Gulf of Oman (north-west Arabian Sea) usually originate in the vicinity. If, however, they come from the Bay of Bengal, they must cross the Western Ghats, which are approximately 3,000 ft. high, with peaks ranging from 5,000 ft. to 7,000 ft. On meeting the mountains the cyclone seems to be temporarily destroyed, and in consequence the ports on the Malabar coast are singularly immune from violent storms. Several cases have been studied by Dallas in which a cyclone, encountered on a certain date to the east of the Western Ghats, has reappeared one or two days later in the Arabian Sea, some distance from the Indian coast, and has continued to move in its original direction. Dallas explains this by imagining that the vortex motion is driven into the higher atmosphere on meeting the mountains, remains there while crossing them, and afterwards sinks down until it is again a surface phenomenon. Cleveland Abbé (25) gives details of a somewhat analogous proceeding in the case of the passage of barometric depressions over the Rocky Mountains.

Redfield, in his early researches on the subject, estimated the height of the hurricanes of the Antilles as a mile. He often observed a layer of alto-stratus moving above the nimbus cloud of the hurricane without any visible alteration in the ordinary westward track of the alto-stratus being caused by the hurricane. He then estimated the height of this layer as approximately a mile.

On the other hand, Viñes (34) and Algué (53) maintain that cirrus clouds radiate directly from the storm centre, and hence that the storm whirl reaches to much greater heights than those previously quoted. It is nevertheless thought by many writers that the clouds are not true cirrus, but false cirrus which float just above the summit of the cumulo-nimbus.

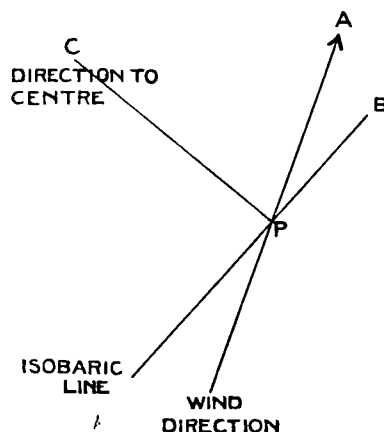
The most probable explanation is that the true cirrus clouds are well above the storm whirl, and that their movement merely indicates that of the general current which carries the whirl. It is clear that no valuable information on this important point can be given until exact measurements of cloud heights have been made in all parts of the tropics where these storms occur.

I.—5. LOCATION OF THE STORM CENTRE.

The importance of this is self-evident, both for the mariner and the forecaster. Had the storm been merely a circular whirl, as the early workers on the subject imagined, with the winds following the isobars, the determination of the bearing of the centre would have been very simple, since a sufficiently exact bearing could have been obtained by a direct application of Buys Ballot's law. It is known, however, that the winds blow spirally inwards and that the angle between the wind direction

and the isobaric line is approximately 30° . The value of this angle is nearly the same all the way round the storm area, although it is somewhat greater, 35° to 40° , in the north-east quadrant, and somewhat less, 20° to 25° , in the south-west quadrant. The quadrants for which this angle is greatest and least respectively probably vary with the direction of motion of the storm.

In an approximate way these figures enable the bearing of the centre to be estimated by the rule given by Milham (11, p. 273).



Let P A represent the direction towards which the wind is blowing ; draw P B, a line making an angle of 30° with P A, on the right of P A in the northern hemisphere, and on the left of it in the southern hemisphere : then P B will be the position of the isobaric line, and the line P C, at right angles to the isobaric line, and on the opposite side of the wind direction, will give the bearing of the centre. The above method is only approximate, since the angle between the wind and the isobars varies considerably in different storms ; and also the observer may not know which quadrant of the storm he is in, and therefore can only use the mean value of 30° . Eliot discusses this question in great detail in his *Handbook of Cyclonic Storms in the Bay of Bengal*, and it is possible that the method is more successful there than in any other part of the tropics, since the paths pursued are much less curved.

The direction of the ocean swell affords another valuable indication of the position of the centre, for if the latter is proceeding over a broad and uniform expanse of ocean, the swell moves directly from it, and in this way has often been a valuable sign when the centre has still been 500 or 600 miles distant.

The appearance of the huge bank of nimbus cloud on the horizon is a warning of the near approach of the centre, since the nimbus travels round the inner storm area and close to it.

Numerous rules for mariners are given in the many treatises on tropical storms. The chief are :—

(1) To avoid running before the wind, particularly when the centre of the cyclone is to westward (northern hemisphere), as this would bring the vessel directly into the centre and across the track of the coming cyclone.

(2) To avoid as far as possible the so-called “ dangerous half ” of the cyclone : that is, the north and north-east portion when the cyclone is moving north-west, and the south and south-east portion when it is moving north-east. All this applies to the northern hemisphere. These quadrants are considered the more dangerous because the wind velocity at any point is the resultant of the velocity caused by the revolution about the centre and the velocity of the general winds in the region through which the cyclone is moving. In the opposite quadrants these two velocities are opposed, and hence the resultant velocity is actually somewhat smaller than the velocity of the storm wind itself.

I.—6. THEORIES ON THE ORIGIN OF TROPICAL CYCLONES.*

The cause and dynamics of tropical storms are still very imperfectly understood, but a few important features are fairly clear. It is a well-known phenomenon that when a body of liquid is in slow rotation at the commencement, and is drawn towards some fixed centre, the velocity of each particle of the fluid increases as it approaches the centre. If the motion is perfectly symmetrical, the velocity of a particular particle about the centre is inversely proportional to the radial distance. The most familiar instance of this is the swirling motion that is developed in a bath when the plug is withdrawn from the bottom; the effect of the displacement of the water, from an average distance of a few feet from the centre, to about an inch from it, is sufficient to increase the inappreciable rotation that was present at the commencement into a vigorous vortex. There can be little doubt that the rotation of a cyclone is produced by such a displacement towards the centre. The initial rotation in this case arises chiefly from the rotation of the earth, since the actual motion of the air at any place is the resultant of the motion of the ground below it and the observable wind, the former of which is by far the greater. If now the centre be north of the equator, we see that the true eastward velocity north of it due to rotation of the earth is less than the velocity on the south side, the difference being such as would be produced by a counter-clockwise rotation about the vertical. This being magnified by an approach of the air to the centre, a counter-clockwise whirl is developed. The opposite is true in the southern hemisphere. Thus, if this analogy is correct, all cyclones in the northern hemisphere should rotate counter-clockwise, while all those in the southern hemisphere should rotate clockwise. This invariable difference in the directions of rotation of storms north and south of the equator is one of the best known facts about these storms, and affords an immediate and convincing verification of this part of the theory.

If, however, the surrounding air near the ground approached the centre without any outward displacement taking place above, there would be an accumulation of air above the central region, and consequently a real increase of atmospheric pressure there; whereas we know that the pressure in the middle of a cyclone is lower than elsewhere. Hence, while the air on the ground is moving inwards, that above it must move outwards; and the reduction of pressure inside shows that the amount of air that moves outwards above must be greater than the amount that moves inwards below. Such an outward motion of the upper clouds is suggested, though scarcely proved, by the distribution of the "cirrus," which is usually described as radiating from the centre.

As the outward and inward motions appear, so far as can be detected from the phenomena observed while the cyclone is developing, to occur simultaneously, it is not easy to say which of them is cause and which is effect. It is natural, however, to suggest that the outward motion, being the greater, is the cause of the other. Now if such an outward displacement took place in the upper air, it would leave behind it a region of reduced pressure, and the lower air would flow in towards the centre on account of this. Further, it is unlikely, on account of inertia and friction, that this would take place so rapidly as to neutralise the diminution of pressure completely, so that a low pressure would remain. Thus an outward displacement of the upper air affords an adequate explanation of the distribution of wind and pressure at the surface.

Two types of theory have been advanced to account for tropical cyclones; in their essential features they are both consistent with what has already been said, but they differ in the causes assigned to the outward displacement, which is a necessary feature of both. The first of these is the convectional theory. This requires a local heated region, over which a column of very moist and warm air develops. The initial effect of both the heating and the evaporation is to cause an increase in the volume of the air affected, and hence the upper air is lifted up by the expansion below it. It then flows out so as to readjust its level, giving the outward displacement we need for our theory. The formation of clouds and rain in the lower air is

* This discussion is by Dr. Harold Jeffreys.

a consequence of the fact that as the air moves inwards it comes to a region of lower pressure, where it expands and cools to some extent, and consequently cannot retain all the water vapour it held previously.

One difficulty of this theory is that these storms always form over the ocean, and always in summer. The land in summer becomes much hotter than the sea, and therefore we might expect on this theory that more cyclones would take place on land than at sea, whereas actually they all originate at sea. This objection would be met if it were shown that moisture is much more important in producing these disturbances than a rise in the temperature of the ground, equal to the difference between the summer temperatures of land and sea, would be. For this to be true requires a very high vapour pressure in the saturated air, which can only be obtained near the equator. This may, therefore, be the reason why revolving storms of this type are confined to the tropics.

Another difficulty is that the conditions over vast areas of the ocean must be very uniform, and that there is little reason why one region 200 kilometres across should be singled out as the place of origin of a storm rather than any other. It may be, however, that the whole of an extensive region is on the verge of developing into cyclones, and that only a trifling difference is needed to localise the disturbance when it develops. A way in which an outward displacement may arise from such a difference and lead to a persistent storm is described by Sir Napier Shaw in his Introduction.

It may be remarked that it is not necessary to the continuance of a storm that the causes that brought it into being should retain all their efficacy. In particular, it is not necessary that a strong vertical current should persist. When the revolving column is started, mere inertia will keep it going for a considerable time in spite of friction. This is probably the chief reason why such storms are able to move so far towards the poles when they have once been formed.

A revolving storm would naturally be expected to have a motion of translation on this theory. The conditions of its formation require it to start in the Tropics, but not at the equator, since a storm formed at the equator could acquire no rotation. Thus all such storms start in the regions of the trade winds, and the air forming their cores has initially the general motion of the places where they form. It retains this, only changing it in consequence of the widespread pressure difference in the regions through which it passes. Thus these storms have usually velocities of translation not very different from those of the general winds of their surroundings.

The chief alternative theory is the mechanical theory first suggested by Dove, supported by Thom, Meldrum and Fassig. The formation of circular whirls at the boundary between opposing currents of water in a millpond is well known, and this theory suggests that tropical cyclones develop in much the same manner at the boundary between two winds of extent comparable with 1,000 kilometres or more. The velocities in these millpond eddies, however, never exceed those in the main currents, while those in tropical cyclones always do so. In the absence of quantitative dynamical investigation, it would, therefore, be very dangerous to adopt the theory in this simple form as an explanation of tropical storms, though it might do for those of the temperate zone. Nevertheless it is true that such conflicting winds do exist on opposite sides of all the zones of formation of tropical cyclones, and that the only ocean in which there is no region flanked by opposite currents is the South Atlantic, where these storms do not occur. What probably happens is that the meeting of these winds leads to the formation of eddies and ascending currents, and that these form an important stimulus in deciding the locality of formation of cyclones according to the convectional theory. The most probable explanation is to be found, therefore, in a combination of the two theories.

I.—7. FREQUENCY OF TROPICAL STORMS.

The number of storms experienced in any particular region varies very much from year to year. Meldrum detected a relation between the frequency of storms near Mauritius and the sunspot period, and this has received further support from more recent observations. The records from the West Indies, the China Sea, and the Bay of Bengal, however, show no relation to sunspots nor to one another.

I.—8. STORM WARNINGS.

Storm warning systems, in varying degrees of perfection, have existed for many years in all regions affected by these storms. The main difficulty, encountered everywhere, except perhaps in the Bay of Bengal, is that the storms originate hundreds of miles away from land and travel over vast stretches of ocean where there are no land stations to report to the main shores. This is especially the case in the North Pacific, where the Philippine Islands are particularly unprotected, having only a few stations to eastward in the Carolines. On the other hand, the many and excellent stations of the Philippine Archipelago itself serve as outposts and issue detailed warnings to the China and Japan Coasts. It is hoped to establish soon a long line of stations running west to east from the Philippines to, and beyond, the Carolines, and also a similar line running northward from the Carolines, through the Bonin Islands to Japan. The best equipped service is undoubtedly that of the United States Weather Bureau in the West Indies, and a short account of recent improvements in this service will now be given.

During the Spanish-American War, Congress urged the inauguration of special protective measures for the large fleet in the Gulf of Mexico and the Caribbean Sea, and in June, 1898, authorised the Weather Bureau to establish and operate weather reporting stations at selected points in the West Indies and along the adjacent coast of the Caribbean Sea and the Gulf of Mexico.

Although the primary object of the new service was the protection of the U.S. naval forces against hurricanes, it was also found to be necessary on account of the rapid growth of commercial interests in these waters with the opening of the Panama Canal. Skilled observers of the Weather Bureau were located at ten well-distributed points within the hurricane area, and weather conditions were cabled twice a day to Washington throughout the hurricane season (June to November inclusive). At Headquarters the observations were charted, forecasts made, and storm warnings immediately telegraphed if disturbed conditions appeared likely in any locality. Soon after America entered into the recent War, steps were taken for a still further increase, and the number of storm-warning stations in the West Indies from which reports are cabled to Washington at 8 a.m. and 8 p.m. is now 30. Daily records are maintained at these stations, for climatological reasons, during the rest of the year. During 1918 the eastern portion of the area, *i.e.*, the Lesser Antilles and Porto Rico, which can be regarded as the gateway to the hurricane belt, has been made a separate forecast district, with San Juan, P.R., as district centre.

The success of this system led to the inauguration in the spring of 1919 of an extensive climatological service, embracing all the islands of the West Indies and the adjacent coasts of Central and South America, and extending from Barbados to Panama, and from Curaçao off the north coast of South America to Nassau in the Bahama Islands. Efficient climatological organisations already existed in Cuba, Jamaica, and the English and French Islands of the Lesser Antilles, but it is hoped there will be co-operation and systematic publishing of results and synchronous taking of observations among all these organisations, in order to establish first-class records, which will incidentally prove of additional use in the forecasting of hurricanes.

Additional plans of the Chief of the Weather Bureau for this tropical organisation—whose headquarters are to be at San Juan—include experiments in upper air conditions over the Tropics, to advance our knowledge of the general circulation of the atmosphere and of the development of storms within the hurricane area, and to aid in charting aerial routes for the aviator of the future.

Details of the various branches of the storm warning systems are not of any intrinsic interest and will not be discussed here. The use of certain flags and cones is customary in all parts of the Tropics, but the details differ in different regions and are constantly suffering modification in any particular region. For information on this point, as also for port facilities, etc., the reader is referred to some recent number of the Pilot Chart or Sailing Directions for the region in which he is interested.

SECTION II.—NORTH ATLANTIC OCEAN.

A.—WEST INDIAN HURRICANES.

West Indian hurricanes are storms of great severity, which have their origin near the equator, and sweep over a wide area of the Caribbean Sea and the Gulf of Mexico, at intervals, during the summer and autumn months only. The occurrence of these storms has been carefully chronicled for centuries, and detailed descriptions of the most destructive are to be found in many publications.

The pioneer work of Redfield, Reid, Piddington and many others, led to the results that these cyclones originate between the equator and the tropics, and that once formed, they always move away from the Equator. In the northern hemisphere they move first towards the west, turning a little northwards until they arrive about latitude 30° , *i.e.*, the northern limit of the north-east Trades. Arrived at this point their path is directed from south to north, next swerving to the east, while continuing to move northwards.

The zone of origin is within the belt of calm, sultry and rainy weather of the Doldrums, which belt, in this season of the year, lies north of the equator, and is bounded on the north by the north-east, and on the south by the south-east Trades. These south-east Trades actually cross the equator when the belt of calms is farthest north and being deflected by the rotation of the earth, become south or south-west winds.

It will be readily seen that if the mechanical theory be true, ideal conditions exist in the Doldrums for the formation of "whirls" in the lower strata of the atmosphere between the opposing currents.

When a storm develops in this region it is carried westwards by the prevailing westward drift of the general or primary circulation within the tropics.

The north-eastward recurving of these storms is dependent on the pressure distribution over the eastern and southern portions of the United States. The magnitude and the position of high-pressure areas over the United States and the western part of the North Atlantic Ocean determine the departures of these storms from normal courses.

Cyclones of the tropical zone of the Atlantic, north of the Equator, are most numerous in the western part of the ocean, near to the Antilles, and in the Gulf of Mexico.

From 1493 to 1855 there are records of 216 storms from this part of the ocean, distributed throughout the different months of the year as follows :—

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
5	2	6	1	1	4	29	59	51	40	12	6

and for the 12 years 1885–1896 the Hydrographic Service of the United States gives :—

June	July	Aug.	Sept.	Oct.
6	4	16	24	25

It is necessary to point out that the storms included in the first series are not all of tropical origin. Many, especially those in winter, are temperate zone cyclones which have come down from the American continent to the north of the Gulf of Mexico. In the posterior parts of these northern-born cyclones very strong winds blow from north and north-west, leading to intensely cold winters in the interior of the continent.

From the above tables it is evident, however, that the tropical cyclones are most numerous from June to October, and all later work has shown this to be the period of maximum frequency.

The opening of the Panama Canal has naturally resulted in an increased use of the West Indian and contiguous waters as routes for trading vessels and, as a corollary, in the increased importance of meteorological observations and data pertaining to this area, not only for climatological, but for forecast purposes as well.

In 1899 a chain of cable-reporting stations was established along the margin of the hurricane regions by the Chief of the United States Weather Bureau, and all well-developed storms occurring within the area have been carefully reported and charted from day to day. More recently, steps have been taken to extend the field of the Weather Bureau Service in the West Indies and adjacent seas, at the same time to equip more completely the existing individual stations, and to obtain two daily observations instead of the single daily report sent hitherto. As a result, the centres of these disturbances are now located much more accurately, and more data are available as regards intensity and size. An admirable report, showing tracks of hurricanes from 1876-1911 inclusive, has been drawn up by O. L. Fassig (28), and it is on a study of this that the present account is largely based. The charts have, however, been brought up to date (1919) from information compiled from the *Monthly Weather Review* of the U.S.A. from 1911-1919, from the tracks of hurricanes in the Monthly Pilot Charts of the North Atlantic Ocean, published by the Meteorological Office (36), and from the Hydrographic Charts of the U.S.A.

II.—1. FREQUENCY OF HURRICANES.

In early years the data on which the records of storm frequency were based were few, and hence certain discrepancies are found between the figures given by different observers. For example, the records of the United States Weather Bureau show 11 storms of hurricane force in the year 1886, while the late Reverend Father Viñes, Director of Havana Observatory, refers to 20 storms in the same year, a figure which doubtless includes some minor disturbances. In later years, however, more complete information has been available, and hence the exact determination of path and intensity has been facilitated, so that the agreement between different observers is rendered more close.

Fassig gives the following figures for the years 1876-1911 :—

	May	June	July	Aug.	Sept.	Oct.	Nov.	Season
Number of storms ..	1	8	5	33	43	42	2	134
Percentage frequency..	1	6	4	25	32	31	1	—

and for the years 1912-1919 (inclusive), the following figures have been obtained:—

	May	June	July	Aug.	Sept.	Oct.	Nov.	Season
Number of storms ..	—	—	3	6	11	3	2	25
Percentage frequency..	—	—	12	24	44	12	8	—

The two tables only give approximate agreement between the percentage frequencies ; this is easily understood when the fact is taken into account that the tables represent very different periods of time, namely 35 years and 8 years respectively, since the number of storms occurring year by year is very variable. (See Plate I, Fig. 1). For example, of the 25 storms reported from 1912 to 1919, eight occurred in 1916 alone, and only one in 1919. In fact, in only two previous years out of the last forty were more storms noted than in 1916, namely in 1886 and

VARIAION OF YEARLY FREQUENCY OF WEST INDIAN HURRICANES

NUMBER OF STORMS.

YEARS

Year	Number of Storms
1878	1
1879	0
1880	5
1881	4
1882	4
1883	2
1884	2
1885	4
1886	2
1887	4
1888	11
1889	11
1890	6
1891	8
1892	1
1893	7
1894	2
1895	5
1896	4
1897	5
1898	1
1899	4
1900	5
1901	7
1902	1
1903	3
1904	5
1905	1
1906	8
1907	3
1908	3
1909	7
1910	3
1911	1
1912	1
1913	1
1914	0
1915	0
1916	4
1917	8
1918	4
1919	6
1920	1

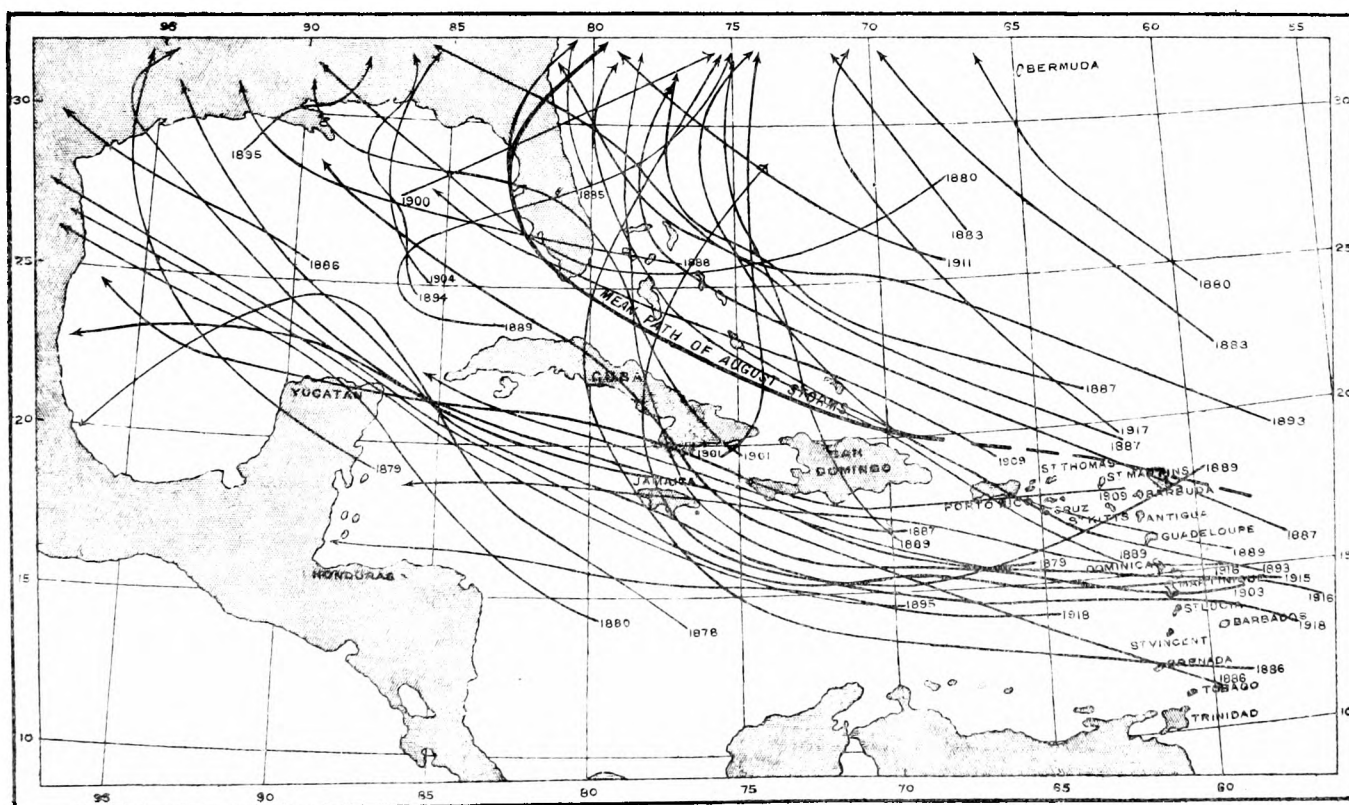
A map of the North Atlantic Ocean showing the mean path of storm centres, normal pressure, and high pressure areas. The map includes a grid of latitude and longitude. The mean path of storm centres is indicated by a thick black line with an arrow pointing towards the northeast. The normal pressure is shown as a dashed line labeled 'NORMAL PRESSURE'. High pressure areas are marked with 'H I G H' and '30.10'. The map also shows the outlines of North America, Europe, and Africa. Various symbols (circles, squares, triangles, diamonds) are plotted along the storm path, representing individual storm centres. The map is titled 'MEAN PATH OF STORM CENTRES' and includes a scale bar at the bottom.

▲ SHOW ORIGIN OF JUNE AND JULY STORMS
 □ SHOW ORIGIN OF AUGUST STORMS.
 ○ SHOW ORIGIN OF SEPTEMBER STORMS
 ◆ SHOW ORIGIN OF OCTOBER STORMS.

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The map displays the Caribbean Sea and surrounding landmasses, including North America, Central America, and the Caribbean Islands. A grid of latitude and longitude lines is overlaid. A dashed line represents the mean path of typhoon and hurricane storms, with arrows indicating the direction of movement. The path generally trends from the northwest towards the southeast. Specific years are marked along the path: 1886, 1889, 1901, 1906, and 1916. Labels for various islands and regions are present, including YUCATAN, CUBA, JAMAICA, TURKS ID., SAN DOMINGO, PORTO RICO, ST. THOMAS, ST. MARTINS, BARBUDA, SCRUB, ST. KITTS, ANTIGUA, GUADELOUPE, DOMINICA, ST. LUCIA, ST. VINCENT, GRENADA, TOBAGO, and TRINIDAD. The text 'MEAN PATH OF TYPHOON AND HURRICANE STORMS' is written along the dashed line.

Figure 2.



Pa. 26881/443 Wc 15372 B. D. 6258/579 625. 7/22.

1887. Besides these eight hurricanes in 1916, there were several minor disturbances which, although locally severe, were of such short duration that their tracks were not charted. Altogether, the frequency for the 44 years, 1876–1919, is as follows:—

	May	June	July	Aug.	Sept.	Oct.	Nov.	Season
Number of storms ..	1	8	8	39	54	45	4	159
Percentage frequency..	1	5	5	24	34	28	3	—

The above table shows that 86 per cent. of the hurricanes occur during the months of August, September, and October, leaving only 14 per cent. for the remainder of the season. More detailed observations of the various storms show that the active season does not really begin until the second decade in August, and is then maintained until near the close of October, thus covering about 10 weeks. The abrupt increase in the frequency in August and the equally abrupt decrease at the close of October are remarkable features of the seasonal distribution.

The variation of the yearly frequency is shown by the graph on Plate I, Fig. 1. It ranges from a total absence of storms, as in the years 1877, 1897, 1913 and 1914, to a maximum of 11, occurring in the years 1886 and 1887.

The average frequency for the entire hurricane season is four storms, with a distribution throughout the season of one storm for each of the months of August, September, and October, leaving one for the remainder of the season.

The Government Meteorologist of Jamaica has published in his Weather Report, No. 449, for November 1915, a corrected list* (37, 1915, p. 620) of severe storms and hurricanes that have passed over Jamaica and done more or less damage there between the years 1655 and 1915. In correcting his list, he has omitted those which, though represented on some charts as crossing Jamaica, were not felt as severe storms on the island or missed it completely.

The increase of frequency in August and September can be explained on the thermal theory as follows: The belt of calms (*i.e.* the Doldrums) separates the general wind circulation of the northern from that of the southern hemisphere, and this belt shifts northward or southward with the sun, but lags, so that the sun reaches its maximum north declination in June, while the "Meteorological Equator" is farthest north in August. This belt is the birthplace of tropical cyclones or hurricanes, but it is only when it lies farthest north that the component of the earth's rotation about the vertical becomes so great that local convection can give winds of hurricane strength in the region into which the air is drawn.

Why the storms should be more frequent in some years than in others is not yet understood.

II.—2. TRACKS OF HURRICANES.

Very little is known as to the exact places of origin and extinction of these storms, but it is probable, as mentioned above, that they originate within the "Doldrums." Some of them originate to the south of the Cape Verd Islands.

The storm field varies in diameter from 20 to 100 miles. Originally the whirl is of small radius, but of great intensity. As it travels its size increases, but generally its intensity diminishes. The same air particles do not form part of the whirl throughout its entire career; on the contrary, there is a new supply of air taken from the districts traversed as the whirl moves onwards.

The West Indian hurricane belt embraces roughly the Caribbean Sea, the Gulf of Mexico and the West Indies, extending from longitude 55° W. to 95° W. and from latitude 12° N. to 30° N. The points of origin are distributed fairly uniformly throughout this area. (See Plate I, Fig. 2).

The tracks of these storms, as stated above, are approximately parabolic. There is a well-marked main path of greatest frequency throughout the northern half of the Caribbean Sea, extending almost due east to west between the Windward

* The *lower* limit of wind velocity adopted for qualifying in this list is one of 60 miles per hour.

Islands and Jamaica, taking a north-west course through the Yucatan Channel, and crossing the Florida Peninsula into the North Atlantic, with a north to north-east trend. (See Plates II and III.)

There is a secondary path not so well defined, extending from the northern group of the Windward Islands in a west-north-west direction across the Bahama Islands and recurving east of Florida in the North Atlantic Ocean.

Between these two paths lie the Greater Antilles—Cuba, Jamaica, Haiti and Porto Rico. Of these, Porto Rico and Haiti are comparatively free from the devastating winds near the hurricane centres; the western half of Cuba is crossed in the recurve of a large percentage of the storms of the Caribbean Sea, *i.e.*, those of the main branch referred to above; and over Jamaica, 15 storms of hurricane severity have been reported during the last century (1815-1915).

These two main hurricane tracks coincide with the two branches of the great equatorial current of the North Atlantic Ocean. The main stream of this passes through the Caribbean Sea and the Yucatan Channel into the Gulf of Mexico and out again into the Atlantic, through the narrow channel between Havana and Key West. Here it meets the northern branch of the equatorial current, which is a wide surface drift of equatorial waters passing through the Bahama group of the Islands, forming later in its course the eastern portion of the Gulf Stream (see track of Ocean currents facing page 579, U.S.M.W.R., December, 1917).

In the charts for each month of the hurricane season (Plates II and III) the actual paths of each storm, as reported, are shown, and also the mean or normal path for each month, the latter being obtained, as in Fassig's work, by plotting the average latitude of the storm centres for every 2° of longitude. These normal tracks therefore represent the mean geographical paths for their respective periods and are not actual storm paths. It may be noted that they do not necessarily pass through either the mean point of origin or the mean point of recurvature.

The normal track for the entire season, as determined from 159 hurricanes occurring during 1876-1919 is shown on Plate IV, Fig. I, along with some of the most abnormal tracks on record.

From the normal track given it is seen that the first branch of the parabolic trajectory extends approximately between the parallels of 18° and 20° N. in a direction west by north; it then extends to latitude 28° N. moving first north-westwards and then north. The point of recurve of the normal track, which is not the mean point of recurve of the actual storms, is seen to be in latitude 28° N. and longitude 82° W., *i.e.*, over Central Florida. From this point the trend is north-eastward over the North Atlantic, along the second branch of the parabola.

The normal paths for the individual months do not differ greatly from the normal path for the season, though in individual tracks there are, of course, great variations and abnormalities. (See Plate IV, Fig. 1). There are, however, certain peculiarities month by month in the place of origin, and the subsequent path followed, and in the position of the point of recurve.

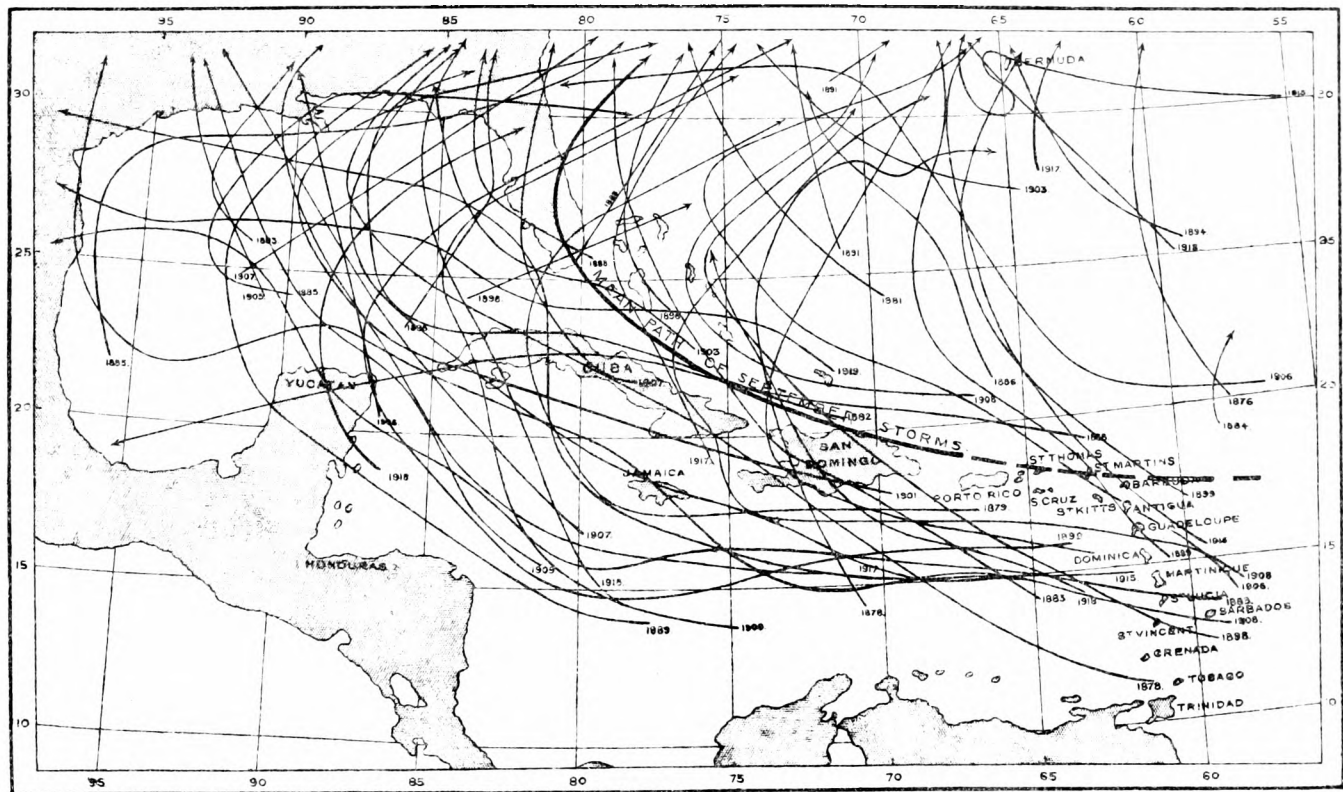
The mean latitude of the point of origin from May to November is 20° N., and it has this value for each month except October, when it is 22° N.

In longitude, however, there is more variation. In June and July the mean longitude of the point of origin is 80° W.; in August, 70° W.; in September, 71° W.; and in October, 76° W.

Thus the August and September storms have their origin much further east, and consequently the majority of them (about 80%) originate in the first branch and pursue a normal parabolic track. Those having their origin in the western waters of the Caribbean Sea (*i.e.*, those in June, July and October) have a tendency to move immediately north-west and north, *i.e.*, they start in the recurve portion of the parabola and then enter the second branch; or in the higher latitudes in the western portion of the hurricane area they may immediately move north-eastward along the second branch.

Of the June and July hurricanes, which have the most westerly points of origin, as many as 30% are formed in the recurve and only a little over 50% in the first branch. These storms are comparatively infrequent, and during the past century

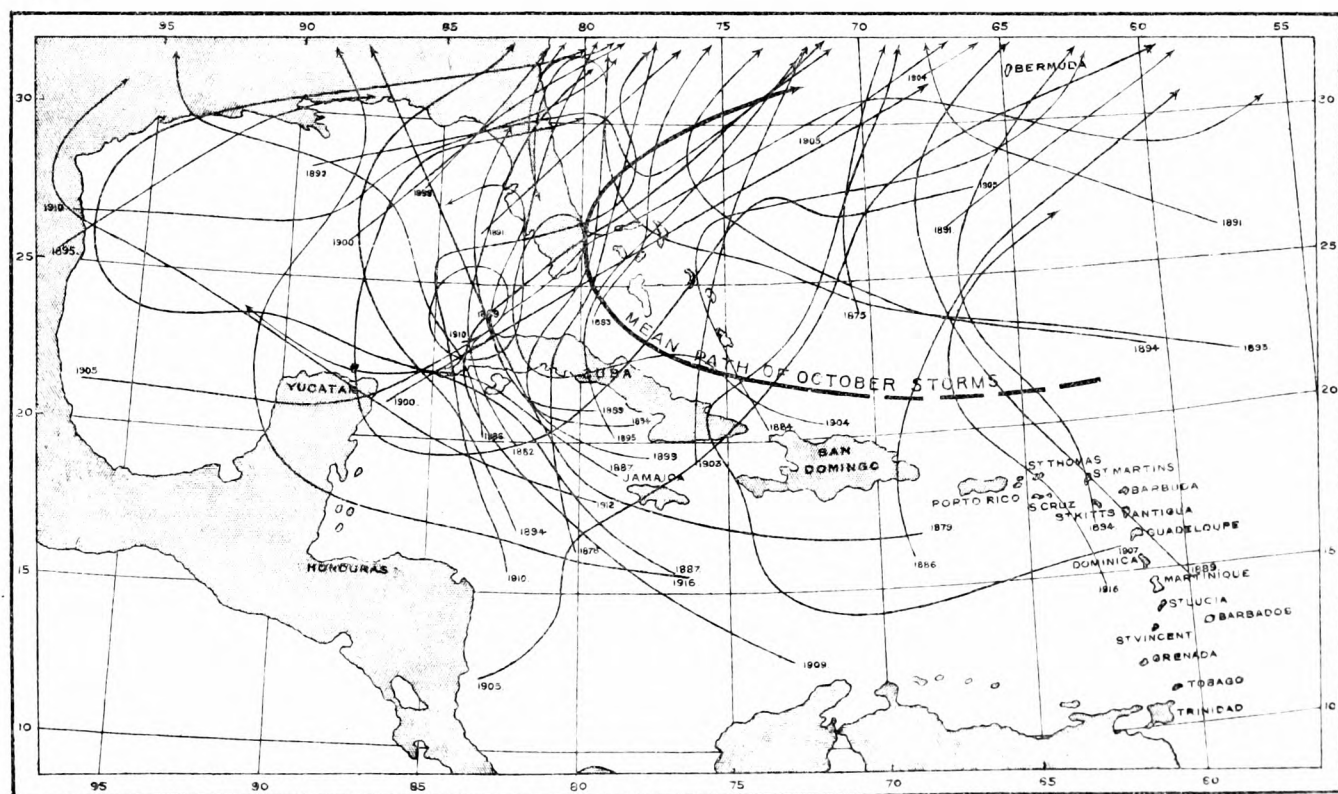
Figure 1



PATHS OF WEST INDIAN HURRICANES DURING SEPTEMBER FROM 1876-1919.

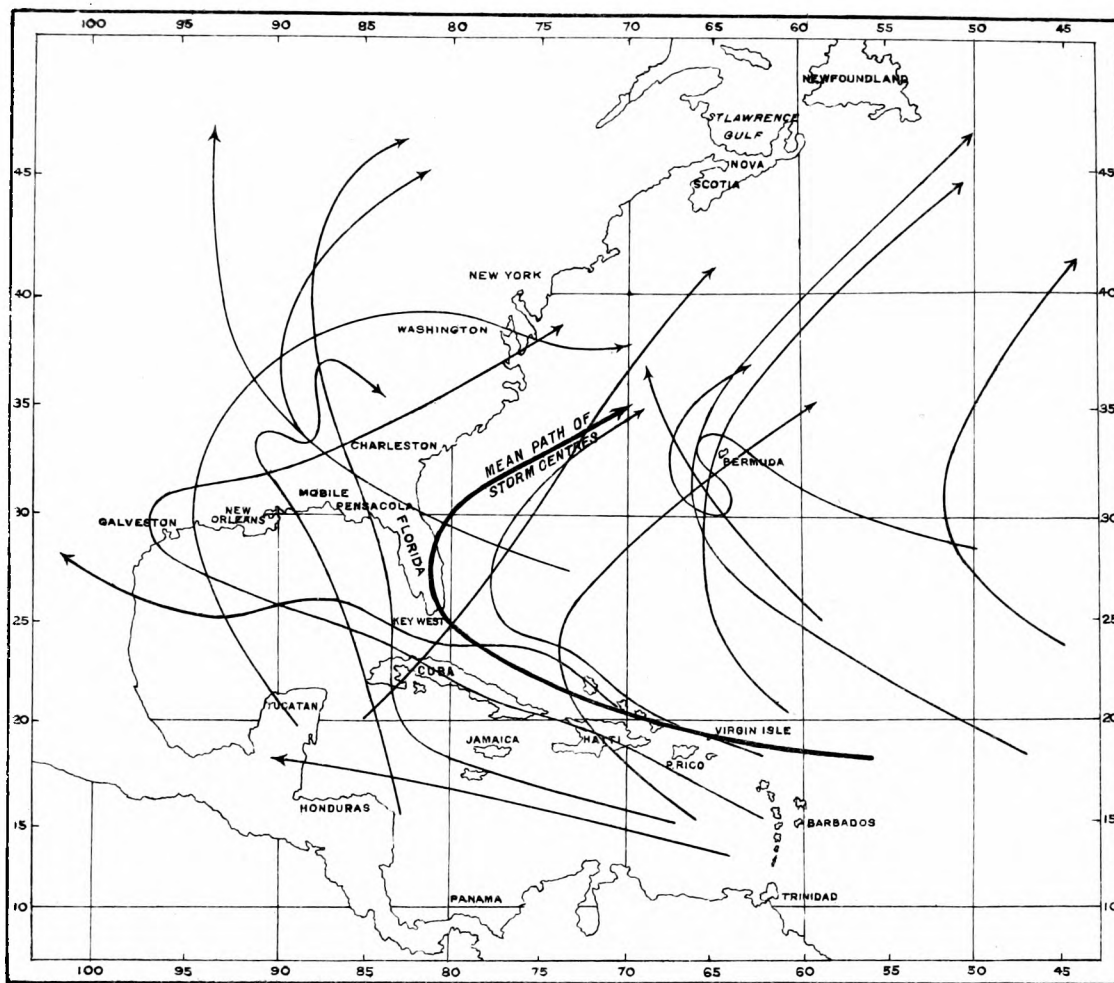
From Fassig's "Hurricanes of the West Indies" (with additions.)

Figure 2.



PATHS OF WEST INDIAN HURRICANES DURING OCTOBER FROM 1876-1919.

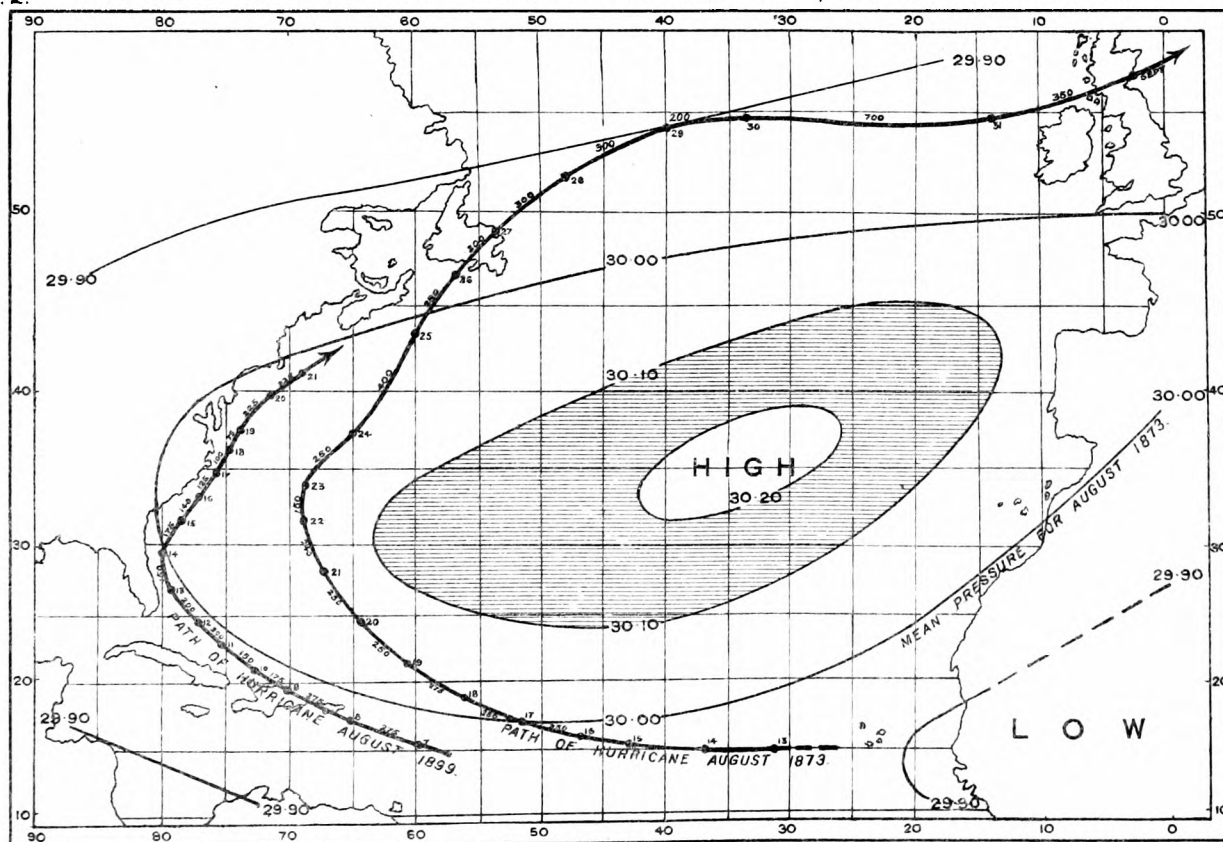
From Fassig's "Hurricanes of the West Indies" (with additions.)



ABNORMAL TRACKS OF WEST INDIAN HURRICANES.

From, Hildebrandsson and de Bort *Les bases de la Météorologie Dynamique* (with additions for 1900-1920.)

Fig. 2.



HURRICANE PATHS OF AUGUST 14-31, 1873, AND AUGUST 7-20 1899, AND THE DISTRIBUTION OF ATMOSPHERIC PRESSURE OVER THE NORTH ATLANTIC.

The black dots indicate the positions of the centres of the storms at 8 a.m. each day.

From Fassig's *"Hurricanes of the West Indies."*

the average has been one storm in every three years. The tracks are shown on Plate II, Fig. 1. The paths pursued led in most cases north-west or north; only in two instances (1887, 1916) did a storm arise in these months as far eastward as the Windward Islands.

Six hurricanes of June and July failed to recurve within the Tropics, three of these passing up the valley of the Mississippi, one passing up the east coast of Florida, and two disappearing in the Gulf of Mexico.

The August storms, originating almost always east of Cuba, pursue a comparatively long track in the first branch and recurve in a higher latitude than the earlier and later storms. The mean track and the individual tracks are shown on Plate II, Fig. 2.

Many of these storms cross the Gulf of Mexico in a north-west direction and fail to recurve, passing over the mainland of Mexico and across the south-western States. These storms occasionally originate far to the east of the Windward Islands; a notable instance is the hurricane of August 14–31, 1873, which formed the subject of careful study by Captain Toynbee. (See Plate IV, Fig. 2).

Storms in Porto Rico occur oftener in August than in any other month, but even then they are infrequent.

The September storms, also originate well to the eastward end of the hurricane area, but the distribution of origins is much more scattered, as many as 20% of the origins occurring in the recurve. Only a small percentage of the storms fail to recurve, but many enter the southern States before recurving. (See Plate III, Fig. 1).

The August and September hurricanes extend further across the Gulf of Mexico than those of June, July and October. The latitude of the point of recurve of September storms is the same as that for June and July storms, although the recurve of the September storms is somewhat farther east. A noteworthy abnormal September storm was the great Galveston hurricane of September 5th, 1900. (See Plate IV, Fig. 1). This originated at a point 15° N. and 62° W., and had a very remarkable track, curving northwards as far west as 100° W. It had an exceptional increase of violence on making land at Galveston, and caused 3,000 deaths there and over 6,000 in the whole of Texas. The wind force fell off after the storm had passed Galveston, but increased again in the neighbourhood of the Great Lakes. The disturbance reached its maximum intensity over Newfoundland and eastwards over the Atlantic, where hurricane winds prevailed for two days.

October Storms.—These are far less regular in track than the September storms. A striking feature is the convergence of tracks toward the Yucatan Channel and the western end of Cuba. The individual storms are, however, very erratic in their translation, and it is unsafe to assume that any given storm will recurve within fixed and narrow limits. This is especially the case with regard to latitude, the point of recurve being sometimes in low latitudes, and occasionally as far north as 40° N. The tracks are shown on Plate III, Fig. 2. In longitude the variation is not so marked; the point of recurve for the majority is between 75° W. and 85° W. but cases also occur at 67° W. and 99° W.

The average latitude for the point of recurve for October is 25° N., this being the most southerly for the season.

As many as 43% of the October storms have their origin in the second branch and move in some direction between north and east.

II.—3. THE RECURVE.

The point at which these storms recurve is of the utmost importance, especially with regard to the forecasting of the subsequent path. Also the recurve is often the seat of maximum energy of the disturbance, since after the recurve, and as the area of the storm increases, its fury seems to subside.

The general north-eastward recurving of the storms is dependent on the pressure distribution over the eastern and southern portions of the United States. The

magnitude and position of the high pressure areas over the United States, and the sub-permanent high over the middle latitudes of the North Atlantic Ocean, determine the departures of these storms from their normal courses.

The following rules have been given by Garriott for the guidance of the forecaster in determining the course of a hurricane (26):—

- (a) "A hurricane does not move directly towards a region of high pressure when such an area is not moving perceptibly, but follows in behind it. If the high moves east or north-east off to sea at a normal rate of progression, opening up a trough after it, the hurricane moves north or north-east in a normal path. If the high hangs persistently over the eastern coast of the United States, the hurricane is deflected far to the west before it can recurve.
- (b) "If rain falls freely before the hurricane comes to land, it is likely to die out quickly; if the downpour begins after reaching land it is probable that a long and vigorous march is yet before it.
- (c) "When a West Indian hurricane is moving westwards, in the longitude of eastern Cuba and is north of that Island, it will recurve east of the south Atlantic coast of the United States, when an area of high pressure covers the north-western States.

If the hurricane is moving westward over Cuba or the Western Caribbean Sea, when an area of low pressure occupies the north-west, and the pressure is high in the eastern States, it will probably move to the Gulf of Mexico and reach the Gulf Coast after recurving.

- (d) "It may be assumed that, with a nearly normal distribution and movement of atmospheric pressure over the United States, hurricanes will recurve near to longitude 80° W., and between latitudes 25° W. and 28° N. When a hurricane is central east of Cuba and an area of high pressure is advancing eastward over the Gulf and South Atlantic States, the hurricane will probably recurve east of the Bahamas. When the hurricane reaches central Cuba, or longitude 80° W., and an area of high pressure is over the west Gulf or south-western States, the hurricane will probably recurve over Florida or the east Gulf. When the hurricane reaches the 75th meridian, and an area of high pressure is over-spreading the interior and eastern districts of the United States, with stationary or falling barometer over the west Gulf or south-western States it will probably advance westwards over the Gulf of Mexico.

"When a hurricane is moving north-westward towards the south Atlantic or middle Atlantic coasts of the United States, and the pressure is abnormally high over the north-eastern States and the Canadian Maritime provinces, the chances are that the storm will not recurve but will be crowded in upon the coast and develop destructive energy."

The average point of recurve for the various months is as follows:—

	Latitude	Longitude
June and July	28° N.	87° W.
August	30° N.	83° W.
September	28° N.	81° W.
October	25° N.	80° W.

Thus the advance of the season is marked by a slight increase in the latitude of the point of recurve, the most northerly point being reached in August; after this there is a gradual retreat southwards until October. The movement of hurricane paths from south to north and return southwards coincides very closely with the movements of the Trades and the equatorial belt of calms.

II.—4. VELOCITY OF MOTION IN THE DIFFERENT REGIONS.

The velocity of motion for average normal storms is now so definitely established as to be a decided practical advantage to the forecaster ; as the velocity of motion itself is comparatively slow, of the order of 12 miles per hour, a more timely warning of the approach of the storm can be given once its point of origin and initial progress have been determined.

Individual storms show large departures from the mean, but the variations here are less than are the corresponding ones for higher latitudes. There is a decided systematic variation of the daily motion of these storms as they proceed along their courses. This may be put in evidence either by finding the average movement in the first, second, third day, and so on, from the commencement of the storm, or by finding it in days at definite intervals before and after the recurve. Both methods have their advantages and disadvantages. To measure the time from the origin has the drawback that the growth of a storm is often slow in the early stages, so that it may be some days old before it is recorded. To measure it from the recurve, however, has the more serious drawback that a very large number of storms have no recurve, either dying out while still moving westward or originating in the eastward branch. Some storms have been nearly stationary when encountering an anticyclone or other obstacle. For instance, the centre of the storm of October 14 to 20, 1910, apparently moved in a small circle, remaining in the same position between Havana and Key West for five successive days. That of September 1 to 9, 1915, remained near Bermuda for five days ; it doubled back along its own course, its velocity in the recurve being only about 100 miles per day. Fassig states that the velocity of progression in the first branch is in harmony with the average velocity of the westward drift of the atmosphere in the portion of the Trade Wind belt in which these storms occur. The recurve takes place when the storm enters the eastward drift of middle latitudes.

Fassig gives figures for the average daily movements of 136 hurricanes observed between 1876 and 1911. Days in the first branch are counted from the origin, and those in the second branch from the recurve, in the case of recurving storms, and from the origin in the case of storms that moved eastward from their commencement. To these have been added results derived from the data obtained from 1912 to 1919, so that altogether 44 years' observations are included. For the later days of the paths Fassig's results are compiled from only a few storms, but it is not clear from the table what the number of observations available in each case is. In combining the results, therefore, his data and the later ones are given weights proportional to the number of storms in the same class that spent corresponding days south of latitude 30° N. In the absence of a strong secular variation in the distribution this would not give rise to any important error. The normal velocities are as follows, in miles per day.

FIRST BRANCH.

Number of Day from Origin	May to July	August	September	October	Year
1	273	357	292	224	297
2	248	325	252	223	272
3	210	285	247	201	250
4	273†	285	261	260	270
5	400*	279	210	251†	254

* Indicates 2 or 3 examples only ; † indicates 4 or 5 examples. All others, with one exception, have at least 9.

SECOND BRANCH.

Number of Day from Com- mencement of Eastward Motion	May to July	August	September	October	Year
1	279	257	260	249	258
2	340	383	408	401	391
3	—	356*	495	428	457
4	—	200*	404†	497	401

We see, therefore, that in the first branch and in the first day of the second branch, which is the day in which the eastward movement starts, and therefore the day of recurve in the case of recurring storms, the mean velocity is about 11 miles per hour. In the second branch the velocity rises to nearly 19 miles per hour in two days. During the recurve itself the velocity is slightly, but definitely, less than in the earlier part of the path. The difference is much more marked in tropical cyclones in other regions. There is no progressive variation in the daily motion as storms proceed along the first branch. In the second branch the storm may develop into a temperate-region cyclone, afterwards proceeding to Newfoundland or even right across the North Atlantic and into Europe, as in the case of the 1873 cyclone shown on Plate IV, Fig. 2. Its velocity usually increases as it gets further north, the ordinary velocity of translation of a cyclone in middle latitudes being 20 to 30 miles per hour.

II.—5. DURATION OF HURRICANES.

Fassig uses the term "duration" to denote the time for which a hurricane is south of latitude 30° N. In the majority of cases this includes the first branch and recurve of the storm, the average point of recurve being in latitude 28° N., and sometimes as many as three more days in the second branch. There are great differences between the durations of different storms. The average duration is about six days, with extreme limits of one day and 19 days. The average duration in the first branch is about three days, and in the second branch two days. These times vary somewhat with the progress of the season, the storms of August and September spending a somewhat longer time in their westward motion than do those of the earlier and later months of the season. Many storms reach the latitude of 30° N. before the recurve is completed, so that the duration may be considerably less than the actual life of the storm. The following figures have been obtained by combining Fassig's tables with the records of hurricanes from 1912 to 1919, both inclusive.

NUMBER OF HURRICANES TABULATED ACCORDING TO DURATION IN THE FIRST BRANCH

Duration (days)	May to July	August	September	October	Season
1	4	5	8	0	17
2	2	4	9	9	24
3	1	7	7	2	17
4	3	2	4	3	12
5	2	3	2	2	9
6	—	8	6	1	15
7	—	1	3	—	4
8	—	1	2	—	3
9	—	—	1	—	1
Total number..	12	31	42	17	102
Mean duration (days)	2.7	3.9	3.7	2.4	3.5

* Indicates 2 or 3 examples only; † indicates 4 or 5 examples. All others, with one exception, have at least 9.

NUMBER OF HURRICANES TABULATED ACCORDING TO DURATION IN THE RECURVE AND THE SECOND BRANCH

Duration (days)	May to July	August	September	October	Season
1	1	6	14	8	29
2	9	12	17	12	50
3	—	1	10	5	16
4	—	1	2	3	6
5	—	0	2	1	3
6	—	1	1	—	2
Total number..	10	21	46	29	106
Mean duration (days)	1.9	2.0	2.2	2.2	2.1

It may be pointed out again that, as in §4, many storms are recorded in only one of these tables, while others were first recorded when north of 30° N., and therefore are not included in either. The total number of hurricanes recorded in the 44 years was 160, but only 148 of these originated south of latitude 30° N. The following table gives the number and mean duration of these storms in the various months. Durations are given in days.

Month	Number of Storms	Longest	Shortest	Mean
June	9	6	3	4.1
July	7	9	1	4.9
August	37	10	2	5.3
September	52	19	1	6.0
October	43	12	2	5.7
Total	148	19	1	5.6

II.—6. RAINFALL.

Some details as to rainfall in the West Indies, due to hurricane activity, are given below. An idea of the amount of precipitation during hurricane rains is given from the following details with regard to Porto Rico (37, 1916, pp. 329-337).

The influence of the hurricane season is clearly shown in the figures giving the average frequency of *excessive* rains throughout the year, for a period of 13 years (1899-1911).

Precipitation is considered excessive when it equals or exceeds 2.5 in. (63.5 mm.) in 24 consecutive hours; or 1 in. in 1 hour.

AVERAGE FREQUENCY OF EXCESSIVE RAINS AT SAN JUAN

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Number of excessive rains.	12	1	6	11	16	19	24	27	25	20	20	12	193
% Frequency ..	6	1	3	6	8	10	12	14	13	10	10	6	

Thus 70 % of the excessive rains during the year occur in the hurricane season, June to November.

The distribution of rainfall produced by the exceptionally severe storm on August 8, 1899, is shown on Plate V, Fig. 1. The centre of the hurricane passed directly across the centre of Porto Rico from east to west, and the rainfall was accurately measured by trained observers all along the path of the storm. The weight of water precipitated upon the island in the 30 hours during which the

storm prevailed there has been calculated. Calculations based upon an average fall of 10 inches over the entire island indicated that the total weight of rainfall was approximately 2,600,000,000 tons, equivalent to 720,000 tons per square mile, or 1,100 tons per acre. The maximum 24-hour rainfall was 23 in., measured at Adjuntas.

In one of the most intense hurricanes on record in the history of the Mexican Gulf Coast, that of September 29, 1915, the following information as to rainfall is available.

The total precipitation at New Orleans during the passage of the hurricane from 2.35 a.m. to 11.30 p.m. of the 29th was 8.20 in. The rate of precipitation increased just before the wind shifted from north-east to east near the middle of the day; fell off both during the early morning and the afternoon, when the wind was from the east; and increased again as the wind was shifting from east to south-east. Precipitation almost ceased when the wind veered from south-east to south.

The heaviest precipitation occurred near the centre and within a distance of 25 miles to the east of the centre; heavy precipitation also occurred over a large area in the eastern segment of the storm, while to the west of the path of the centre the precipitation diminished rapidly, and 50 miles to the west of the centre track there was only a negligible amount.

An interesting paper (30) on the influence of tropical cyclones on the weather in the Valley of Mexico gives some explanation of the extraordinary rainfalls that have been recorded in Mexico City since 1877, when the Observatory was first founded.

On the evening of September 30, 1915, about 5 p.m., torrential rains began and lasted till 7.30 a.m. of the following day, with the exception of from 7.55 p.m. to 8.30 p.m. The fall is given as 89.7 metres (probably 89.7 mm. is meant) and its intensity as 1.5 mm. per minute. This was probably the maximum intensity during the downpour. The notable intensity of this rain suggested a cyclonic cause, and on investigation it was found that a tropical cyclone had crossed the Gulf and was centred on this day a little north of New Orleans. The great distance of this cyclone, and the height of Mexico City above sea level, made it appear unlikely that the heavy rains were a direct result of such a distant disturbance. The motion of the nimbus clouds was from north-east, another remarkable fact, on which Lopez does not comment. A remarkably similar case, however, occurred in October 1916, when a cyclonic storm, whose trajectory was very similar to that of the earlier one, traversed the Gulf; and again excessive rains, of intensity 0.75 mm. per minute, were reported in Mexico City. The clouds on the day of greatest rain were coming from south-east at Tacubaya and from west at Puebla. The influence of tropical cyclones on the weather was then investigated by the author, with the following results:—

- (1) Of the eight tropical cyclones which had appeared in the Gulf of Mexico since the weather map of Mexico City Observatory was first published, all influenced the weather of the Central Plateau.
- (2) Those which recurved to the north of the peninsula of Yucatan caused overcast days, with a dense bank of nimbus coming from the first quadrant and causing the most intense rainfalls ever experienced here.
- (3) When the cyclone has reached the coasts of Tamaulipas, the weather has not been bad, but the rains have increased in the district touched by the disturbance. For instance, the flood of Monterrey caused by the cyclone of August, 1909, caused torrential rains from the 26th to 29th, the total amount being 434 mm.

Maps and tables of these storms can be seen in the original paper.

The suggested explanation is that these are hurricane rains developing in the rear quadrant of the cyclone, where the areas of rain and cloud have been shown by observation to extend as far as 500 nautical miles in radius from the centre of the disturbance (*i.e.*, 925 kilometres, or 8° of longitude). To the north and west of the cyclone the rain area does not often extend to a greater distance than 200 miles

from the centre. The precipitation is augmented by the mountainous configuration of the country. Lopez suggests that the rain area surrounding a West Indian hurricane is similar to that shown by Algué for typhoons of the Philippines, namely, of elliptical shape, prolonged to the rear, where the rains are always most intense. The very variable wind directions, however, suggest that the phenomenon involves other determining factors.

The following important points :—

- (1) Barometric changes,
- (2) Strength and direction of winds,
- (3) Size of disturbances (diameter),
- (4) Size of area of destructive winds,
- (5) Cloud information,
- (6) Forecasts or systems of warnings now in use,

are all dealt with in detail in the General Introduction, and, as they are common to all tropical revolving storms it is not necessary to repeat them in connection with West Indian hurricanes.

Before closing this section, however, we shall give accounts of typical storms for the various months of the hurricane season and a fuller account of an exceptionally severe storm.

As far as possible these accounts will refer to typical storms of recent years, since numerous detailed reports of earlier storms are available in previous reports of Viñes, Garriott, Fassig, and others.

II.—7. TYPICAL JUNE AND JULY STORM: THE MIDDLE GULF COAST STORM OF JULY 1-10, 1916.

The year 1916 was remarkable in that three hurricanes were reported in July, whereas the frequency for the past century is only one in every three years.

The storm reported here in detail is individually quite typical of those occurring in the early part of the "hurricane season." Its path is shown on Plate V, Fig. 2 (Track I), and it is seen to agree with the general principles laid down for June and July storms in §II, 2 of this present report (West Indian Section).

The first definite indications of this disturbance were noted on the morning of July 1 at Swan Island (17° N., 84° W.), where the barometric 24-hour fall since the morning of the 30th was 0.06 in. By the morning of the 2nd it was clearly evident that the disturbance was well defined and had a northward movement. Fresh southerly winds and rain prevailed at Swan Island; the barometer read 29.74 in. Warnings were telegraphed to Weather Bureau stations along the Atlantic and Gulf Coasts.

The progress of the storm until the evening of the 3rd is seen from the chart. So far the storm was not of much intensity; notices were issued to that effect.

On July 4 a report was received from 125 miles north-west of Havana, giving a barometer reading of 29.72 in. with a south-east wind of 40 miles per hour. Reports from ships also came to hand on the morning of July 4, which showed that the storm had passed through the Yucatan Channel during the early night of the 3rd and had apparently attained only moderate intensity until just before that channel was reached, after which there was a marked increase in its activity, the effects being felt as far east as Havana. The lowest barometer during the period, 29.40 in., was reported from a ship in latitude $22^{\circ} 43'$ N., longitude $85^{\circ} 58'$ W., at 2 a.m. of July 4; a strong gale was then blowing from the south-east, indicating that the storm centre had passed but a short distance to the westward.

At 8 p.m. on July 4 pressure was falling along the Gulf Coast, where north-east storm warnings were then issued. At 9.50 p.m. advices were issued to the effect that the storm centre had passed through the Yucatan Channel, and caution was advised for all vessels in the Gulf of Mexico.

On the morning of July 5 the barometer along the middle Gulf Coast ranged from 29.56 in. to 29.60 in. with north-east winds, which at Pensacola reached a velocity of 48 m.p.h., indicating that the storm centre had moved across the Gulf with unusual rapidity and was then somewhere between Mobile Bay and the mouth of the Mississippi. The storm passed inland during the afternoon, with a barometer reading of 28.92 in. at Mobile at 4.45 p.m. (Plate VI, Fig. 2). The maximum wind velocity at that time was 106 m.p.h., the highest ever reported at that station. At 8 p.m. the barometer had risen slightly and stood at 29.05 in.

At Pensacola the lowest barometer was 29.31 in. at 1.30 p.m. (Plate VI, Fig. 1), and the maximum wind velocity was 104 m.p.h. at 2.32 p.m., the highest on record for the station.

On the morning of July 6 the storm was central over southern Mississippi, with a barometer reading of 29.48 in. at 5 a.m. at Meridian (Plate VI, Fig. 3). After this the storm hovered over Mississippi and Alabama for three days with steadily decreasing intensity, but with torrential rains that caused great floods in the rivers of the East Gulf States, and enormous damage to growing crops.

By the morning of the 10th the storm centre in its vagaries had moved into Tennessee (Nashville 29.70 in.), and by the evening was over eastern Tennessee (Chattanooga 29.80 in.)

The damage was of the usual severe character. The high tides were responsible for the major portion of the damage on the coast. At Mobile the tide was more than 2 ft. above the previous highest tide (of 9.87 ft. above mean tide level in September, 1906) and the entire business district was inundated. Of the total height of the tides about 5 feet appears to have been due to the storm (37, 1920, p. 136). At Pensacola the tide was 9 ft. above the normal high tide, or $3\frac{1}{2}$ ft. lower than the highest reached during the storm of September, 1906. At Galveston the storm did not affect the tide in any way.

The torrential rains, which set in over the East Gulf States and Western Georgia, continued in the form of heavy showers for about a week, causing enormous losses of staple crops.

II.—8. TYPICAL AUGUST STORM: STORM OF AUGUST 10-24, 1915. (37, 1915, pp. 406-408.)

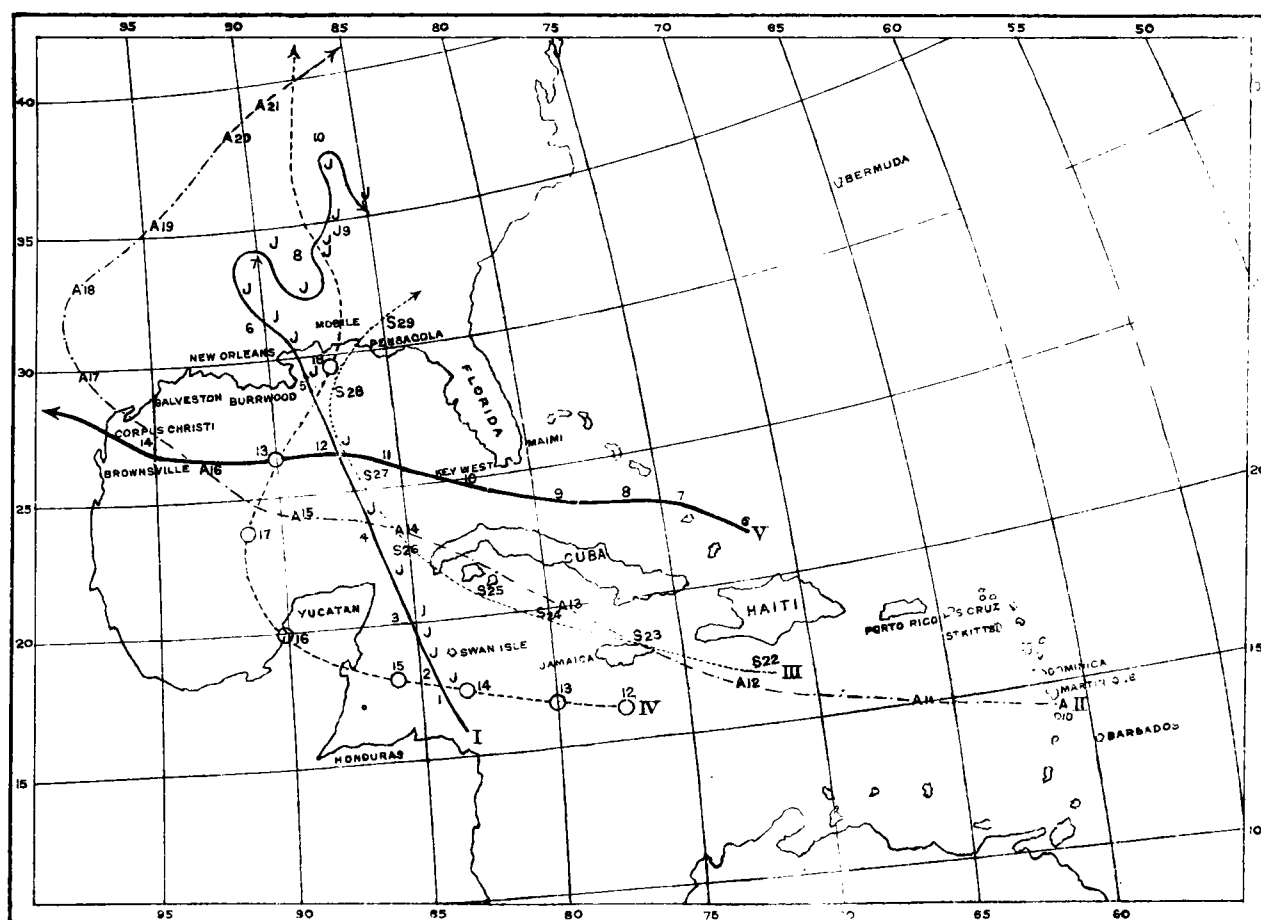
The track of the storm is shown in Plate V (Track II). The origin is seen to have been a long way to the east, and the first branch correspondingly long. The recurve was in a high latitude, about 32° N. All of these characteristics are usual in August storms. The following is a summary of the available information.

On August 10, the storm was first observed between Barbadoes and Dominica. At 9.45 a.m. warnings were sent to all West Indian stations, and at 2 p.m. similar warnings were sent to all Atlantic and Gulf stations. At 4 p.m. a special report from Roseau, Dominica, showed a barometer reading of 29.46 in., with light air from north-west.

On August 11, at 8 a.m., the centre was near the island of St. Croix. At the same time the barometer at San Juan (Porto Rico) read 29.60 in., with a gale of 60 m.p.h. from north-east, indicating a much lower pressure to southward. Pressure was falling rapidly on the west, as shown by the reports from Santo Domingo and Port-au-Prince, Haiti. Warnings were issued as to the position of the centre, and the movement was given as 18 to 20 m.p.h., west-north-westwards.

On the morning of August 12 the centre was south of Haiti, 17° N., 73° W. The barometer reading at Port-au-Prince was 29.60 in., the highest wind velocity 30 m.p.h. from east. Much lower barometer readings, with gales, were recorded in southern Haiti; a barometric height of 29.68 in. was recorded at Kingston, Jamaica. Northerly gales were blowing east of the Island. The pressure was falling to west and north-west. At 12 noon the centre was near the east coast of Jamaica, moving a little north of west. Warnings were issued to this effect. During the night the centre passed north of Jamaica.

Figure 2.



TRACKS I-IV SHOW TYPICAL HURRICANES FOR JULY-OCTOBER, RESPECTIVELY; TRACK V SHOWS SEVERE HURRICANE SEPTEMBER 1919.

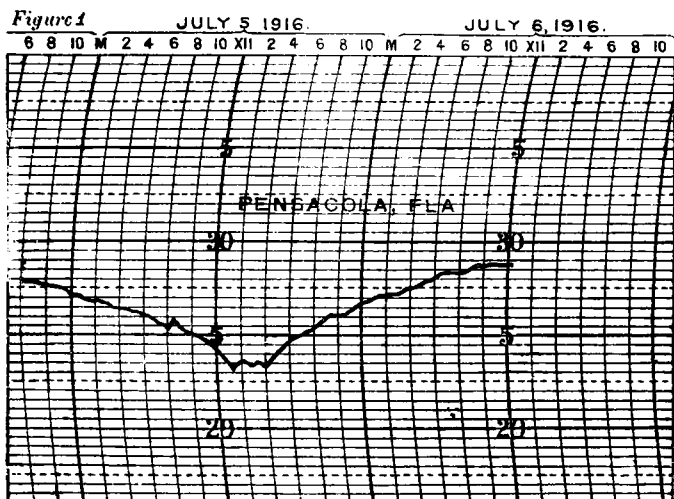


Figure 2.

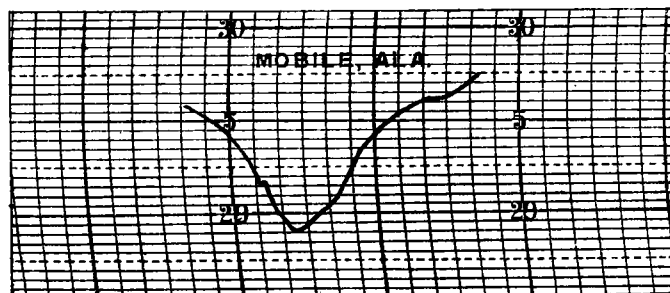
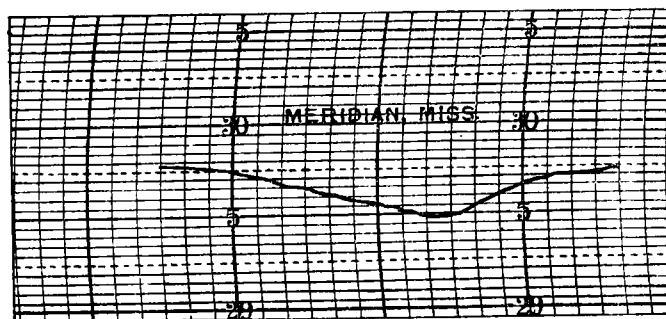


Figure 3.



FIGS. 1, 2 AND 3. BAROGRAMS FOR A PORTION OF THE MIDDLE GULF STORM OF JULY 1-10, 1916, (SEA LEVEL RECORDS.)

"Monthly Weather Review," July 1916.

FIG. 4. PLOT OF CORRECTED ANEROID READINGS (INCHES) AT VELASCO, TEX, AUG 16, 17, 1915.

FIG. 5. BAROGRAM (INCHES) AT GALVESTON, TEX. NOON AUG. 16 TO 3 P.M. AUG. 17, 1915.

FIG. 6. BAROGRAM AT HOUSTON, TEX. 8 A.M. AUG 16 TO 12 P.M. AUG 17, 1915.

"Monthly Weather Review," Aug. 1915.

Figure 4.

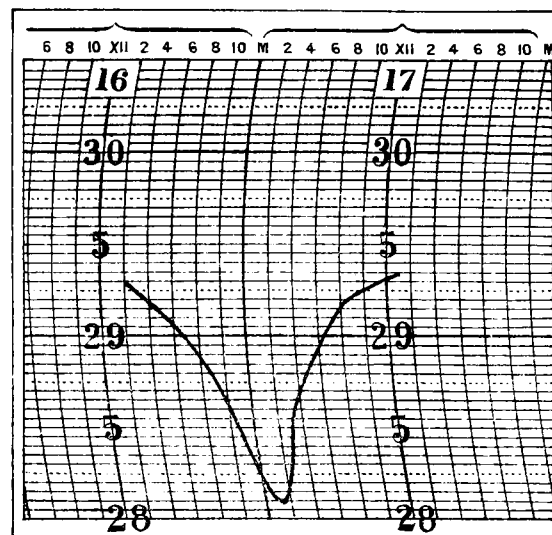


Figure 5.

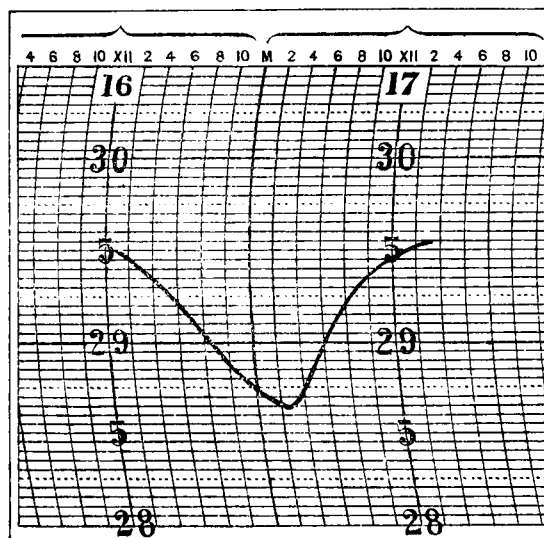
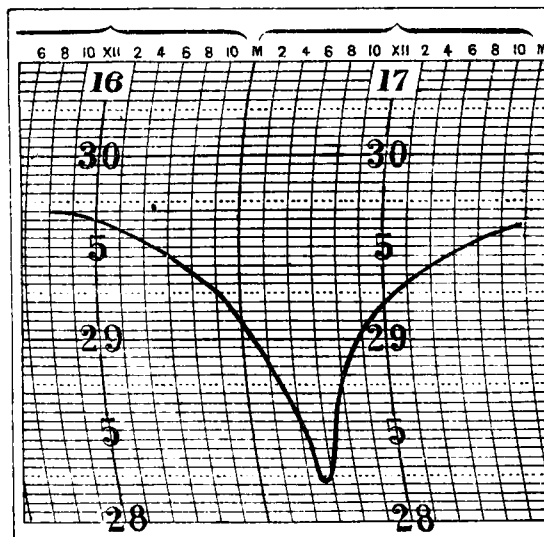


Figure 6.



At 8 a.m. on August 13 a whole gale from south-east was blowing at Kingston. The barometer reading at Key West was 29.92 in. ; the wind there was 16 m.p.h. from east. During the day the storm moved as the warnings had forecasted, and reached western Cuba by the morning of the 14th. Hurricane warnings were then ordered for Key West and Miami, stating that the easterly winds would attain hurricane force there during the 14th.

On the morning of August 14 the centre was near the Isle of Pines, Cuba, and moving in a direction a little north of west. It was apparent that by the next day the storm centre would probably reach the north-central Gulf of Mexico, and Gulf shipping was advised to take every precaution. The intensity was undiminished. At 5 p.m. hurricane warnings were continued from Key West to Boca Grande, but were lowered at Miami, since there was no longer any danger of storm winds at that station.

On August 15 the storm was south of the centre of the Gulf ; the direction of motion was nearer to north-west than before. The barometer was falling at all Gulf Stations. Special observations indicated the necessity for warnings along the west coast, and north-east warnings were ordered from New Orleans to places as far west as Brownsville, Texas.

On August 16 the centre was apparently approaching the east Texas coast ; warnings were issued from Mobile to Apalachicola. The barometer in the morning gave 29.62 in. at Galveston, and the wind was 34 m.p.h. from north-east. By noon the barometer was 29.53 in. at Galveston, and the wind had increased to 56 m.p.h. from north-east. The tide was rising slowly, and the sea was excessively rough. At 8 p.m. the barometer reading at Galveston had fallen to 29.05 in. with a wind velocity of 73 m.p.h. from the north-east ; heavy rain was falling. The storm passed inland during the night of August 16. At 2.45 a.m. on August 17 the barometer read 28.63 in. at Galveston, with a maximum wind velocity of 93 m.p.h. from the east. At 5.30 a.m. the barometer at Houston read 28.20 in., and the estimated wind velocity was 80 m.p.h. from the north-east. On Plate VI curves are given showing the hourly readings of the barometer during the 16th and 17th at Velasco (Fig. 4), 40 miles south-west of Galveston, Galveston itself (Fig. 5), and Houston (Fig. 6) in Texas. At Galveston the barometer read 29.22 in. at 8 a.m., and the wind velocity was 52 m.p.h. from north-east. At Houston at the same time the barometer read 28.72 in., and the velocity was 80 m.p.h. from south-east. Torrential rains had fallen at both places, and were extending into the interior of east Texas.

The storm recurved to the northwards during the 17th ; high winds blew over the interior of Texas, reaching 60 m.p.h. from the north at San Antonio during the day. The velocity during the recurve was much reduced. The future track of the storm was steadily north-eastward with decreasing intensity, heavy rains falling throughout its course. The winds were high, reaching gale force at St. Louis.

On the morning of August 24 it passed out into the Gulf of St. Lawrence, with a barometer reading of 29.80 in. at Father Point.

From examination of the barometric tendencies it is seen that the actual storm centre passed much closer to Houston than to Galveston, and, according to the wind directions (NE., E., SE. and S.) a little to the southward and westward of both stations.

Velocity of Travel and Diameter of "Centre."—At a point north-east of Sandy Point, Texas, the calm when the eye of the storm passed lasted from 2.20 to 2.40 a.m. The time taken for the storm centre to pass from the coast to Houston, a distance of about 60 miles, was nearly four hours, making the average rate of progression at this time 15 m.p.h. As the calm at Sandy Point lasted one-third of an hour, it can safely be assumed that the diameter of the storm centre was about five miles.

Confirmation of this is found in the official report from Houston, in which it is stated that in Houston the broken and uprooted trees pointed to the south-west, while six miles south-west of Houston they pointed to northward, indicating violent winds in opposite directions within a distance of six miles, from which the diameter of the central zone may be taken as six miles.

The rate of travel between the Isle of Pines, Cuba and Cape San Antonio was about 13 m.p.h. The "calm" over San Antonio lasted for one half-hour, making the diameter of the storm centre $6\frac{1}{2}$ mis.

No official record of the tide at Galveston is available, since the gauges were swept away. The universal opinion, however, was that the water was somewhat higher than in a corresponding storm of 1900, and an estimate of the highest point reached was about 12 ft. over mean low tide. The tide was highest about the climax of the storm, a little before 3 a.m. on August 17. Much damage was done by the tidal wave.

A curious, though entirely natural consequence of the storm was the high temperature that prevailed along the southern coast of Texas, beginning on August 15, when the winds blew from the land; the fall in temperature that usually follows the passage of a storm centre was entirely absent. In this instance the winds blowing from a warm land area brought with them the high temperatures that prevailed over the interior districts, and the condition persisted until the winds again blew from the water surface from the south-eastward.

The following data show the conditions at Corpus Christi and Brownsville :—

Date.	Maximum Temperature During Day		Wind Direction at 8 p.m.	
	Corpus Christi	Brownsville	Corpus Christi	Brownsville
August 15	91° F	92° F	NE.	N.
August 16	94°	97°	NW.	NW.
August 17	97°	(a) 104°	NW.	S.
August 18	(a) 100°	(a) 104°	(b) SE.	SE.
August 19	98°	100°	S.	S.
August 20	90°	99°	SE.	S.
	(a) Highest temperature on record		(b) Had been south during day	

The damage done by this storm was enormous. Damage was done to crops in the West Indies, but there was no serious damage to shipping in the Caribbean Sea, owing to Weather Bureau warnings; there were several wrecks in the Gulf, however. The losses on the Louisiana and Texas coasts and in the interior of east Texas were such as might be expected from a great storm. Over southern Louisiana there was no loss of life, and the property loss probably did not exceed a million dollars. It was confined mainly to the rice crop and the live stock in the marshes.

The greatest loss of life and property occurred in the vicinity of Galveston, and thence northward and westward for a considerable distance. The number of deaths was 275, though this was small compared to a similar storm in 1900 of about equal intensity, when the death roll in Galveston alone was 3,000, with about 6,000 deaths elsewhere. The damage to property in Galveston by the present storm was about six million dollars, and in Houston one million dollars. Crops in fully one-half of the state of Texas suffered severely; nearly all open cotton was blown away, and much cotton, late corn and rice was flattened by the wind and rain. Damage was done by winds as far north as the Ohio Valley, but much greater damage was caused by the severe floods resulting from the torrential rains that extended from Texas north-eastwards to New York.

II.—9. TYPICAL SEPTEMBER STORM: STORM OF SEPTEMBER 22–30, 1917.

This storm also may be classed as a hurricane of the first magnitude. It first showed true cyclonic characteristics on September 22, south of Haiti, advancing thence in a general west-north-westerly direction to a position off the mouth of the Mississippi, whence it recurved sharply to the north-eastward and entered the United States near Pensacola, Fla. Dissolution began soon after the storm struck the land and by the morning of September 30 the remnants had disappeared over south-eastern Georgia. The track is shown on Plate V, Fig. 2 (Track III).

Early in the morning of September 23 the storm passed with great intensity directly north of the Island of Jamaica, moving in a north-westerly direction. Kingston reported a barometer reading of 29.14 in. at 4.45 a.m. Great damage was reported on the north side of the Island.

On September 24 the storm centre was apparently in the vicinity of the Grand Cayman Islands, and advices were issued accordingly. By 4 p.m. the storm was apparently nearing the Yucatan Channel or extreme western Cuba, and great caution was urged for all vessels in the Gulf of Mexico. The disturbance continued its north-westerly course, and on the morning of the 26th all vessels in the Gulf were again advised to exercise extreme caution.

On September 25 the centre was just south of western Cuba, where the barometer at Isle of Pines in the morning read 29.42 in., with a north-east wind of 30 m.p.h. On September 26 the centre was a little west of 25° N., 85° W.; a steamer in that vicinity reported a strong south-east gale and a heavy sea. On the morning of September 27 the centre was 150 miles south or south-east of the mouth of the Mississippi, a steamer in the vicinity (26° 30' N., 87° W.), reporting a barometer reading of 29.56 in., with a south-east gale of 74 m.p.h. In the evening the centre was 75 miles south of the mouth of the Mississippi, a steamer in the vicinity reporting a barometer reading of 29.62 in., with a south-east hurricane of 90 m.p.h. or more.

On September 28 the centre was close to the mouth of the river, a steamer anchored at Pilottown, La., reporting a barometer reading of 29.18 in., with a north-east hurricane. The same steamer at 9 a.m. reported a barometer reading of 29.06 in., while the wind had backed to north and was still blowing a hurricane. Pilottown was probably very close to the centre, for by noon the wind had shifted to north-west, the velocity had dropped to 74 m.p.h., and the barometer had risen to 29.24 in. After 4 p.m. of the 28th no telegraphic reports were received from Mobile during the progress of the storm, and none from Pensacola after noon of the same day. A belated message from Mobile stated that the lowest barometer reading during the storm was 29.16 in., and the maximum wind velocity was 70 m.p.h. from the north. There had been no injurious tides, owing to the fact that the prevailing winds were from the north, and the damage was limited mainly to roofs and frail structures.

The storm evidently recurved very close to, and just east of, the mouth of the Mississippi, moved thence north-eastward, passing to the southward of Mobile, and at 7 p.m. passed south of Pensacola, Fla., with a barometer reading of 28.51 in., a maximum wind velocity for 5 minutes of 103 m.p.h. from the south-east, and an extreme velocity of 125 m.p.h. from the same direction.

The storm tide* at Pensacola reached 2.8 ft. at 2 p.m. on the 28th. At Fort Barancas, Fla., it was 5.8 ft. at 8 p.m. the same day. At Mobile the water in the river was 5 ft. below low water in the afternoon.

* The term "storm tide" is used by Cline to denote the height of the actual tide above the predicted tide, so that it represents the elevation of the water surface due to the storm

The variations in barometric pressure and wind velocity are given below. The pressure is shown graphically on Plate VII, Fig. 1.

PRESSURE, WIND AND TIDE AT PENSACOLA, SEPT. 28, 1917.

Time.	Barometer.	Wind.		Tide.
		Direction.	Velocity.	
September 28, 1917.	Inches.		Miles per hour.	Above normal. Feet.
7.00 a.m.	29.73	NE.	25	2.0
8.20 "	29.69	E.	36	2.5
10.00 "	29.61	"	53	3.0
11.00 "	29.56	"	56	"
11.30 "	29.52	"	60	"
11.45 "	29.46	"	67	"
Noon	29.45	"	72	3.5
12.30 p.m.	29.43	"	80	"
1.00 "	29.38	"	80	"
1.30 "	29.31	"	76	"
2.00 "	29.21	"	84	"
2.30 "	29.13	"	82	"
2.35 "	—	SE.	96	"
2.45 "	29.09	"	90	"
3.00 "	29.08	"	84	"
3.15 "	29.03	"	90	"
3.30 "	29.00	"	94	4.5
3.45 "	28.93	"	96	"
4.00 "	28.90	"	96	"
4.15 "	28.86	"	96	"
4.30 "	28.81	"	96	"
4.45 "	28.75	"	96	"
5.00 "	28.71	"	96	"
5.15 "	28.62	E.	94	"
5.30 "	28.54	"	96	"
5.37 "	—	"	100	"
5.45 "	28.51	"	96	"
6.00 "	28.51	"	92	"
6.15 "	28.51	NE.	98	"
6.20 "	—	"	88	"
6.30 "	28.52	"	80	"
6.45 "	28.56	"	84	"
7.00 "	28.62	N.	78	"
7.15 "	28.65	"	92	"
7.30 "	28.80	NW.	88	"
7.45 "	28.83	"	88	"
8.00 "	28.90	"	80	"
8.15 "	28.92	"	92	"
8.30 "	28.99	"	84	"
8.45 "	29.04	"	84	"
9.00 "	29.09	"	78	"
9.15 "	29.11	"	80	2.5
9.30 "	29.17	"	84	"
9.45 "	29.19	"	71	"
10.00 "	29.22	"	70	"
10.15 "	29.24	"	60	"
10.30 "	29.30	"	70	"

On September 29 the storm was centred over south-eastern Alabama, with greatly decreased intensity (29.48 in. at Montgomery), but with sufficient rains to necessitate the issue of warnings of a moderate flood over the lower Alabama River. In the evening the centre was over south-western Georgia, with a still further decrease in intensity (29.64 in. at Thomasville); by the morning of the 30th the remnants had passed off the coast of Georgia.

All the available facts that have come to hand serve to furnish evidence as to the hurricane's great intensity throughout virtually its entire course. The centre of the track crossed Jamaica, and great destruction was caused on that Island, the banana industry being almost ruined. The town of Nuevo Gerona on the Isle of Pines was devastated, many of the staunchest structures in the town being destroyed. In the Pinar region of western Cuba orchards and other crops were ruined.

* II.—9A. STORM OF SEPTEMBER 8–22, 1922.

A storm of unusual violence occurred in September, 1921. It was first observed on the 8th, to the south-east of Barbados, and soon passed into the Caribbean Sea. Its centre crossed Haiti on the 10th, and then turned north-east, reaching Bermuda on the 15th. It was of small diameter and great intensity throughout its course. Its origin was unusually far south. A barometer reading of 28.38 inches was recorded near the centre when it was near Mona Passage. It appears to have increased in depth after the recurve; and a reading of 28.32 inches was recorded 47°N., 45°W. on the 17th. A detailed report of the passage of the storm past Bermuda was made by Captain H. P. Douglas, of H.M.S. *Mutine*. In the Camber, an area with little or no fetch, the water was in such a state that no boat could have lived in it. The lowest barometric pressure was 28.928 inches at 10 a.m. on September 15th. The temperature of neither dry nor wet bulb varied by more than 1°.2. F. during the passage. The greatest wind velocity recorded was 100 m.p.h. from S.W. at 9 a.m. on the 15th, when the anemometer was blown down. The time is local time which is 4h.19m.20s. slow on Greenwich Mean Time.

II.—10. TYPICAL OCTOBER STORM: STORM OF OCTOBER 12–18, 1916.

As stated above in this report, the tracks of October storms are very erratic, and it is difficult to select one as "typical" when the types are so numerous.

The present storm, however, seemed to pursue a nearly "average" track, being only remarkable in that it held a westerly course in low latitudes for as long as four days, reaching longitude 87° or 88° W. before turning northwards. The Track is shown on Plate V, Fig. 2 (Track IV).

The point of origin of this disturbance was uncertain. A hurricane had passed over the locality just previously (October 7 to 13) and it was noticed that even after its passage, pressure continued to fall over the Caribbean Sea, especially to the southward of Jamaica, and on the morning of the 11th the first indications of a fresh cyclonic circulation were observed, the centre being a short distance south of Jamaica. The disturbance did not at this time appear to be of a severe nature. By the morning of the 13th the centre had apparently moved to the western Caribbean, probably to about 16° 30' N., 78° W. Advisory warnings were then distributed and special reports called for.

During the succeeding 24 hours the storm appeared to increase greatly in intensity, and at 11.30 a.m. of the 14th it passed very close to Swan Island, the barometer reading at that place being 28.94 in. The wind was then blowing with hurricane force from the north. The observer reported that the speed of the wind reached 100 miles an hour at times, and hurricane force from 8 a.m. of the 14th until 3 a.m. of the 15th. Warnings were sent out and all the shipping advised to take every precaution.

By the evening of the 15th the centre was not far south of the Yucatan Channel, and on the morning of the 16th it crossed the northern portion of the Yucatan Peninsula, moving north-westward or northward. During the night of the 16th to 17th the storm passed into the Gulf of Mexico, and at 8 a.m. of the 17th it was central about 24° N., 88° W. North-east warnings were then ordered for the Gulf Coast from Carrabelle, Fla., to Bay St. Louis, Miss.

* Added January, 1922.

At 1 a.m. on the 18th the centre was in 27° N., 89° W., with a barometer reading of 28.93 in., and a heavy easterly gale. At 8 a.m. the centre was in the vicinity of Fort Morgan, Ala. The tide was then a foot above the normal at Pensacola, Fla. The storm then moved inland, the centre passing almost directly over the city of Pensacola at 9.30 a.m. with a barometer reading of 28.76 in. There was a south-east wind of 48 m.p.h., and the tide was 3 ft. above normal. At 10.12 a.m. the wind reached a five-minute velocity of 114 m.p.h. from the south-east, with an extreme velocity of 120 m.p.h. from the south-east at 10.13 a.m.; the anemometer went down at 10.14 a.m. After the lull attending the passage of the storm centre the wind again increased from the west, reaching an estimated velocity of 120 m.p.h. After 11 a.m. the wind subsided to less than a gale. These automatic records of pressure, wind direction and velocity for Pensacola are shown on Plate VII, Fig. 2.

At Mobile the lowest pressure was 29.22 in. at 8.35 a.m., being 0.46 in. higher than at Pensacola. The wind velocity, however, was 115 m.p.h. from the east at 8.25 a.m., practically the same as at Pensacola, with an extreme of 128 m.p.h. from the east at 8.28 a.m., this being somewhat higher than at Pensacola.

The storm was very intense and of moderate area.

Precipitation was not excessive in the vicinity of the storm centre, but was torrential some distance away, both to eastward and to westward, Burrwood, La., reporting 11.88 in. during the 24 hours ending at 8 a.m. October 18th. The storm centre moved rapidly inland, and the hurricane warnings were soon changed to storm north-west, the latter being lowered at 9 a.m. The storm did little damage, comparatively speaking, as ample precautions had been taken on all sides, and, furthermore, the storm moved so rapidly that its force in any one locality was soon spent.

There was, however, one shipping casualty in the extreme western Caribbean, in which some 20 lives were lost.

From the 18th onwards the storm moved over Indiana, with a lowest reported pressure of 29.58 in. there, and at 8 p.m. on the 19th it covered the upper Mississippi Valley and the Lake Region, with indefinite formation and with falling pressure to the north-westward. During the 20th strong gales prevailed over the Lower Lakes, with several casualties to shipping and considerable loss of life. Over the Upper Lakes the winds were not so violent, and on the morning of the 21st the storm centre had passed north-eastward beyond the province of Ontario.

II.—11. EXCEPTIONALLY SEVERE HURRICANE.

No better example of an exceptionally severe storm can be cited than that which occurred as recently as September 6 to 14, 1919. Only a summary of the large amount of information relating to this storm can be given here; for fuller details the reader is referred to the *Monthly Weather Review* for September and October, 1919.

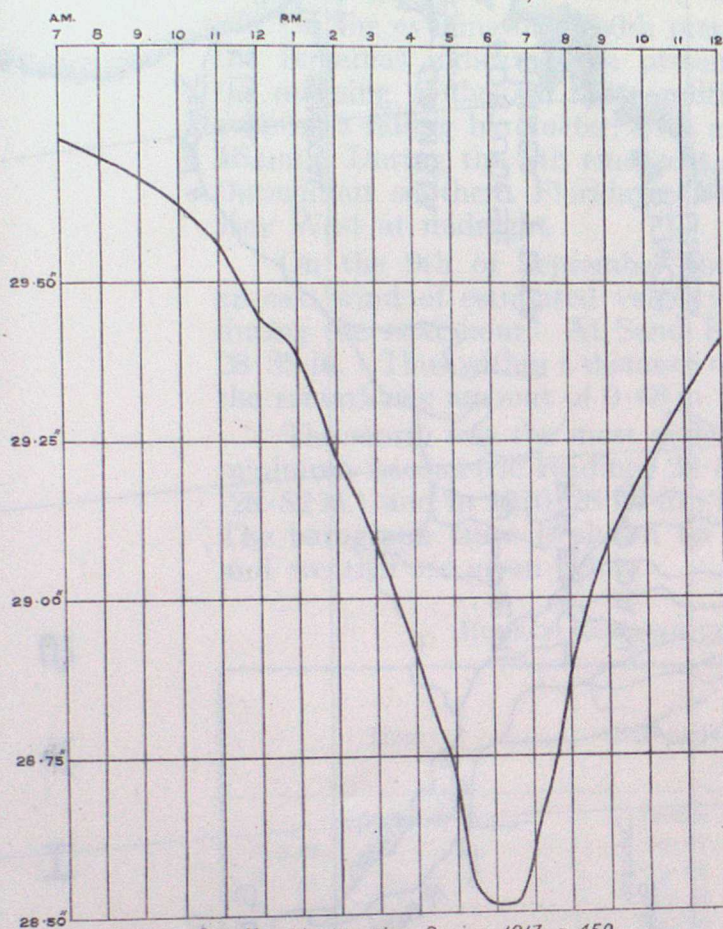
The path of the storm is shown on Plate V, Fig. 2 (Track V). The first indications were apparent on the evening of September 6, probably about 130 miles west-north-west of Turks Island, West Indies; the storm was not recognised as severe, however, until September 8, when it was located south of and near the Andros Islands.

The storm was unusual, both in direction and rate of travel, and pressure was relatively high to the north of the centre. The movement was unusual in that storms originating north of the Islands generally move north and north-eastward, and this storm was only the second September storm of any consequence during the 45 years ending 1919 to travel westwards and thus to reach the south Texas coast, the other having occurred in 1910. The present storm was by far the more violent of the two, and was probably the greatest of all known Gulf storms. The rate of movement was unusually slow, the storm taking eight days to travel from the eastern Bahamas to the interior of extreme southern Texas, the average rate being 200 miles a day, *i.e.*, only about four-fifths of the usual rate for September storms.

The storm was probably a re-development of a minor disturbance that was first noticed on the evening of September 2, a little west of the Island of Antigua,

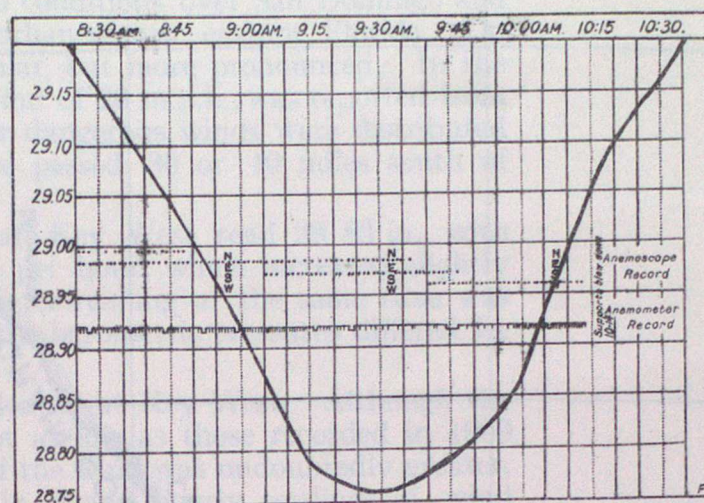
Figure 1.

PRESSURE VARIATION AT PENSACOLA, 28TH. SEPT. 1917.



See Monthly Weather Review 1917, p.459.

Figure 2.



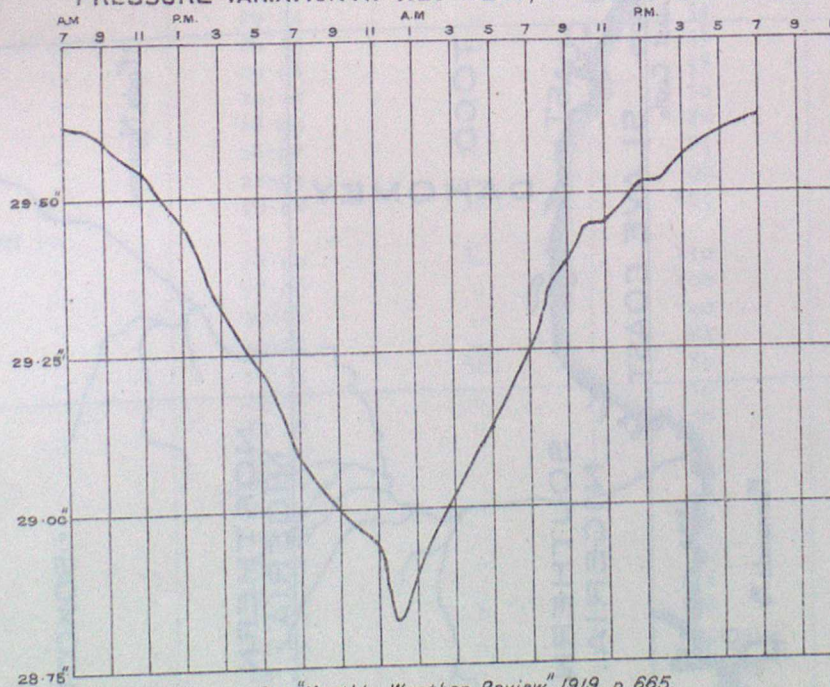
GRAPHS OF PRESSURE, WIND DIRECTION AND WIND VELOCITY AT PENSACOLA, FLA., DURING PASSAGE OF HURRICANE OF OCTOBER 18TH, 1916. Anemoscope

records dots at one-minute intervals; anemometer records a tooth for every mile of wind, the pen being held down for the tenth mile.

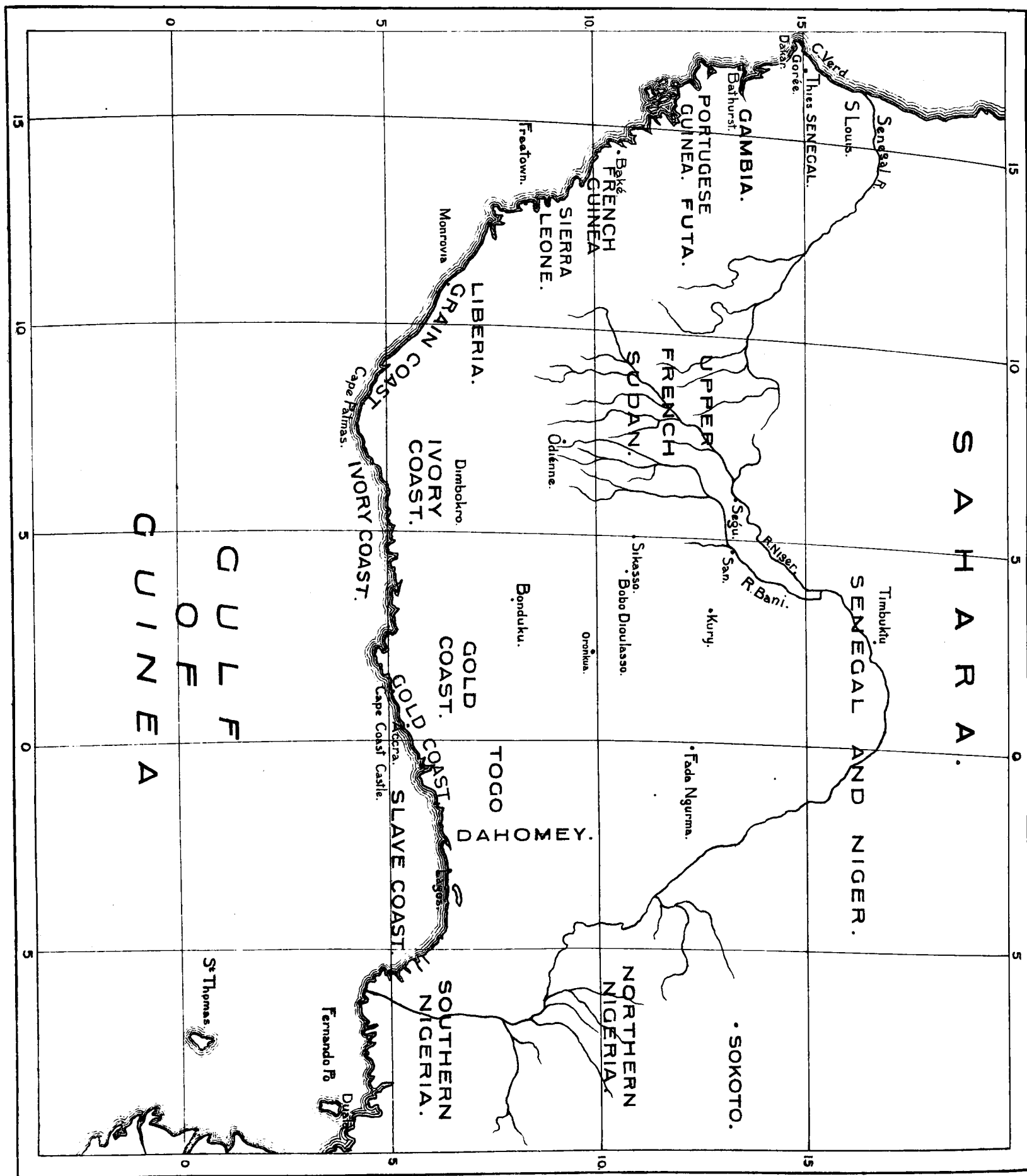
From "Monthly Weather Review" 1916, p. 584.

Figure 3.

PRESSURE VARIATION AT KEY WEST, 9TH.-10TH. SEPT. 1919.



See "Monthly Weather Review" 1919, p. 665.



and then moved west-north-westward at a normal rate, recurving during the 5th, and causing a shift of wind at Turks Island and Haiti.

On the evening of the 6th pressure and wind conditions over San Domingo and the Bahamas indicated the presence of a disturbance over eastern Florida. On the morning of the 7th the conditions were similar, but more pronounced. In the evening a falling barometer, with a north-east wind of 26 m.p.h., was reported from Miami. During the 8th emergency warnings for dangerous winds were distributed throughout southern Florida. The storm centre passed 30 or 40 miles south of Key West at midnight.

On the 9th of September the barometer at Key West read 28·83 in., with an east wind of estimated velocity of 105 miles per hour, which increased slightly during the next hour. At Sand Key the barometer reading at the same time was 28·35 in. Thus within a distance of eight miles the barometric pressures differed by the remarkable amount of 0·48 in.

The storm was the most violent ever experienced at Key West. Although the minimum barometric reading, 28·81 in., was not as low as those recorded in 1909 (28·52 in.), and in 1910 (28·47 in.) the violence of the wind was undoubtedly greater. The barograph trace is shown on Plate VII, Fig. 3 and hourly readings of wind and weather are given below.

HOURLY READINGS OF WIND AND WEATHER AT KEY WEST

Time	Barometer	Wind		Weather
		Direction	Velocity	
September 9.	Inches.		Miles per Hour.	
7 a.m.	29·61	NE.	36	Light rain.
8 "	29·61	NNE.	38	"
9 "	29·58	N.	36	Threatening.
10 "	29·56	NNE.	39	Light rain.
11 "	29·54	NE.	40	"
12 noon	29·50	"	37	"
1 p.m.	29·46	"	42	"
2 "	29·40	"	44	Moderately heavy rain.
3 "	29·31	"	48	"
4 "	29·27	"	50	"
5 "	29·22	"	54	"
6 "	29·13	"	58	"
7 "	29·08	"	58	Heavy rain.
8 "	29·05	"	70	"
9 "	28·99	"	80	"
10 "	28·97	"	85	"
11 "	28·93	"	90	"
12 midnight	28·81	E.	105	"
September 10.				
1 a.m.	28·90	E.	110	"
2 "	28·96	"	100	"
3 "	29·02	"	90	"
4 "	29·07	"	85	"
5 "	29·13	SE.	80	"
6 "	29·20	"	70	"
7 "	29·26	"	70	"
8 "	29·35	"	70	"
9 "	29·39	"	70	"
10 "	29·44	"	60	Light rain.
11 "	29·46	"	85	"
12 noon	29·50	"	50	"
1 p.m.	29·53	"	48	"
2 "	29·52	S.	48	"
3 "	29·56	"	45	"
4 "	29·57	"	40	"

In the terrific gusts that prevailed during the height of the storm walls were blown out of staunch brick structures ; and large vessels, firmly secured, were torn from their fastenings or moorings and blown on to the banks. The loss in Key West was estimated at 2,000,000 dollars.

Owing to the very slow progressive movement of the storm, gales lasted in this vicinity from 7 a.m. of the 9th to about 9.30 p.m. of the 10th. The centre, when at its nearest point, was probably about 30 or 40 miles from Key West.

The usual phenomena preceding, accompanying and following storms of tropical origin were present, and while no thunder was heard, diffused lightning was noted at intervals for several hours before the maximum force was reached.

The rainfall was extremely heavy and continuous. The total amount (estimated) is given as 13.39 in., the heaviest fall occurring during the early morning hours of the 10th.

Similar details are given for Sand Key, Fla., the rain beginning there on the 8th, just before midnight. During a squall between 3.15 a.m. and 4.35 a.m. on the 9th, 0.36 in. fell. The rain continued till the night of the 10th, but the amount could not be determined, as the rain-gauge was washed away.

No reports were received from the Gulf of Mexico after the morning of the 10th until after the storm had passed into Texas during the 14th. On the morning of the 14th the centre was not far from the coast of Texas, between Corpus Christi and Brownsville ; during the day it passed inland, with marked, but steadily diminishing, intensity.

The storm entered the Gulf on September 9, and the first effect noted at Galveston was a slight regular swell from south-east, which began to appear about 7 p.m. on the night of the 10th. Cirrus clouds made their appearance on the morning of the 11th and continued until the lower clouds finally obscured them. These cirrus clouds were observed to be moving from the south-east. On the 13th, alto-cumulus clouds, moving mostly from north-east, were the predominating upper clouds. During the afternoon of the 13th, strato-cumulus clouds made their appearance, and by sunset the sky was practically covered by these lower clouds. From this time these lower clouds continued, interspersed with quickly moving scud, until the storm was over.

Moderate rainfall was measured, a trace falling on the 13th after 7 p.m., followed by showers on the 14th, 15th and 16th, the total rainfall of the storm amounting to 2.35 in.

The winds were light and northerly up to the 12th. During the morning of the 13th they were light to fresh from north, becoming strong from north-east at about 2 p.m., and shifting to east at 6 a.m. on the 14th. At 2 p.m. on the 14th the wind shifted to south-east, continuing from this direction until the storm was over. The maximum velocity for a five-minute run reached at Galveston during the storm was 53 m.p.h. from the east at 7.23 a.m. on the 14th. The diurnal oscillations of the barometer were apparent throughout the entire approach of the storm. The barometer had fallen below normal on the 10th, and reached its lowest point at 4.30 a.m. on the 14th, with a reading of 29.58 in. On the night of the 12th there was a rather marked increase in the barometer reading, probably caused by the southward and eastward drift of a high-pressure area to the north-westward of the station. This development undoubtedly prevented any recurving of the tropical storm, and tended to prolong the westward movement of the storm area.

Swells of the sea gradually increased in intensity, becoming heavy and frequent during the 13th, and continuing throughout the 14th.

The storm tide at Galveston reached its highest point of 8.8 ft. at 7 a.m. on the 14th, and fell gradually from this, though it was above normal for a week after. The low-lying parts of the island began to be flooded by the rising tide, and by 7 a.m. of the 14th most of the streets of the city were covered with water to a depth of from 2 ft. to 3 ft. or more. Great precautions were taken, and the loss of life in the Galveston district was small ; the total damage (almost all caused by the tide) was estimated at 272,000 dollars.

Reports from Corpus Christi show that cirrus and alto-cumulus clouds, with occasional patches of cirro cumulus, and a few banks of alto-stratus, prevailed during September 13, 1919. These clouds were moving from almost due east all the time. In the evening the alto-cumulus clouds covered the sky, and did not disappear until the approach of the heavy nimbus clouds. In spite of a steady north wind, the weather was very oppressive all day. The water in the bay was rather high and rising somewhat in the evening, which was unusual, as north winds are generally associated with low water. The storm centre reached land very near to Corpus Christi, the lowest barometer there being 28·65 in. at 3 p.m. September 14.

At Brownsville, a rather greater distance south of the centre, the lowest reading was 29·13 in. at 1 p.m. September 14.

There were 284 casualties in the Corpus Christi Bay, where the tides were unusually high; the damage to property, etc., was enormous. Along the Mississippi the highest tides of the season were experienced; but the winds were not unusually high, and little or no damage was reported.

SECTION II.—NORTH ATLANTIC OCEAN.

B.—STORM-SQUALLS AND TORNADOES OF WEST AFRICA.

The most severe type of storm encountered in the Atlantic Ocean is the West Indian hurricane, which has been dealt with in some detail above. It was seen there that the hurricane belt embraces roughly the Caribbean Sea, the Gulf of Mexico and the West Indies, extending from longitude 90° W. to 56° W., and from latitude 13° N. to 30° N. (See Part I, General Introduction.) Between 55° W. and 35° W. tropical cyclones have never been met with, but further east, especially east of 29° W., in the neighbourhood of the Cape Verd Islands, they have occasionally occurred. They are, however, much less severe than those of the Antilles, and move off more quickly to the north-west.

Further north, between the Azores and Madeira, barometric depressions of the type of the temperate zone are frequently encountered; these have their attendant squalls and secondaries, but these rarely lead to a wind force comparable to that attained in tropical cyclones, and it is not proposed to discuss them here.

To the east of the Cape Verd Islands, and on the west coast of Africa and the Guinea coast, storm squalls and tornadoes are of considerable frequency.

These storms are of short duration, and always come from some easterly point, that is, they form inland over the continent and move in a westerly direction out to sea. Their destructive energy does not approach that of the summer tornadoes of the valleys of the United States, and only occasionally do they attain sufficient force to demolish buildings and staunch structures, or to uproot trees.

The geographical area over which these storms occur comprises almost the whole of West Africa north of the equator, up to 20° N. or 23° N. They are comparatively infrequent south of the equator, though according to Hann (7), occasional tornadoes have been reported in the French Congo.

As regards longitude the area is even more extensive. The most easterly point at which a tornado has occurred is at Bodelé (17° N., 17° E.). The storms have also been observed and studied in great detail by Hubert (67) and (68) between Dakar (15° N., 20° W.) and Fada Ngurma (12° N., 0° W.). Thus the northern part of the storm area covers 37° of longitude; while further south, the storms occur from the coast to a considerable distance inland.

An attempt has been made to draw up a table of frequencies of the storms from the Meteorological Returns from Lagos, Northern Nigeria and Sierra Leone. But this has been abandoned, as no information was available as to the relative intensity of the storms, the kind of storm, nor the rainfall, etc. Moreover, this would not have provided information as to the absolute frequency, since the same storm was reported at more than one station.

A marked seasonal variation was, however, apparent, the maximum occurring in May, with the secondary maximum in September.

In this connection it is interesting to note that the returns of the destruction of shipping on these coasts have their maximum in May.

II.—12. THE PREVAILING WINDS.

Before we attempt to describe the storms themselves, it is necessary to give a short account of the prevailing winds over this part of Africa, since recent research has shown these storms to be due to the conflict between two aerial currents—the harmattan and the monsoon—being nothing more than squalls accompanied by a temporary rise in the atmospheric pressure, called a “crochet de grain.” They are independent of barometric depressions, and bear no dynamical resemblance whatever to the true revolving storms discussed in the rest of this memoir.

The prevailing surface winds over this part of Africa are the harmattan and the monsoon. The harmattan is a remarkably dry wind coming from the interior of the continent and bringing with it much dust from the Sahara. In the dry season it is rather warm (very warm in March and April), but in the summer months it is cold. Its occurrence implies the existence of relatively high pressure to north and low to south. In northern winter the equatorial belt of low pressure is at its southern limit, a circumstance which tends to establish a north-easterly gradient along the Guinea coast, and the harmattan is therefore the prevailing surface wind throughout the dry season, that is from late November to early March.

The direction of this wind is mainly from some easterly point, generally from north-east, though according to some authorities (66) it has the following daily variation.

Time.	7 h.	9 h.	Noon.	16 h.	21 h.
Direction from ..	N.22° W.	N.12° E.	S.64° E.	S.34° E.	S.8° E.

The harmattan prevails to a height of about 2,000 metres (6,600 ft.), as is shown by the clouds which are carried by it. Its strength rarely exceeds force 4 on the Beaufort scale (5·5–8·0 metres per second).

The monsoon is a warm moist wind blowing only near the ground. Its usual direction is south-west or south-south-west. It is definitely confined to the summer months, its times of commencement and cessation at any place nearly coinciding with the two days in the year when the sun is in the zenith at noon there. During early spring the south-west monsoon begins to establish itself, especially on the coasts and in the southerly regions; and this period marks the beginning of a conflict between the two winds.

During March the harmattan prevails inland and the south-west monsoon on the coast.

By April the monsoon predominates south of latitude 8° N., but north of this the two winds co-exist in conflict.

In May the monsoon has developed considerably in intensity and is the predominating surface wind up to latitude 12° N., the harmattan being consigned to still more northerly districts.

The months of June, July and August constitute the rainy season proper, when the south-west monsoon prevails in all districts. This monsoon is, when fully developed, laden with water vapour and prevails to a height of about 800m. (2,600 ft.).

From September onwards, the reverse process takes place, namely, the progressive stemming of the monsoon by the harmattan, which, by the end of November, is again established in all districts as the surface wind.

In September, the harmattan begins to be felt north of 14° N. and gradually drives the monsoon southwards, until by early November the latter is only felt locally in the extreme south of the area under consideration.

From this brief account of the prevailing winds it is seen that the year can be divided into three distinct periods as follows :—

- (1) The dry season—roughly from November to March—when the prevailing surface wind is the harmattan.
- (2) The rainy season—June, July and August, when the prevailing surface wind is the monsoon.
- (3) The seasons of indeterminate winds, especially for districts south of 14° N., during the months of April, May, September, and October.

The theory now generally accepted is that the harmattan blows all the year round, but that it is confined to the upper atmosphere, that is, to a zone immediately above the monsoon (roughly from 800 to 2,000 metres) during parts of the year when it is not definitely established as the surface wind—namely, during the rainy season (June–August), and during April, May, September and October in the southerly districts (*i.e.*, from the equator to 14° N.). The storms of these regions appear to result from the conflict of these two superposed currents.

It must be remembered that the winds on the coasts are frequently anomalous, owing to land and sea breezes.

II.—13. CONDITIONS FOR THE FORMATION OF STORMS.

In support of this hypothesis concerning the formation of storms the following points may be mentioned :—

- (1) There are very few storms during the months (December–March) when the harmattan prevails alone.
- (2) There are very few storms in the southerly regions after the monsoon is definitely established there, unless a descent of the harmattan has taken place.*
- (3) The zone of maximum storm frequency is in the north (about latitude 10° – 12° N.), where the conflict between the two winds is always most keen.
- (4) The maximum number of storms occurs in April and May, when the monsoon is developing, and in September and October when it is receding before the harmattan.
- (5) Should a storm occur during the “harmattan months” (December–March) it has been observed that this always takes place several hours after the establishment—due to local or abnormal conditions—of a surface wind opposite in direction to the harmattan, which continues to blow above.
- (6) The direction taken by the storms is approximately that of the harmattan, which is, at its strongest, certainly the more powerful of the two winds.

Thus the water vapour, brought from the south and south-west by the monsoon, is driven back westwards by the harmattan, and falls in the form of rain along paths roughly from east to west. Consequently in the more northerly regions, where the duration of the rain is short and the humidity considerably reduced, whatever rains there are come in the form of storm rains and are always directed from some easterly point. A barometric depression has never been observed to precede any of these storms.

For the more southerly regions (68) a period of ordinary monsoon rain (from the south) occurs during the monsoon season. This rain is never accompanied by electrical phenomena.

It is quite definitely established that storm days are preceded by an appreciable increase both of temperature and of humidity. As we have seen above, when a storm breaks, the temperature falls rapidly, owing to the arrival on the surface of a cold air current, whose coolness may be produced by the evaporation of rain. Very often the rain and the violent wind commence almost simultaneously.

* See page 266.

Zones favourable to storm formation are those in which the establishment of ascending currents is facilitated ; that is, either over the great plains, which easily become over-heated, or at the heads of valleys in mountainous country. For the latter case, information has been collected by Captain von Schwartz (71) for the group of the Sierra Foré (French Guinea), and the following is a brief résumé of the points given by him as conducive to storm formation :—

- (1) Rapid heating of the ground, intense evaporation, and the production of ascending air currents.
- (2) The formation of a cloud nucleus having a slight gyratory motion.
- (3) The attraction of neighbouring clouds by the nucleus, and the accentuation of the gyratory motion.
- (4) The gradual ascent of the cloud mass, which penetrates into the zone of the harmattan and then, after the descent of the latter, takes a westerly course, modified by the general configuration of the ground and following, by preference, the valleys.

Lastly, Captain von Schwartz points out that the hour at which the storms burst is about 14 h. when the moon is at first quarter, 17 h. at full, 20 h. at last quarter, and midnight at new moon. This point has not been made by any other investigator in these districts, but comes from a reliable observer. He expressed it with some diffidence, however, and confirmation from a longer period of observation than he appears to have had is needed before much reliance can be placed on it.

A valuable table is given by Hubert at the conclusion of his remarks on storms. This is shown on p. 261 and gives in a concise way the chief features in the successive stages of a storm.

This work of Hubert is one of the few complete and detailed accounts available on the storms of this part of the world. Various references are, however, made in Hann's *Klimatologie* (Édition III., Bd. 2), and these are quoted below :—

Senegal.—In the rainy season, roughly from June to October, the so-called " tornadoes " are frequent. These are sudden squalls, or thunder squalls, which are more or less frequent, during the wet season, along the whole coast of West Africa.

These are not at all comparable in destructive force to the summer tornadoes of the central valleys of the United States, and only occasionally attain sufficient force to break trees or carry away houses. There are occasional " dry tornadoes " in this district, which are accompanied by a marked fall of temperature.

At Boké (French Guinea) the tornadoes always come from the south-east or east ; they are most frequent at the beginning and end of the rainy season, and rare in July and August.

In Sierra Leone the thunderstorms or tornadoes always form above the land in the east, and draw westwards out to sea. They have two maxima (of frequency) in May and October, but may occur at any time during the rainy season. The tornadoes may be described as tempestuous wind gusts accompanying quick passing thunderstorms, and may be said to be analogous to our summer thunderstorms.

Liberia.—The tornadoes (again described as " short, violent thunderstorms ") are frequent from the end of March to October, the maximum number again occurring in May ; the storms abate in July and August, but are very violent and accompanied by heavy, stormy rains in September and October.

Gold Coast.—Tornadoes, accompanied by thunderstorms of short duration, come from almost all directions between north-east and south-east. They produce a marked lowering of temperature, and usually take place in the afternoon or early evening hours, during the period April to October.

Niger Coast and Kamerun.—Occasional " dry tornadoes " take place along the Niger Coast, also tornadoes accompanied by heavy rains during the rainy season. These all form in the east and move westwards.

At Fernando Po violent tornadoes are recorded, always coming from the east or east-north-east, and accompanied by heavy rain, a record of 150mm. (6 in.) of rain having been measured in one hour. The maximum number of storms occurs in May.

STORMS (GENERAL ACCOUNT).

Successive Phases.	Temperature.	Atmospheric Pressure.	Wind.			Rain.	Electric Phenomena.	Observations.
			Monsoon.	Harmattan.	Surface.			
1st phase (several hours).	Rising.	Normal.	Normal; movements of small cumulus towards the east. Ascending currents.	Normal.	West.	None.	None.	—
2nd phase (several hours).	Rising.	Normal.	The cumulus increase in size and begin to change to cumulo-nimbus.	The cumulo-nimbus pass slowly into the zone of the harmattan, their summit reaching to a great height, and their base being near the boundary between the two wind zones.	West.	None.	Flashes in the cumulo-nimbus of the harmattan.	At the boundary between two wind zones, the clouds are chiefly nimbus.
3rd phase (less than one hour).	Rising.	Normal.	Very few clouds.	The base of the clouds sinks suddenly.	West.	None.	Flashes in the cumulo-nimbus continue.	—
4th phase (some minutes).	Falls suddenly.	Crochet de grain	Clouds driven back to the west.	Cumulo-nimbus completely transformed to nimbus; the harmattan is blowing at the surface.	East, very violent.	Commencement of the rain.	Thunder and lightning.	The nimbus move with great velocity (about 60 kilometres per hour, i.e., 38 miles per hour).
5th phase (one hour)	Falls again slightly, then remains constant.	Continuation of "Crochet de grain."	As above.	As above.	East, strong.	Heavy rain.	Number of very strong discharges.	—
6th phase (variable duration).	Remains constant.	"Crochet de grain" continues normally and can end by a small depression.	As above.	Cumulo-nimbus or nimbus diminishes.	East, velocity not so great.	Rain diminishing slowly becomes fine rain.	Discharges become more and more infrequent.	
7th phase...	Rises again slowly.	Normal.	Normal.	Normal.	West.	None.	None.	Fine weather.

* See Plate ix, Fig. 1.

In Kamerun the tornadoes are much less frequent ; this can be regarded as the southern boundary of the district in which they occur regularly.

At Duala (a district lat. 4° N., long. 10° E.) frequent thunderstorms are reported, but only 28 tornadoes in the last five years ; 17 of these occurred in March and April.

South of the Equator very few references are made to tornadoes, though occasional ones are recorded in the French Congo.

II.—14. DESCRIPTION OF TYPICAL STORMS.

The storms experienced in this part of the north-west of Africa, are of two main types :—

(1) Storms with tornado ("tornado"), of which there is a slight modification known as the "dry tornado."

(2) Storms without tornado ("orage").

The chief characteristic of the tornado is the well-known cloud form, which is an invariable feature of its composition.

The following is a brief account of the formation, approach and duration of a storm with tornado (9 and 65).

The prevailing winds of the period, usually south-west, always give place to a day of calm, or of a very feeble north or north-east wind, when a tornado is approaching ; the atmosphere is usually oppressive, due to overwhelming heat. The first definite evidence is given, however, by the appearance of a small black cloud mass, which becomes visible in the south or south-east, and passes slowly towards the north, clearly indicating the general motion of the disturbance. Meanwhile, the sky, hitherto cloudless, is traversed by several white cloud flakes, coming from the north-east in the direction of the surface wind which now begins to freshen.

As the cloud mass approaches it is seen to be funnel-shaped, or sometimes it is a large black disc rather like a mushroom without stump. Its motion is very variable ; it may take any time from five minutes to half-an-hour to pass from a low altitude to the zenith. This accounts for many of the shipwrecks caused by tornadoes, especially in the old days of sailing ships, when boats flying with full sail were unable to furl their sails before the tornado was upon them. At the moment when the front edge of the cloud mass reaches the zenith—or occasionally a short time before or after this—a gust of wind of extreme violence is loosened from the south-east. This squall usually lasts from twenty minutes to half an hour, and as the storm moves northwards, the surface wind shifts to east, north-east, north and north-west, and finally back to south-west, or to whatever direction prevailed before the storm arose. One case was observed by Hubert in which the wind shifted in the clockwise direction.

The intensity of the wind increases progressively with the shifts, and is in general very violent when the final shift takes place, this being accompanied by extremely heavy rains, which last for varying times, but never for less than a quarter of an hour.

These rains are associated with a marked lowering of temperature.

Dry Tornadoes.—If the storm consist only of a sudden wind movement, and the black cloud passes without rain or further storm, it is known as a dry "tornado." Such storms are comparatively infrequent, and usually occur only at the beginning or end of the storm season, *i.e.*, in April or October, when the atmospheric humidity is low. They are most prevalent in Senegal and in the more northerly regions, where the humidity of the monsoon is never as great as it is further south.

They take the form of simple squalls and, during a period of from twenty minutes to half an hour, produce violent wind gusts of destructive force. Usually, but not invariably, these storms are accompanied by thunder and lightning. The main feature of the dry tornado is the marked lowering of temperature produced by it, which is usually as great as for the tornado proper.

Storms without Tornado.—The following storm in August, 1872, was reported from Gorée (15° N., 18° W.):—

The morning was fresh and agreeable with only occasional light winds from south-west. The sky was crossed by thin white flakes of cloud, which radiated in fan-like shape from the south-east and which slowly changed shape.

Before sunrise the temperature was 27° C. in the shade, and by 13h. it was 30° C. The heat was very oppressive on account of the complete saturation of the air. This general state of the atmosphere persisted, the temperature continuing to increase slowly until it reached 31° C. at 16h. Several nimbus clouds crossed the sky from south to north, while the direction of the surface wind oscillated between west and south-west. The surface wind was, however, very light, and at times there was complete calm.

At 16h. the sky was three-quarters covered with low clouds, which were accumulating on the horizon. The calm persisted.

About 18h. a small black cloud, coming from the east, passed overhead, and several large raindrops fell from it.

By 22h. similar small clouds, moving over from south-east, had become numerous, and in a short time the sky was covered with them. Lightning flashes and distant thunder commenced on the horizon, the thunder claps being very short and abrupt. Quite suddenly, between 22h. and 23h., the rains started and were very violent for a considerable time. Some idea of the rate of precipitation can be given from the measurements at a moment of maximum intensity, which yielded a fall of at least one millimetre per minute.

While this rain was falling the air became fresh and the temperature fell quickly through several degrees. The storm then moved away westward.

II.—15. SOME CHARACTERISTIC STORMS OBSERVED BY HUBERT (67).

1. *Storm of Ségu* (13° N., 6° W.), May 21, 1910.

The storm formed under particularly favourable conditions, since the storm whirl passed slightly to the north of the observer; it was thus possible to follow and observe it during all the time it was manifested. The following is a summary of the events:—

Before 9h. alto-cumulus clouds were seen coming from the east. These were observable up to 14h., when they became masked by lower clouds.

At 17h. they reappeared and were similar in appearance and direction of movement to those seen before 9h. Later they vanished slowly.

The monsoon had prevailed constantly on all the preceding days, but on the day of the storm was not apparent until after sunrise.

Before 9h. several small cumulus clouds began to appear, thus indicating the presence of ascending currents in the monsoon zone. Up to 13h. the number of these clouds increased rapidly.

The surface wind during the morning was south-west; this wind fell about 13h.

About 13h. cumulo-nimbus clouds were apparent in the zone of the harmattan, superposed above the cumulus, in the current of the monsoon. The distance which separated the two cloud zones was very small compared with that which separated the cumulus from the alto-cumulus in the high atmosphere; nevertheless the two lower cloud zones were quite distinct, and the cumulus of the monsoon continued to move below the cumulo-nimbus of the harmattan.

Slowly the latter clouds became more abundant and gradually descended, until the zone of the cumulus proper became quite indistinct. At the same time an east wind became noticeable at lower and lower heights, thus establishing the descent of the harmattan.

The absolute velocity of the cumulo-nimbus clouds was soon seen to be very great, and evidently increased as the wind descended. Lastly, a violent gust of wind, which raised a great cloud of dust, marked the break of the storm. The harmattan was then definitely predominating at ground level. Electric discharges were numerous and copious rain fell, this being localised to the north of Ségu. (See Plate IX, Fig. 2.)

After the break of the storm the velocity of the surface east wind diminished progressively, and the storm cloud (of which the south side only was visible) was seen to shrink slowly, and finally it vanished. Towards 17h. the last cumulo-nimbus clouds disappeared to the north, and the surface wind shifted back to south-west and continued to blow regularly.

It is seen that the duration of the storm from start to finish was about four hours, but the period of violent winds and rain, which occurred about 15h., only lasted for a very short time.

From the account of this and other similar storms four points can be established as essential to storm formation :—

- (1) The existence of ascending currents in the zone of the monsoon.
- (2) The existence of the harmattan in the high atmosphere and of the monsoon at the surface of the earth.
- (3) The rapid descent of the harmattan.
- (4) The progressive stemming back of the monsoon by the harmattan.

In this example the storm manifested at Ségu had originated some distance away on the eastern side ; it had driven back the monsoon, which was blowing until just before the storm broke.

Further examples will now be given describing the actual origin of these storms.

2. *Storm at Dakar* (15° N., 20° W.) on October 1, 1913. The following is a summary of the observations :—

7h.—A light west surface wind prevailed and undeveloped cumulus clouds were visible in the monsoon zone.

8h.—These clouds increased in number and passed slowly into the harmattan zone. Their bases were almost motionless, evidently being near the boundary between the two winds, while their summits, clearly in the harmattan zone, moved towards the west.

The surface wind weakened and became south-south-west.

9h.—A cumulo-nimbus cloud developed rapidly over Dakar itself (this being due to the facility with which ascending air currents form over the small peninsula on which Dakar is situated, the land heating up more quickly than the surrounding sea). Cumulo-nimbus clouds also developed to the east (inland) and these were surmounted by a cirrus veil.

10h.—All the cumulo-nimbus clouds increased rapidly in size ; their bases appeared like a horizontal plateau of greyish hue, while their summits, which reached to a great height in the harmattan zone, continued to move westwards.

11h.—The velocity of the harmattan diminished slowly, but that of the monsoon increased, and the zone of the monsoon increased in height. The small cumulus clouds of the monsoon zone were carried above the base of the cumulo-nimbus ; the latter became rapidly distorted, while the cumulus clouds soon passed right over it. Slowly the cumulo-nimbus vanished, and the threatened storm did not break.

At the same time similar processes had been taking place in the interior of the continent, but here the area over which the ascending currents formed was much more extensive, and the currents were maintained over a longer period than were those over the peninsula, so that the storm evolved regularly.

The observations were as follows :—

In the afternoon the monsoon continued to blow over Dakar and small cumulus clouds moved inland to the east. Nothing abnormal was noticed until 17h., when a cumulo-nimbus cloud was seen a considerable distance east of Dakar, situated in the harmattan zone and moving slowly westwards.

18h.—The monsoon had increased in intensity, while the cumulo-nimbus had drawn much nearer, its height and its westward velocity having considerably increased. Electric discharges had commenced and were numerous. The frontal zone of the cumulo-nimbus slowly changed into a vast and very flattened nimbus, which slowly sank and thus established the partial descent of the harmattan.

19h.—The cloud mass, which was now almost entirely nimbus, descended further, but the intensity of the monsoon was such that this cloud was stemmed somewhat in its downward movement, and the monsoon was actually blowing at the surface when the nimbus reached the zenith and passed over Dakar.

20h.—The sky cleared for some time and the monsoon diminished in intensity.

20h. 45 m.—A gust of east wind was felt on the surface, this signifying the complete descent of the harmattan ; the nimbus clouds reappeared.

Figure 1.

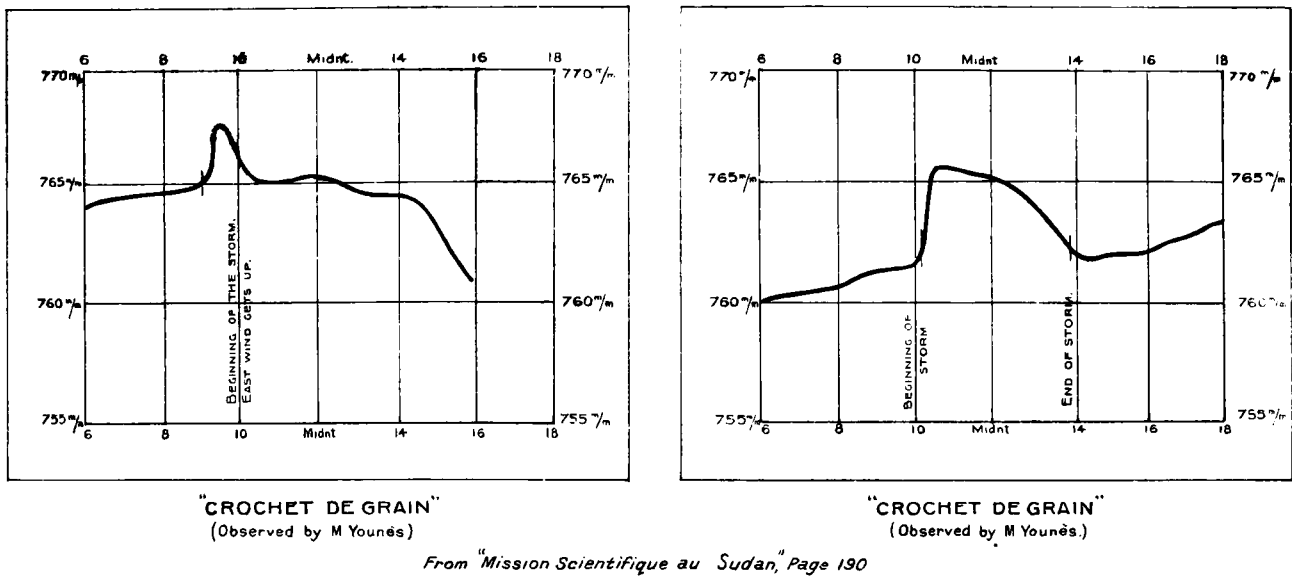
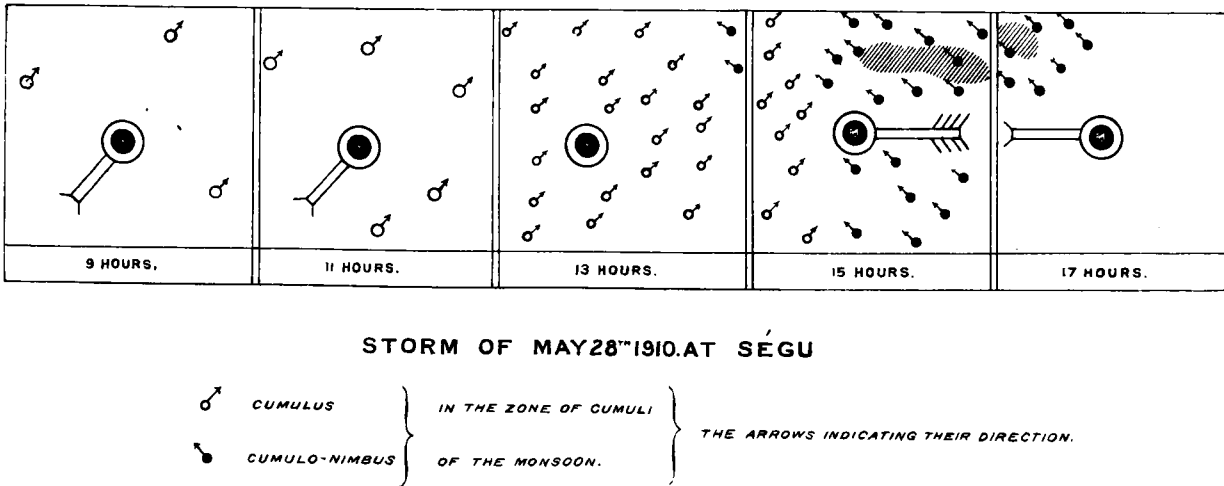


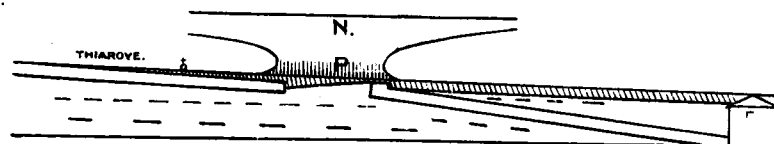
Figure 2.



The point surrounded by a circle indicates the position of Ségu. The double trace with feathers shows the direction and force of the surface wind. Lastly the shaded portion shows the places where it rained.

From "Mission Scientifique au Sudan," page 207.

Figure 1.

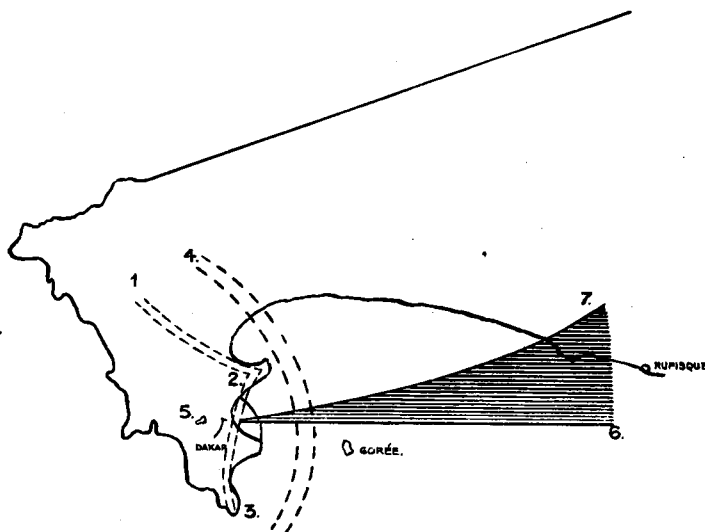
STORM OF SEPTEMBER 28TH 1913 AT DAKAR.

N. NIMBUS.

P. RAIN.

From "Mission Scientifique au Soudan," page 214.

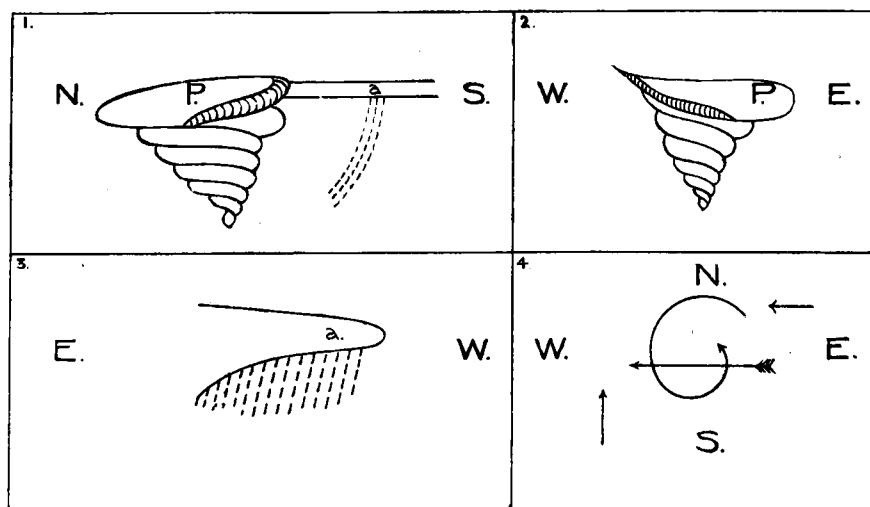
Figure 2.



POSITION OF CLOUDCAP (BOURRELET NUAGEUX) ABOVE DAKAR.

From "Mission Scientifique au Soudan," page 217.

Figure 3.



TORNADO AT ORONKUA AUGUST 13 1909.

P. UPPER LAYER OF TORNADO CLOUD.

a. STRATO NIMBUS IN THE BACKGROUND.

The figures are drawn in the following positions

1. In the direction of the Harmattan.

2. " " " " " Monsoon.

3. " " " " " propagation of the Tornado

4. Direction of the rotation of the whirl.

The stippling shows the direction of the rain.

From "Mission Scientifique au Soudan," page 169.

21h. 35 m.—The east wind continued, with thunder and light rain ; the storm had now definitely broken, but was of short duration.

The observed phenomena were very subdued and the storm winds of only moderate force, perhaps because the harmattan had used up great force earlier in stemming the unusually powerful monsoon.

There are three distinct stages in the above account :—

- (1) In the morning a storm was threatened at Dakar. This was reduced to cumulo-nimbus clouds entering the harmattan zone ; the storm did not break because the east wind was raised instead of being lowered.
- (2) In the afternoon a similar formation took place in the interior of the continent. This storm, the characteristics of which were well established before it arrived at Dakar, was almost annulled towards 19 h. on account of the intensity of the monsoon.
- (3) In the evening a second storm was formed, constituted of the unspent elements of the former. This time the storm, though of moderate intensity, was well manifested, because the monsoon was progressively annulled.

3. *Storm of September 28, 1913, at Dakar.*—This was a somewhat exceptional storm.

8h.—In the west, almost above the town, cumulus clouds of the form of monsoon cumuli were seen, already in the zone of the harmattan, which had begun to blow as a surface wind a short time earlier. Unlike the true cumulus of the monsoon, these clouds readily broke up and reformed as cumulo-nimbus. The sky elsewhere was very clear, and nothing seemed to foretell the approach of a storm except the existence of the abnormal east wind at the surface.

8h. 30 m.—A nimbus cloud, elongated and very low, appeared in the distance to the north-east. It formed a very low and almost horizontal dark grey band and took up a direction approximately east to west.

8h. 40 m.—A violent north-east wind got up, raising a cloud of dust and causing very high seas. The nimbus cloud moved rapidly. From its entire central part a large column of rain descended which extended between Thiaroye and Rufisque. (See Plate X, Fig. 1.)

8h. 45 m.—The wind increased in intensity and the nimbus cloud, which was very low, broke into parallel bands.

8h. 50 m.—The rain column moved westwards and crossed the coast between Thiaroye and Rufisque. The nimbus retained its movement from north-north-east to south-south-west, while the surface wind was clearly east to west, and extended in height to the base of the nimbus. Thunder and lightning began in the distance.

8h. 55 m.—The wind increased suddenly, and one minute later rain began to fall at Dakar.

8h. 58 m.—The rain was now heavy and the wind still very violent. The nimbus was visible to westward. In the east the rain was so slight that the sun's rays penetrated through the clouds ; this showed that the squall was subsiding inland. Assuming that the rain travelled from Thiaroye to Dakar simultaneously with the nimbus cloud, the velocity of the latter must have been approximately 60 kilometres per hour (*i.e.*, about 37 m.p.h.).

9h. 2 m.—The sun reappeared, the rain having ceased a short time previously ; the wind remained very violent and only diminished slowly after 10 h. By evening normal conditions were established and the monsoon was again the prevailing surface wind.

It must not be forgotten that the harmattan and the monsoon can co-exist perfectly without causing a storm, provided that they are sufficiently independent of each other ; in other words, provided that the equilibrium of the harmattan is not disturbed by strong ascending currents from the monsoon zone. A cloud cap ("bourrelet nuageux") is usually formed, and serves as a valuable indication of a coming storm ; it has been observed at several places and studied carefully by Hubert over the Cape Verd peninsula. This cloud cap, situated at a height equivalent to that of the limit of the two wind zones, has also been observed at numerous

inland places, especially in the Futa district, *i.e.*, midway between Senegal and French Guinea, in mean latitude approximately 12° N. In the former place its formation is assisted by the special rapidity and strength of the ascending currents which form there, and consequently by the rapid ascent of water vapour to the harmattan zone. The cloud caps are very narrow and elongated, and form a curve like 3-4 in Plate X, Fig. 2, slightly concave to the west and lying in an approximately north and south direction. Occasionally a double curve is visible (as 1-2-3). They usually suffer no displacement, but at times they have a slight westerly movement, which proves that they can penetrate to some extent into the zone of the harmattan. At such times the ordinary cumulus clouds of the monsoon zone are visible below.

The phenomena are most frequently observed in the afternoon or evening, which implies that they manifest themselves after the period of maximum heating of the ground. When their form is concave towards the west, it indicates a low hygrometrical state and a weak and sensibly equal intensity of the two winds. It indicates fine weather; but if the harmattan increase in intensity and if it descends, the cloud cap is seen to move more rapidly, and its orientation changes almost to due west.

When this motion and orientation of the cap is seen, it almost certainly indicates an approaching storm, since there is now definite conflict between the two winds. This fact has been verified by numerous observers, and as the cloud cap has advanced westwards the progressive, simultaneous descent of the harmattan has also been visible. A portion of the cloud cap may become detached, as at 5, the main part being the shaded area 6-7. Thus storms only occur when the harmattan descends and there is definite conflict between it and the monsoon.

On the other hand, strong evidence is available to show that a conflict between the harmattan and the trade winds does not produce a storm.

II.—16. MECHANICAL EFFECTS PRODUCED BY THE CONFLICT OF THE TWO WINDS.

In this connection a brief account of a typical storm at Oronkua (10° N.; 3° W.) will be given.

August 13, 1909.—Storm with tornado (67, p. 168).

Prior to the day of the storm the south-west monsoon had prevailed over all this district in the usual way for this season of the year. The wind was more or less steady and of moderate force throughout the day, and generally fell off in the evening about 19 h.

The clouds in its zone were situated at a height of about 500 metres (1,600 ft.). Above this, the east wind was clearly discernible, blowing in a very regular manner.

The monsoon had brought heavy rain from July 31 to August 10. On August 13 the south-west wind prevailed as usual, but fell at about 17 h. At this moment a whirling cloud column, proceeding from a horizontal cumulo-nimbus, became visible in the east. Above this the sky was quite clear.

The storm broke almost immediately, the cloud whirl advancing at a great rate and causing dense rain along its track. It was very localised and of short duration. The differences between the winds at different places were rendered clear, as follows (*see* Plate X, Fig. 3):—

- (1) By the distortion of the cloud "a" in moving westwards;
- (2) By the whirling column, whose direction of rotation was counter-clockwise;
- (3) By the reappearance of the upper cloud layer "P," which, in its south-west quadrant, became distorted (*see* Plate X, Fig. 3, Section 2), immediately it came into the current of the monsoon (the whole whirl having the usual vertical up and down velocity in addition to its translatory and rotary velocities).

In this case it was also clear that the humidity of the monsoon was constantly feeding the rain clouds of the storm by means of the ascending currents of the whirl.

This and many other similar examples clearly establish the fact that mechanical shearing movements are frequent and usually take place at the base of the storm clouds, *i.e.*, at the limit of the two wind zones.

The area of strong winds is often extremely small, and frequently a storm has passed comparatively close to a station without any change of wind force or direction being apparent there (*e.g.*, storms at Ségu, May 21, 1910; Dakar, July 31, 1913, etc.).

Occasionally a rotation of wind, generally taking the form of a reversal, point for point, of the surface wind, takes place (*e.g.*, the storm at San, 13° N., 5° W., on April 30, 1910). The intensity of the wind is very great for a period of varying length, the extremes of which are ten minutes and one hour. The squall usually takes the form of a violent, arid gust, followed immediately by torrential rain, after which the wind squalls recommence and prevail, on the average, for about twenty or thirty minutes.

II.—17. RAIN.

Storm rains are of a quite different nature from the ordinary rains of the “rainy season,” brought by the monsoon, and from these brought by the trade winds.

The fall frequently exceeds several centimetres, and the distribution is not uniform throughout the entire storm zone. The torrential rains, which fall after the onset of the violent winds, generally diminish gradually after a duration of from twenty to thirty minutes.

In some cases this marks the actual end of the rain; but more often, after gradually becoming more and more scanty, the rains suddenly start again with renewed force and are accompanied by very violent electric discharges. It has been observed that the district in which these discharges are the most numerous and violent is correspondingly a zone of maximum precipitation.

In the southerly regions, particularly on the Ivory Coast, the rains are always of longer duration than in the more northerly storms. This is due to the fact that in the south the available water vapour is more abundant, and the development of nimbus and cumulo-nimbus clouds is always more considerable than in the north.

II.—18. ELECTRIC DISCHARGES.

Electric discharges are usually manifested in the front part of the cumulo-nimbus clouds, and very rarely appear in the rear. Also they have never been observed to take place between the clouds in the monsoon zone and the earth. They take place—

- (1) In the midst of the cumulo-nimbus, whose summit, at least, is in the zone of the harmattan;
- (2) Between the clouds of the monsoon and those of the harmattan;
- (3) Between the clouds of the harmattan and the ground. (This latter case only happens when the storm is in progress.)

Case 1.—This happens very often and always marks the beginning of a storm; it may, however, continue for a considerable time. The cumulo-nimbus clouds are illuminated by lightning flashes at exceedingly rapid intervals, two or three flashes occasionally taking place simultaneously.

The accompanying thunder is rumbling and prolonged.

Case 2.—This is of comparatively infrequent occurrence. The following example is given :—

Storm in Senegal, August 17, 1909, 18 h.—To the east of Bagassi (Senegal) a large mass of cumulo-nimbus, whose upper part, though high, was still in the zone of the monsoon, appeared; above it, in the harmattan current, was a mass of strato-nimbus, moving westwards. The storm took place between the two zones, which drew nearer and nearer to each other, the electric discharges being very numerous and taking place entirely between these two cloud masses.

Case 3.—In this case, instead of a general illumination of the cloud, there is a shaft of light between the cloud and the earth, which is accompanied by a very loud, but short, peal of thunder.

In general this takes place in the elevated parts of the country, and is much more rare than Case 1.

The distribution of intensity of these electric discharges is not regular. There is generally one point—sometimes several—where the intensity is a maximum. This happens even when the cloud mass itself is homogeneous, though this is a rare occurrence, since the cumulo-nimbus or nimbus are usually accumulated in clusters.

The average frequency of discharge, at the time of maximum electric intensity, is about ten discharges per minute.

II.—19. DIMENSIONS OF STORMS.

No very definite figures are available on this point. It is clear, however, that individual storms are of widely different dimensions, the storm band in some cases being very limited in width and occupying only a few kilometres, whereas in other cases it stretches over 40 or 50 kilometres.

In all cases the rain falls over a limited area only, though the length of the storm cloud may vary over as wide a range as the storm band itself.

II.—20. TRAJECTORIES AND VELOCITIES OF STORMS.

A general statement as to the path of these storms has already been made, namely, that they form in the interior of the continent and move approximately westwards out to sea.

Detailed observations which have been made in several districts have shown that the path is, in general, rectilinear. There have been, however, exceptional cases, notably in storms at Sikasso (11° N., 5° W.), Odienné (10° N., 10° W.), Bonduku (8° N., 3° W.), and in the Fouta district, where, over parts of their courses at least, they have pursued curvilinear tracks. This is thought to be due to the physical features of these particular districts, *e.g.*, river beds, etc. Detailed observations (67, pp. 234–6) have been made at Dakar and at San (13° N., 7° W.), and these also show that the path is approximately a straight one.

Velocity.—Numerous observations of the time taken by different storms to pass between San and Kury, a distance of about 180 kilometres, give an average of $2\frac{1}{2}$ to 3 hours, the individual readings being fairly constant.

This gives a velocity of displacement of from 60 to 72 kilometres per hour, a figure which agrees with that found for the Dakar regions, and recently confirmed by M. Chudeau for the district of Timbuktu (16° N., 2° W.).

Davis (4) gives the extreme limits of velocity as 33–67 kilometres per hour.

Direction of the Storms.—The direction taken by the storms is, on the whole, that of the harmattan.

Observations made at San (French Sudan) give precise information for this part of the Sudan, and show that the direction is not absolutely that of the harmattan, but deviates some degrees from it, this deviation being caused by the monsoon.

Storms observed between Sarassarasso and Bobo-Dioulasso (10° N., 7° W.) show an almost similar deviation.

On all the Guinea coast, the Sudan and the high Ivory Coast and in Senegal, storms come from some easterly point, usually between north-east and south-east.

On the low Ivory Coast also, the storms come from between these two directions; near to the sea the path is north-east to south-west, and near Dimbokro the usual track is south-east to north-west. One storm was observed at Bucabo (Ivory Coast) on April 3, 1914, coming directly from the west; this, however, is quite exceptional and is the only such phenomenon the natives have witnessed.

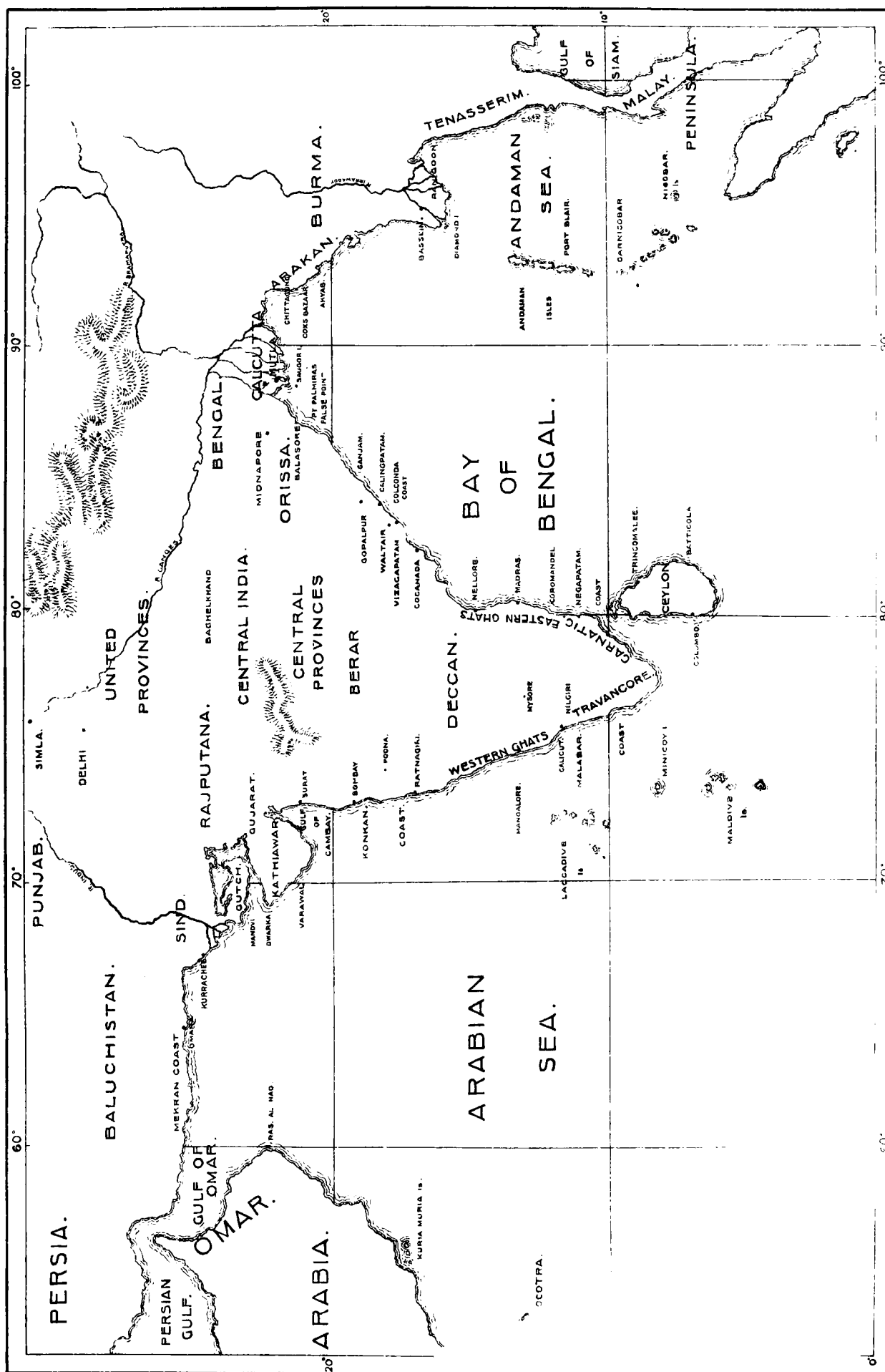


CHART SHOWING VARIATION IN YEARLY FREQUENCY OF STORMS IN THE BAY OF BENGAL.

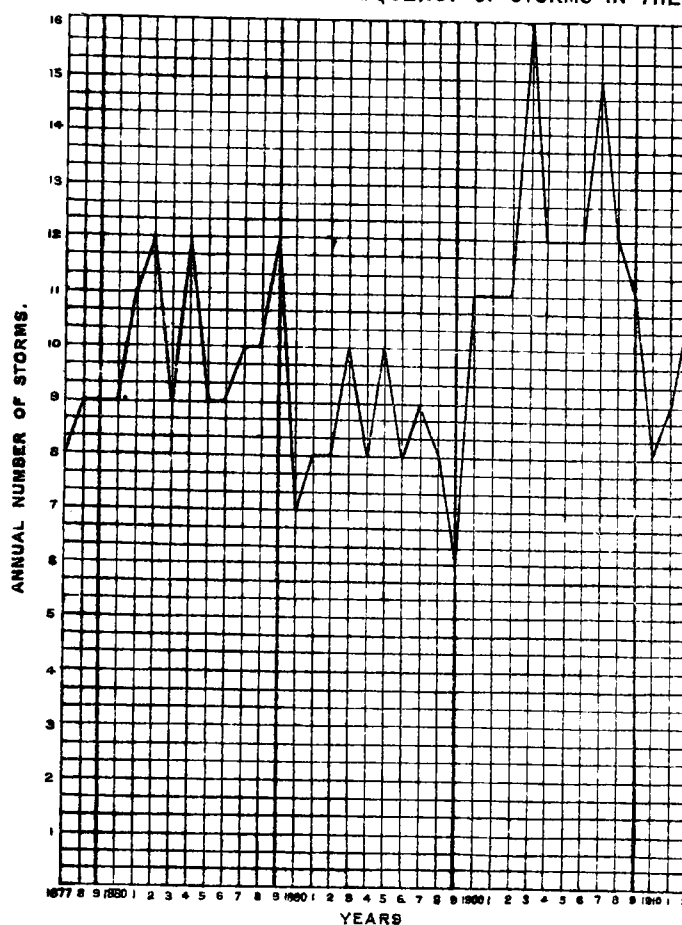
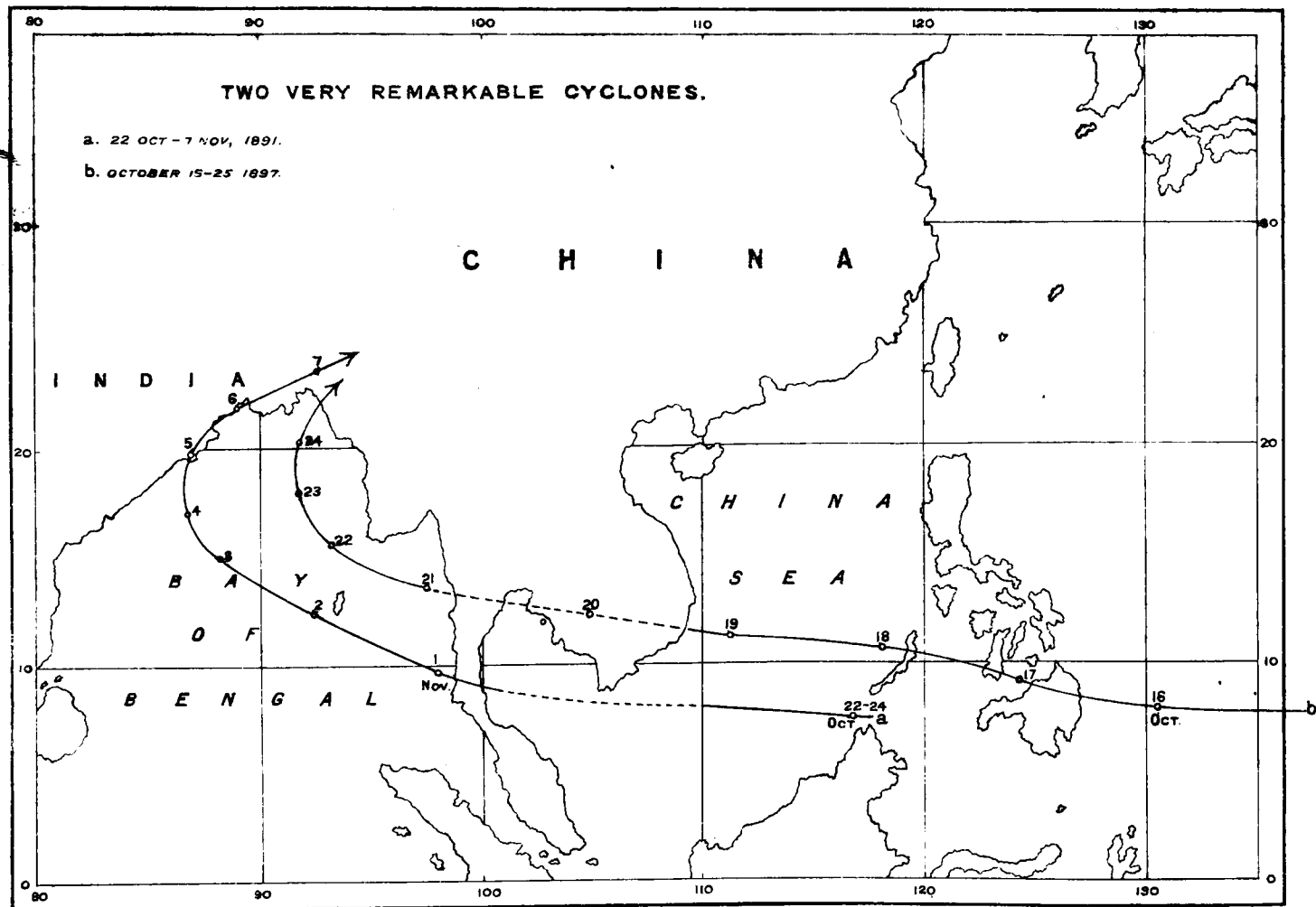


Figure 2.



SECTION III.—INDIAN OCEAN.

A.—CYCLONES IN THE BAY OF BENGAL AND THE ARABIAN SEA.

Part I.—The Bay of Bengal.

The storms of this region have been discussed in great detail in Sir John Eliot's comprehensive work—*Handbook of Cyclonic Storms in the Bay of Bengal* (40), which was published by the Meteorological Department of the Government of India in 1900 (2nd edition). It is proposed, in this present account, to give a short summary of the facts and conclusions arrived at in the above work with regard to these storms, and also to give supplementary data for the years 1900 to 1912, these data having been collected from the *Indian Monthly Weather Review* (42), and the *Pilot Charts of the South Pacific and Indian Oceans*.

The frequency of the storms in some months of the "cyclone season" is very great, so that to avoid confusion the plates given in this section will show the tracks of storms for the individual months of the later years only.

For the tracks of storms for the earlier years, 1877–1899, covered by Eliot's report, the reader is referred to Volume II of the Handbook, which consists solely of plates.

The normal weather and prevailing winds of this part of the world fall into four well-known periods in the course of the year. These are :—

- (1) The north-east monsoon period, from January to March or April, when north-east winds of land origin prevail over the whole or the greater part of the Bay.
- (2) The May transition period, from the end of April to the end of June, during which the winds are changing from north-east to south-west over the Bay.
- (3) The south-west monsoon period, from July to September, during which south-west winds of oceanic origin prevail over the whole of the Bay.
- (4) The October transition period, from October to December, when the south-west winds retreat southwards and are replaced by north-east winds of land origin.

During these periods storms of very varying intensity occur, some resembling European "lows," in which the wind force does not exceed force 8 (Beaufort), others being of moderate intensity with winds of force 8–10, and others being true cyclonic storms with winds of hurricane force, and having the well-known area of central calm, *i.e.*, the "eye" of the storm, which is typical of all intense cyclones.

All storms in the Bay are, however, cyclonic circulations, and the most violent storms almost invariably are of more or less gradual growth and commence as feeble circulations.

The storm area in the case of the most intense and extensive cyclones may be divided into two portions, an outer and an inner storm area.

In the outer area the barometer falls slowly and to a moderate extent, and the winds are of force 6 to 9 or 10, the strongest winds being felt during the squalls.

In the inner storm area the barometer falls very quickly from the outer edge to the central area, which in these storms is an area of calms. The barometric gradient is very steep, the winds are of hurricane force, the shifts of wind rapid, and the sea very high and confused.

The ratios of the magnitude of the three divisions—the outer and inner storm areas and the central eye—differ very greatly in different storms. The size or greatest width of the inner storm area gives a rough measure of the magnitude or extent of the storm, whereas the intensity of the storm is most easily measured by the depth to which the barometer at the centre falls, the normal height of the barometer at the time being the simplest standard of reference.

There is no direct relation between the intensity and magnitude of these storms. The most intense storm on record is the False Point cyclone of September, 1885, in which the greatest barometric fall was $2\frac{1}{2}$ in., but in which the magnitude (measured as above described) was not great. A notable storm, of which both magnitude and intensity were very great, was the Backergunge cyclone of October, 1876. In this storm the central eye was from 15 to 18 miles in its longest diameter, while the inner storm area was remarkably extensive, winds blowing with hurricane force and disabling vessels at a distance of 200 miles from the vortex; also, the barometer was below 28 in. in the central area.

By far the larger proportion of cyclonic storms which occur in the Bay are of small extent and moderate intensity, and in these there is no calm centre and rarely an inner storm area of hurricane winds. The winds in these storms reach at least force 6 and do not exceed force 10; they are quite definitely cyclonic circulations, and their chief importance is that they often bring heavy rain to districts along their track.

III.—1. CYCLONE SEASON.

During the early months of the year, January to March, steady and moderate north-east winds prevail, and fine, clear weather is usual, cyclonic storms being exceedingly rare, both in the Bay of Bengal and in the Arabian Sea. Squally weather is sometimes experienced in the Persian Gulf and along the Mekran coast, and the north-east monsoon occasionally attains the force of a gale in the Bay during February. Records of definite cyclonic circulations at this time are most infrequent; one storm formed over the south of the Bay, to the east of Ceylon, on January 13, 1906, and it is doubtful whether any storm of this nature has been observed in January previous to this year. This storm was entirely analogous to the summer cyclones of the Bay; it was of moderate intensity, the greatest observed barometric fall being 0.19 in. It formed east of Ceylon on the 14th, and moved in a west-north-west direction during the 15th, being central about 60 miles to the north by east of Trincomalee (North Ceylon) at 8 h. of the 16th; its movement during the next 24 hours was very slow and almost due west. The disturbance disappeared completely during the 17th. The strongest winds experienced by vessels were of force 10. The track is shown on Plate XVII, Fig. 2, with the tracks of December storms.

The only other January storm was in 1908, and this is described in § III, 3.

There is no record of any storm of cyclonic nature over the Bay during February, and during March only two have occurred. One of these passed over Car Nicobar on March 26, 1892, and the other was reported from March 5 to 10, 1907. This latter storm was indicated by unsettled weather, which set in over the Andaman Islands on the 5th; by the 7th it was a definite formation over the south of the Bay, and advanced along a course between west and south and broke up over the south-east of Ceylon during the 10th. Its track is shown on Plate XIV, Fig. 1, with the tracks of April storms.

It was a storm of considerable intensity, and the greatest observed barometric fall was 0.5 in.; hurricane winds were experienced by the ss. *Vadala*, and considerable damage was done to the town of Batticola (east coast of Ceylon).

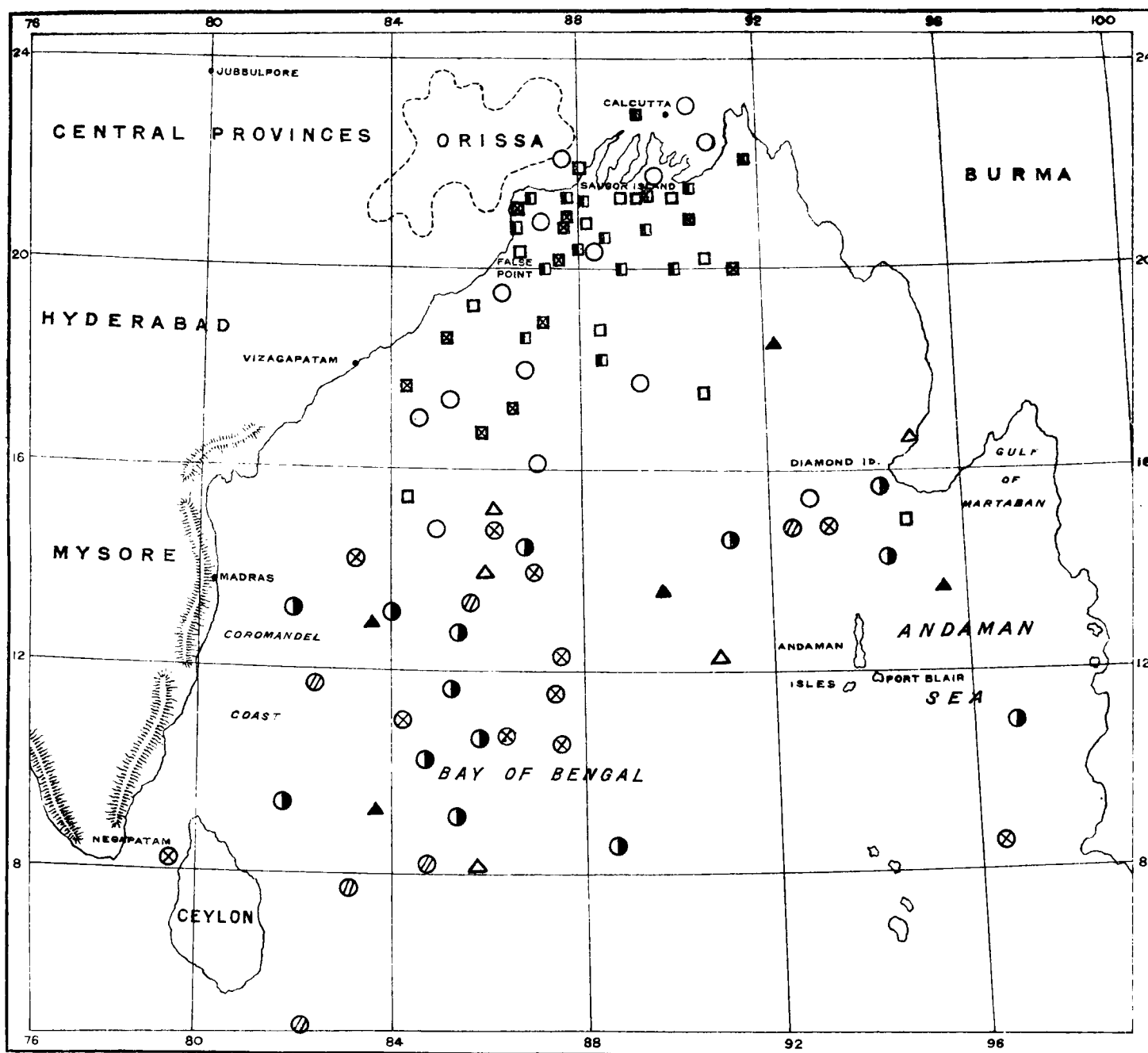
Cyclonic storms which occur in the Bay before the setting in of the monsoon are generally associated with temporary advances of monsoon winds, and in the above case there may have been a feeble advance early in the month, since the winds at Port Blair had a slight southerly component from the 4th to the 12th.

In March, 1910, unsettled weather and gales prevailed over the east and centre of the Bay, but these never developed into a regular cyclone. Marine information as to the origin and character of the disturbance suggested that it was due to a temporary projection northwards of the equatorial belt of low pressure and its associated squally weather.

A brief description of the weather from March to the end of the year is given by Eliot, as follows:—

“In March, due to the increase of temperature in northern and central India, local sea-winds commence at the head of the Bay; these strengthen and back down

CHART SHOWING POINTS OF ORIGIN OF STORMS IN THE DIFFERENT MONTHS OF THE CYCLONE SEASON FOR THE YEARS 1900-1912 IN THE BAY OF BENGAL.



- | | | |
|----------------|-----------------|------------|
| △ APRIL STORMS | ⊠ AUGUST STORMS | |
| ▲ MAY " | ○ SEPTEMBER " | ⊙ DECEMBER |
| □ JUNE " | ● OCTOBER " | |
| ■ JULY " | ⊗ NOVEMBER " | |

Figure 1. TRACKS OF CYCLONIC STORMS IN THE BAY OF BENGAL AND THE ARABIAN SEA FOR THE YEARS 1900 - 1912.

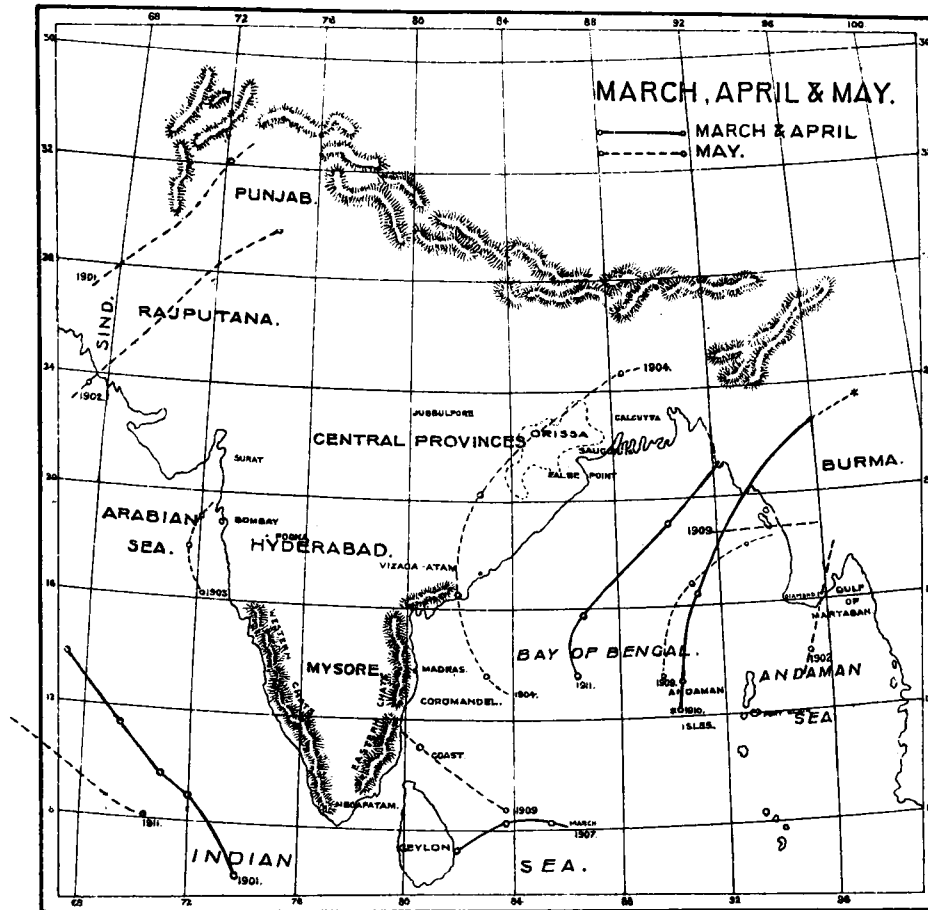
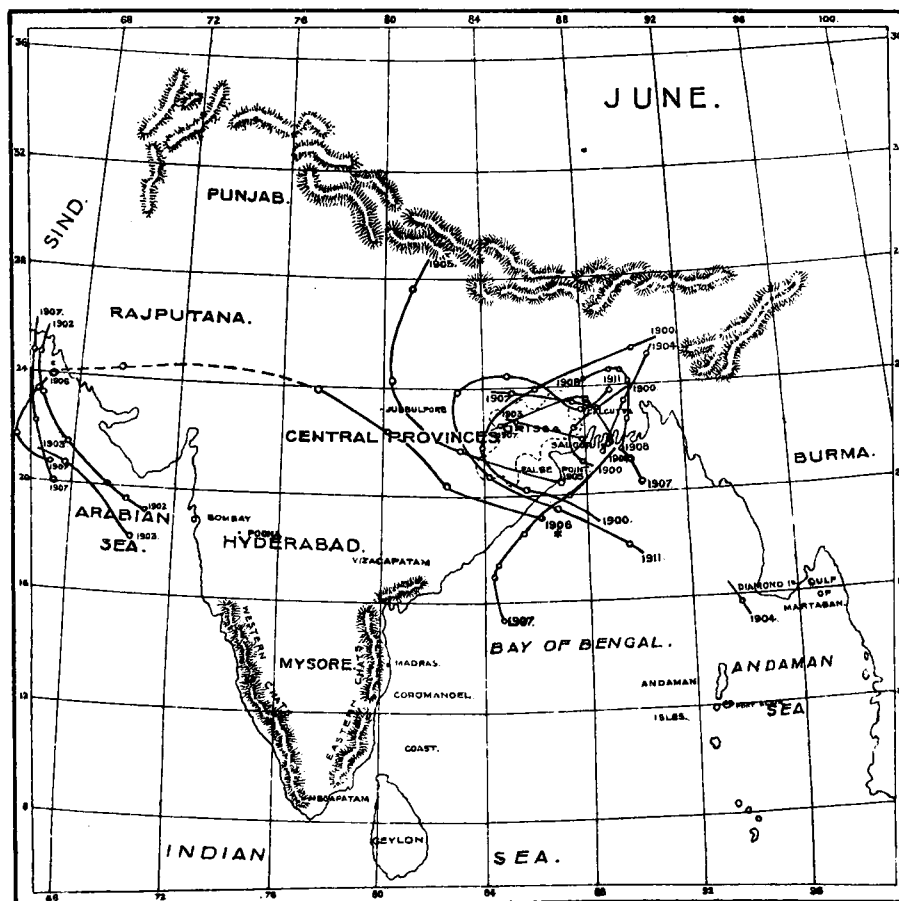


Figure 2.



TRACKS OF CYCLONIC STORMS IN THE BAY OF BENGAL
AND THE ARABIAN SEA FOR THE YEARS 1900 - 1912.

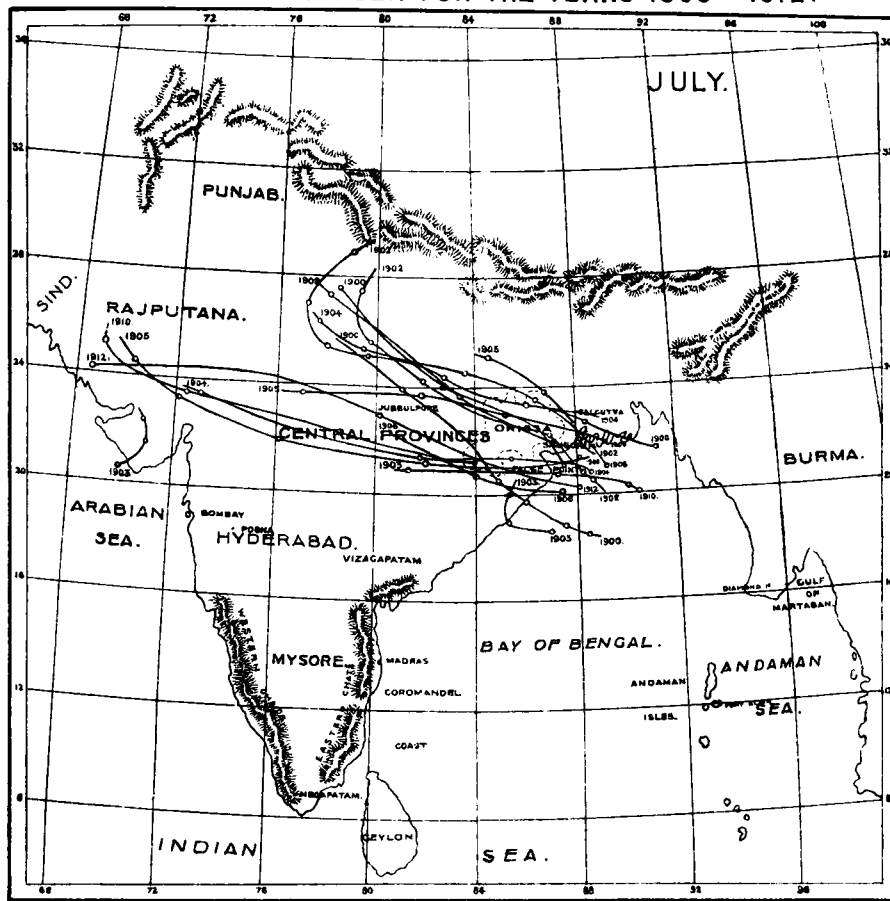


Figure 2.

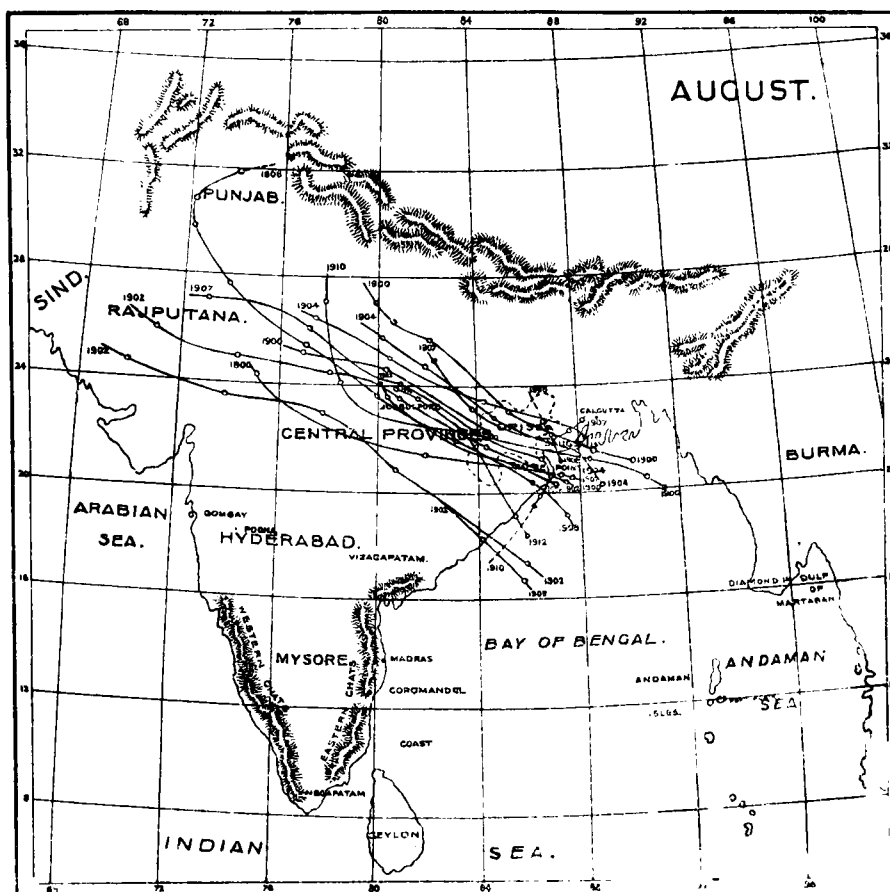


Figure 1. TRACKS OF CYCLONIC STORMS IN THE BAY OF BENGAL AND THE ARABIAN SEA FOR THE YEARS 1900 - 1912.



Figure 2.

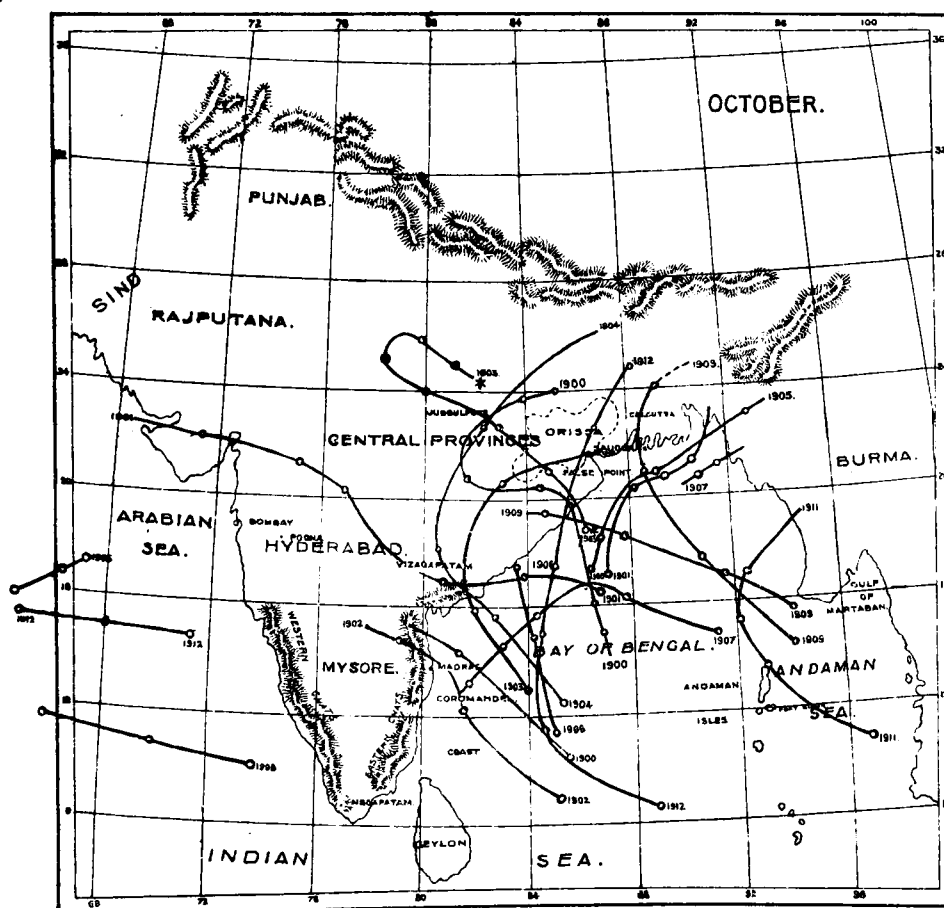


Figure 1
TRACKS OF CYCLONIC STORMS IN THE BAY OF BENGAL
AND THE ARABIAN SEA FOR THE YEARS 1900 - 1912.

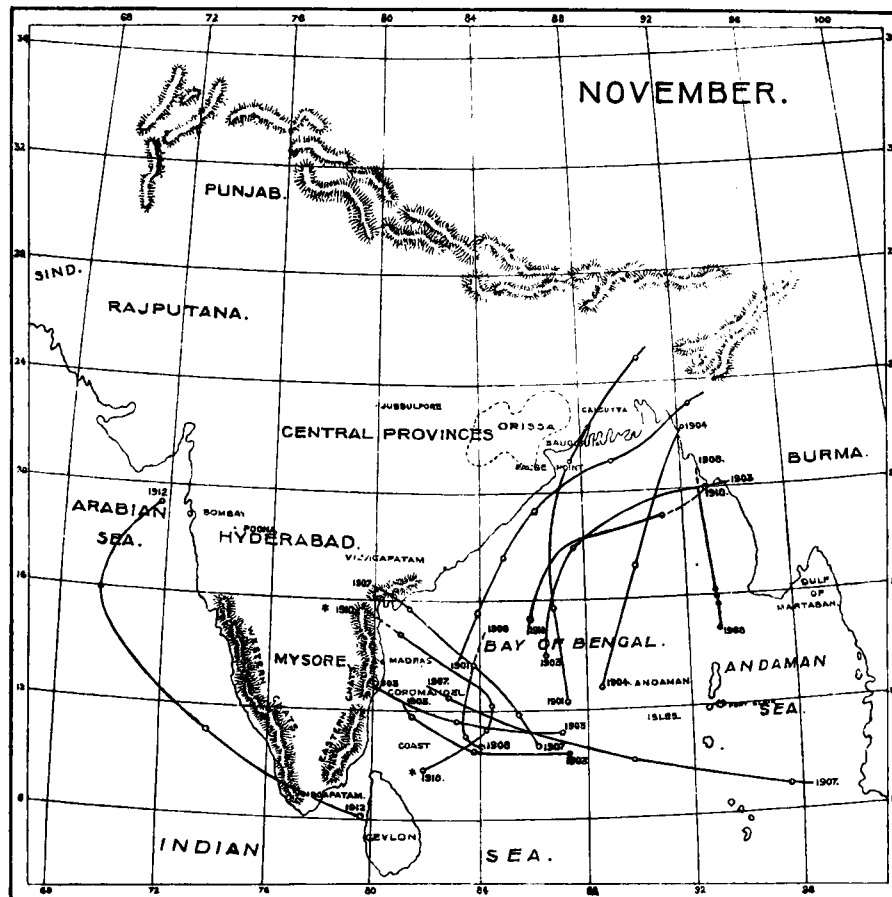
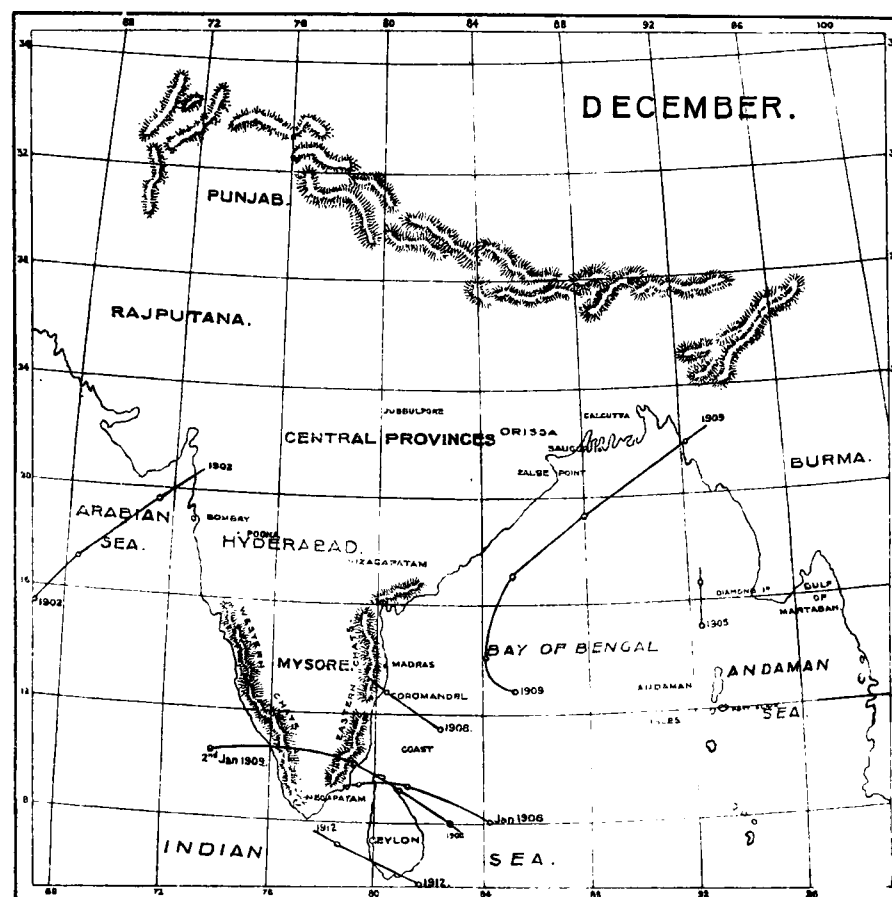
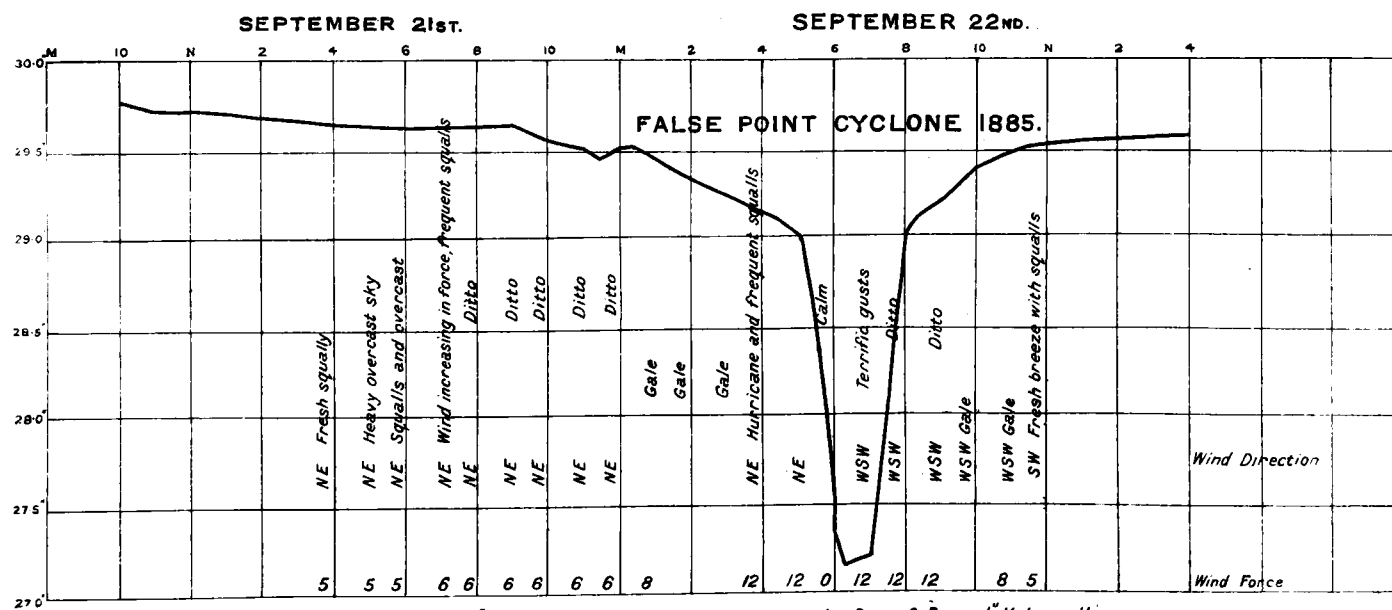
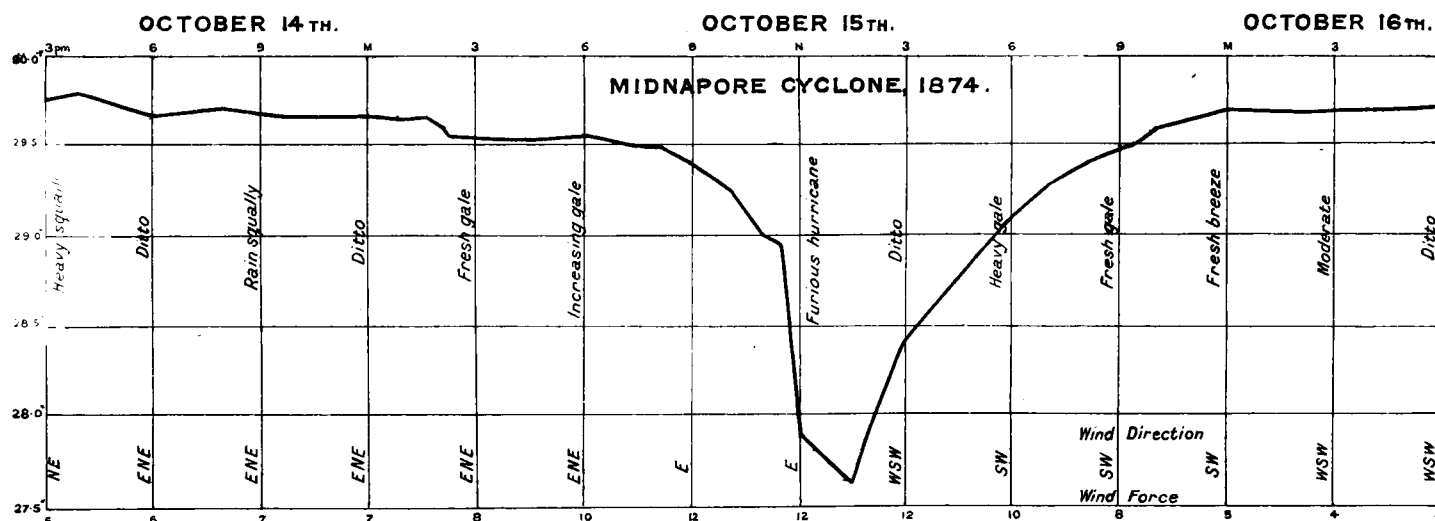
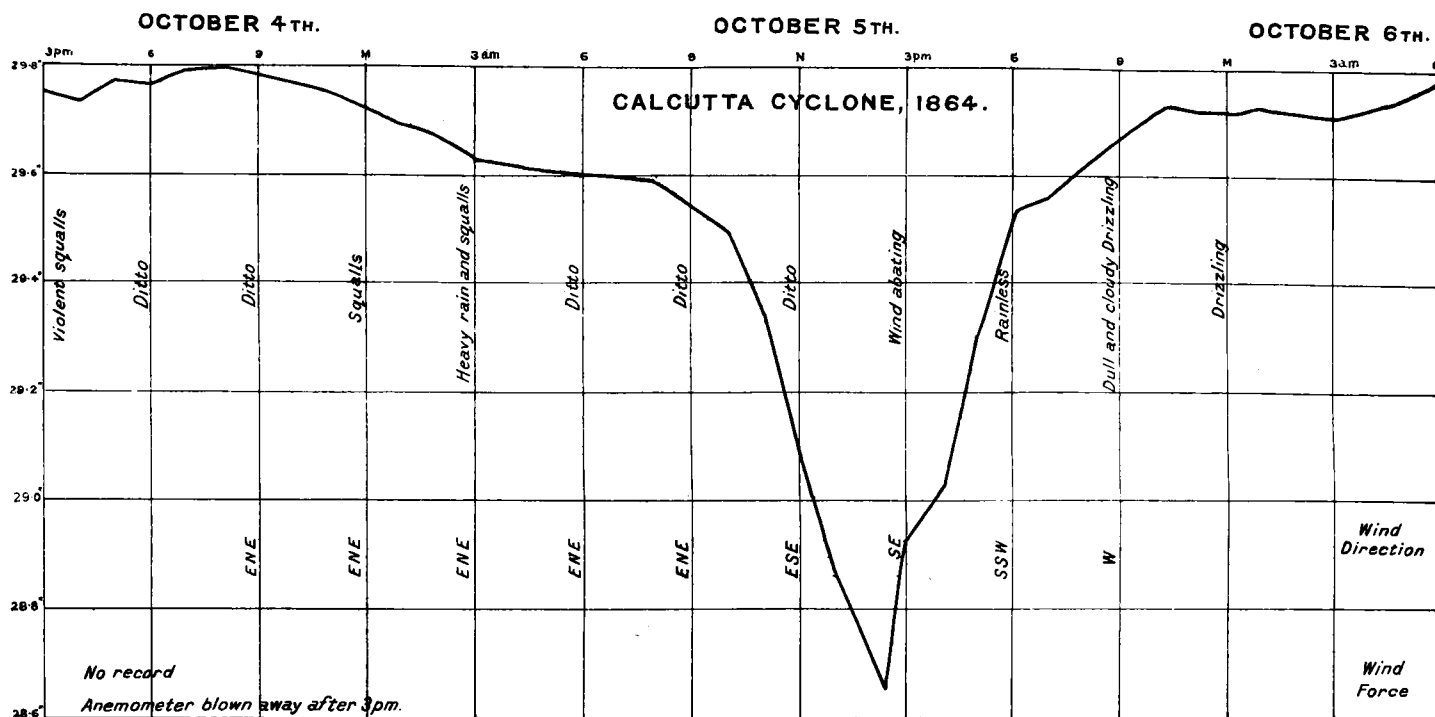


Figure 2.





From Eliots "Handbook of Cyclonic Storms in the Bay of Bengal," Volume II.

the Bay during April, and during all this period there is a gradual change from the prevalence of dry north-east land winds, which become replaced by light, unsteady variable winds in the centre of the Bay during April and May. This continues until the latter part of May or the beginning of June, when, after one or two preliminary feeble efforts, the true south-west monsoons advance rapidly up the Bay, and shortly afterwards penetrate into Burma, Bengal and Upper India.

“ This period, ‘ the rains proper,’ lasts until the middle or end of September, after which the rain-giving winds retreat and tend to back down the Gangetic Plain and the Bay. This retreat is a slow process and lasts until the end of December. In consequence of the peculiar conditions prevailing in the Bay, the south-west winds still blowing over the south of the Bay curve through south, south-east, and east, and thus reach the Coromandel coast as north-east damp winds, thus giving, for a period of about two months, occasional moderate to heavy rainfall to southern India. The commencement of these rains in October in southern India is usually termed the beginning of the north-east monsoon, but the rains ought really to be thought of and called ‘ late or retreating south-west monsoon rains.’ ”

The period described above constitutes the “ cyclone season,” since cyclonic storms can occur at any time during the period when south-west winds are blowing more or less steadily over the entrance and south of the Bay. The character of the storms varies to some extent during this period, being dependent on the general weather conditions prevailing at the time of origin.

During the south-west monsoon period there is a rapid succession of cyclonic storms of moderate extent and small intensity. During the two transition periods, storms are less frequent than during the monsoon period ; but on the other hand, most of the intense and dangerous cyclones are formed during the transition periods, approximately one out of every three of these storms being dangerous, the other two being moderate and resembling the storms of the rains proper.

III.—2. STORM FREQUENCY.

Since the establishment of the Indian Meteorological Department in 1875, cyclones have been recorded and charted in considerable detail and it is unlikely that any storm of definite cyclonic circulation occurring since that date has been missed.

In Eliot's handbook the tracks of storms occurring during the eleven years 1877–1887 are shown in one set of plates, and those for the twelve years 1888–1899 in a second set of plates. These include cyclones of all degrees of violence, from the intense Backergunge cyclone of October, 1876, down to the feeble but frequent whirls of the months of July and August. A third set of Plates in the handbook shows the tracks of all storms during the period 1882–99, in which winds of force 8 (Beaufort) and upwards were actually experienced by vessels.

Plates XIV–XVII show the tracks of most of the storms month by month for the thirteen years 1900–1912.

The monthly frequency of cyclonic storms of all degrees of intensity is as follows :—

1. For the years 1877–1899 (23 years)—

Month	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Season
Number of Storms ..	4	12	22	39	32	43	30	20	8	210
Monthly frequency% ..	2	6	10	19	15	21	14	9	4	—

2. For the years 1900-1912 (13 years)—

Month	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Season
Number of Storms ..	3	9	16	26	23	27	21	17	9	151
Monthly frequency% ..	2	6	11	17	15	18	14	11	6	—

3. For the years 1877-1912 (36 years)—

Month	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Season
Number of Storms ..	7	21	42	65	55	70	51	37	17	365
Monthly frequency% ..	2	6	12	18	15	19	14	10	5	—

It is seen that the highest percentage of storms occurs in September ; in the entire rainy season—July to September—52%, in the May transition period 18%, and in the October transition period 24% of the total number of storms occur respectively. Very few storms occur in the limiting months of the season, April and December.

The variation in the number of storms for consecutive years is shown in Plate XII., Fig. 1. This yearly variation is not nearly so marked as in the case of West Indian Hurricanes, shown in Plate I, Fig. 1. On an average about 10 storms (of all intensities) occur annually in the Bay, the extreme values of 6 and 16 storms occurring in the years 1899 and 1903 respectively.

Frequency of the Different Types of Storm.—The above frequency tables refer to storms of widely different intensities and merely give a measure of the total storm activity in successive months of the “cyclone season” for the years indicated.

The storms fall roughly into three broad classes :—

Class I.—Severe cyclones, in which the wind exceeds force 10, and in which there is often (but not always) the characteristic calm area at the centre.

Class II.—More moderate cyclones, in which the winds range between forces 8 and 10. . .

Class III.—Feeble storms, in which the force does not reach force 8, but which are, nevertheless, definite cyclonic circulations.

Using this classification, the frequency of the different types of storm throughout successive months is as follows. Each storm is allocated to the month in which it originated.

1877-1899.				1900-1912.			
Month.	Number of Storms in			Month.	Number of Storms in		
	Class I.	Class II.	Class III.		Class I.	Class II.	Class III.
April	2	1	1	April	3	—	—
May	7	5	—	May	3	2	4
June	3	11	12	June	4	4	8
July	4	16	19	July	2	13	11
August	1	14	17	August	1	7	15
September ..	6	18	19	September ..	1	7	19
October	7	17	6	October	7	5	9
November ..	14	6	—	November ..	4	7	6
December ..	5	3	—	December ..	3	1	5

For the 36 years 1877–1912 the distribution is as follows :—

Month.	Class I.	Class II.	Class III.
April	5	1	1
May	10	7	4
June	7	15	20
July	6	29	30
August	2	21	32
September ..	7	25	38
October	14	22	15
November ..	18	13	6
December ..	8	4	5
Total	77	137	151

Thus it is seen that, of the 365 storms reported in the 36 years 1877–1912,

77 (*i.e.*, 22%) have been severe,

137 (*i.e.*, 37%) have been moderate,

151 (*i.e.*, 41%) have been feeble.

The probability of the occurrence of a severe storm in any month is as follows :—

April.—Storms are very infrequent, 7 being reported for the 36 years 1877–1912, and only 9 between the years 1748–1879 (9). Should a storm occur, however, the chances are about two to one that it will be severe.

May.—Storms are of comparatively frequent occurrence during May (about two every three years); it is an even chance that a storm forming in this month will be of great intensity.

June.—One or two storms may be expected every year; of these, the chances of a severe storm are about one in six.

July.—Storms are of comparatively frequent occurrence, an average of two or three occurring every year. 90% of these storms are of moderate or feeble intensity, so that the chance of a severe storm is very remote.

August.—Storms are almost as frequent as in July; the chances of a severe storm are, however, even more remote, and only two severe storms have occurred in August during the past 36 years (one, in 1899, which crossed the Bengal Coast near Saugor Island, and the other, in 1900, which passed inland across the Orissa Coast near Balasore).

September.—Conditions are very similar to those of July and August. Two or three storms occur every year, and about 90% of these are of moderate or slight intensity.

October.—Storms occur rather less frequently than during any of the four preceding months, the average being just over one per year. If a storm forms in this month the chances are about one to two that it will develop into a severe cyclone.

November.—One storm may be expected per year in this month, and there is an even chance that the storm will be of great severity.

December.—Storms are not frequent (about one in every two or three years). The chances of a severe storm during this month are about even.

III.—3. ORIGINS AND TRACKS OF CYCLONES.

Almost all cyclonic storms in the Bay of Bengal originate or are produced in the Bay itself. There is not a single example on record of a cyclonic storm having formed in the Arabian Sea and passed across India into the Bay of Bengal. On the other hand several storms which originated in the Bay, especially in the south of the Bay, passed across India and gave stormy weather in the Arabian Sea for several days. These storms will be discussed later in the general account of disturbances in the Arabian Sea.

Occasionally, however, storms have succeeded in crossing the Malayan Peninsula from the Gulf of Siam into the Bay of Bengal. These are comparatively infrequent. Eliot gives three such storms for the years 1875–1899 ; for the years 1900–1912, two have been recorded which originated in the Pacific and crossed from the China Sea through the Gulf of Siam to the Bay, both in the month of October and in the years 1909 and 1911 respectively. These storms were both intense, and in all respects except their point of origin were typical of the usual severe storms of the October transition period.

The tracks of two very remarkable cyclones are given by Algué on page 219 of his book *Cyclones of the Far East* (53). These are shown on Plate XII, Fig. 2, and the storms themselves are described in great detail by Eliot on pages 266–295 in Volume I. of his handbook.

Track (a) is that of the Port Blair Cyclone of November 1–7, 1891. This storm showed the following interesting features :—

- (1) It is the first cyclone on record of which there is clear and decisive evidence that it originated outside the Bay.
- (2) In its earlier stages it was of great intensity, though of small extent. It increased in extent without altering in intensity as it approached the head of the Bay ; it had an existence of at least nine or ten days, and was an intense cyclone for seven days.
- (3) The path of the storm in the Bay was almost unique on account of its great recurvature. Its course was west-north-west in the Andaman Sea, recurving rapidly through north-west and north to north-east and east-north-east in the centre and north of the Bay. In consequence of the recurvature of the storm several ships encountered it twice in their passage up the Bay.

For further details of these remarkable storms the reader is referred to the original accounts.

A map of the Bay showing the various points of origin of the storms of different months during the years 1900–1912 is given on Plate XIII. From this, and from similar maps for earlier years, it is seen that these storms do not form over or near the equator. There is no record, prior to the year 1900, of a storm having formed to the south of latitude 8° N. Recently, however, two storms have formed just south of latitude 8° N., one in December 1908, and the other in December 1912. Both these storms were well marked and of considerable intensity, and the former was of an exceptional character in the following respects :—

- (a) It formed at a time of the year when storms are practically unknown (December 31 to January 6 was the period of its duration), the only other instance on record of a storm formed over the Bay in January being in 1906.
- (b) It was a disturbance of comparatively great elevation, differing materially in this respect from the storms usually formed during the period October to December. These invariably fill up while moving westwards across the plateau of Mysore and the Western Ghats, the average elevation of which, in the part traversed by the storm under discussion, is about 5,000 ft.
- (c) Its passage across the south of the Peninsula was marked by the occurrence of unprecedentedly heavy rain (for the time of year) over Madras. The largest amounts occurred in the Nilgiris, which obtained a total of over 9 in. from the 1st to the 3rd.

These storms are, however, quite exceptional, and it may be accepted as a general principle that the lowest latitude in the Bay at which cyclonic storms are formed or met with is latitude 8° N.

From Plate XIII it is seen * that the majority of the April, May, October and November storms originate in the western half of the Bay at an average latitude about equal to that of Madras. A large number of the storms of these months,

* Plates XIII–XVII do not give the whole of the storms for the various months, but indicate sufficiently the variation in the geographical distribution.

nevertheless, originate in the neighbourhood of the Andaman Islands. The latter fact has led to the belief that this particular area possessed certain peculiarities which favoured the origin of fierce cyclones, though the difference between it and the belt of few storm-origins around it is not very great or clearly defined. The special feature seems to be only its long distance from the Indian coast, so that cyclones forming in the Andaman area have a longer path before reaching land than have those forming further west or towards the head of the Bay, and hence, if conditions are favourable, the former are more likely to develop into large and dangerous cyclones.

Almost all the storms of the rains proper—July to September—have their points of origin north of latitude 16° N., and of these roughly two-thirds form over the head of the Bay and the remaining one-third between latitudes 16° and 20° N.

The tracks of the storms for successive months will now be described. (See Plates XIV–XVII.)

April.—The infrequent storms of April form in the south of the Bay and then move west or west-north-west to Ceylon or the Coromandel coast; or they may form near the Andaman Isles or in the Andaman Sea from where they move northwards to the Burma coast.

May.—The storms originating in the west and south of the Bay move in a westerly direction and strike the Coromandel coast, while those originating further north and east move northwards to the head of the Bay or to the Burma coast.

June.—The majority form to the north of latitude 19° N. or quite at the head of the Bay. It is an even chance whether a storm which has formed in the Bay in June will pass in some northerly direction over Bengal, or in some westerly direction across Orissa.

July.—The July storms all originate in the north of the Bay, the majority of the points of origin occurring even north of latitude 20° N. The track of all the storms is in some direction between west and north-north-west, across the north-west angle of the Bay.

August.—These storms are very similar, in track and in point of origin, to those of July. Five out of every six storms originate to the north of latitude 19° N., and the remainder between 16° and 19° N. These storms occasionally advance in some northerly direction into Bengal, but the usual course is in a west or west-north-west direction across the Orissa or Ganjam coast.

September.—These storms generally form further south than do those of the two previous months, but usually, however, north of latitude 17° N. The majority advance in a westerly direction, striking the north-west coast between Balasore and Cocanada; while about one in every four or five storms advances in a northerly direction into Bengal.

October.—These storms form most frequently in the centre of the Bay between the Andamans and the north Coromandel coast, though they occur also in the Andaman Sea.

They are of rare occurrence to the north of 19° N.

The majority of the storms move westwards to the coast, and about one in every three moves northwards into Bengal or Orissa.

November.—During this month cyclones form in any part of the Bay south of latitude 16° N., or in the Andaman Sea. Rather more than one-half of these form south of 12° N.

About half the storms of this month move westwards to the Coromandel coast, and most of the remainder move northwards and strike the northeast coast of the Bay, which is more liable to cyclones in November than in any other month of the year. On the other hand the part of the Bay which is most free from storms in this month is the coast from Saugor Island to Vizagapatam. It is seen from the above and from the charts showing the tracks of November storms that these tracks show less regularity than those of any other month.

December.—No storm has been known to form in the Andaman Sea during this month. Of the few storms recorded, almost all have originated in the south or south-west of the Bay between Ceylon coast and the Andamans, and have moved in a west-north-west direction, striking the Coromandel coast between Madras and Negapatam.

The above descriptions indicate briefly the general trend of the tracks of centres of cyclones for the various months of the cyclone season. These tracks are very different from the roughly parabolic trajectories marked out by the centres of West Indian hurricanes (*see* Section II, A), and are much less irregular than are those of the latter type of storm.

Of the few irregular tracks of cyclones in the Bay, the majority, as stated above, are to be found amongst the October and November storms.

Other noteworthy abnormal paths of recent years are :—

1. *The Storm of October 3-12, 1903.*—This storm moved in from the north of the Bay and travelled for some days in a normal north-westerly direction, when suddenly the movement changed to east or east-north-east and the storm described a loop over the Central Indian Plateau and the United Provinces. It then moved south-east, returning to approximately the same position as it had occupied several days earlier. The storm was also remarkable for its longevity, and for the very heavy rain it gave to the United Provinces and the neighbouring districts. The track of this storm is marked * in Plate XVI, Fig. 2.

Its track was possibly related to the fact that during its existence there were no monsoon winds over the Arabian Sea, so that there was no rainfall from the western side of India, while, on the contrary, the Bay monsoon was blowing strongly, so that the rainfall was derived from the Bay or eastern side of India ; this would be a relevant fact on the convectional theory of these storms.

2. *The Storm of June 12-15, 1902.*—This, although not an intense storm, had an interesting and most unusual track for June. It formed under the usual conditions in front of the first advance of monsoon winds, and moved over a north-westerly track from its place of origin off the Arakan Coast to the head of the Bay, where it recurved rapidly to the north-east and passed into East Bengal instead of pursuing the customary northerly or westerly direction. No chart of the track was published.

3. *The Storm of June 18-23, 1906.*—This storm formed in the Bay just off the coast near Gopalpur, about latitude 19° N., *i.e.*, rather more to the south than the majority of June storms which form in the head of the Bay. Its track (marked *) is shown on Plate XIV, Fig. 2.

It moved in a normal direction for three days, and then, suddenly increasing its velocity, marched due west across Central India and entered into the Arabian Sea just south of Kurrachee on the 23rd. Its intensity had diminished considerably during the last few days of its course.

Although November is the month in which the tracks are more abnormal than in any other month of the cyclone season, yet the storms of June also show great individual variation. Many of the disturbances formed in front of the first rush of the monsoon are strongly marked, and travel in a westerly direction, but if for some reason the burst of the monsoon is not so vigorous as usual, the storms are often ill-formed and pursue very varied tracks.

Since the majority of the storms—more especially of the dangerous type—mark out a regular course, the problem of determining the path along which a storm will advance becomes comparatively simple.

Of the 210 storm paths studied by Eliot only 13 recurved to any considerable extent in the Bay of Bengal (*i.e.*, about 1 in 16 or 1 in every 2 years); and for the later years, 8 out of 151 storms have recurved in the Bay.

In almost all cases the recurves have been towards the east, the usual change being from north-north-west through north to north-east.

The storm of November 3-7, 1910, which was generated to the north-east of Ceylon, travelled for one day in a north-easterly direction, then recurved sharply to the north-west and reached the Coromandel coast near Nellore. This, however, is the only exception which has been noted in recent years. The track is marked * in Plate XVII, Fig. 1.

III.—4. THE RATE OF ADVANCE OF CYCLONES.

The rate of advance of cyclones varies greatly, not only for different storms, but at different periods during the life of a single storm.

In the early stages of formation, the rate of advance is very slow, usually increasing progressively until the storm is fully formed. There are numerous records of storms remaining practically stationary for three or four days during formation, and the velocity generally is less than four miles per hour in the early stages.

When fully formed, the usual velocity is from 10 to 14 miles per hour, or roughly 240 to 280 miles per day.

An interesting exception to this is the storm of September 15 to 27, 1900, which has been referred to as one of the longest lived storms on record.

Its velocity was below normal throughout its entire existence, but the remarkable fact is that when fully formed, four days after its origin, it remained nearly stationary over the south of the Central Provinces from the 19th to the 22nd. Its velocity on subsequent days was 5, 8, 4, 5 and 8 miles per hour from the 23 to 27 September respectively. (The track, marked *, is shown in Plate XVI, Fig. 1.)

In general, the rate of motion of a fully-formed storm continues uniform while at sea, but immediately on making land there is usually a considerable increase both of velocity and intensity, after which increase the storm field either disperses suddenly on meeting some obstruction or gradually dies away.

In this connection the severe storm of April 13-15, 1910, may be mentioned. (Its track, marked *, is shown in Plate XIV, Fig. 1). This storm formed to the north-west of the Andamans, and during its formation from the 13th to the 14th of April moved only 50 miles. During the next day it moved 280 miles in an approximately northerly direction, and from the 15th to 16th the distance travelled was 600 miles (25 miles per hour), the storm having crossed the Arakan Coast just south of Akyab, where it was of an unusually severe nature. During the 16th the storm was dispersed by the Arakan Hills. This velocity of 600 miles in 24 hours is one of the highest ever recorded. This storm is also remarkable in that it was the first severe storm to occur during the first fortnight of April since the year 1860.

The storms of July 27-August 2, 1902, and of June 15-23, 1906, are examples of a class of disturbances whose intensities and velocities diminish rapidly as their distances from the Bengal Coast increase, but increase again as the Bombay current begins to affect them.

No direct relation is yet established, however, between the intensity of a storm and its rate of progress.

In the case of the few storms which recurve, the rate of motion usually decreases while the recurve is in progress.

III.—5. THE SMALLER STORMS OF THE RAINY SEASON.

In the great majority of these storms strong winds occur only in the south and east quadrants. Hence for many years the cyclonic nature of the storms was overlooked, and they were merely regarded as westerly gales. As the storms nearly always form near the head of the Bay and pass westwards or north-westwards across the Orissa coast, they are very trying to southward-bound vessels leaving the Hooghly river. Although the storms are not usually very severe—the wind force in most cases not exceeding force 8—it must be remembered that they are also of small extent and hence give rise to more rapid shifts of wind than do the larger storms of the transition periods.

The chief indication of the formation of one of these storms is the suspension of the ordinary south-west monsoon and the setting in of north-easterly or easterly winds, and of accompanying fine and dry weather in the midst of the rainy season. The most important feature in cyclonic storms is the south-west monsoon wind which feeds them. This is not a steady wind, like the south-east Trades, for example, but appears to go through a series of pulsations, or variations of strength and alternations of advance and withdrawal. It is found almost without exception that storms of the rainy season form in intervals between these partial retreats and advances of the monsoon current. Hence these storms are one cause of the very unequal distribution of rainfall during the south-west monsoon period. The winds of the south and east quadrants (*i.e.*, south-west winds) bring up the energy that starts and maintains the storm, and consequently rain is drawn away from large areas, to be concentrated along the relatively narrow track of the storm itself.

For example, the storm of July 7-10, 1908, formed over Jessore (23° N., 89° E.) on the 7th, and by the following morning had developed somewhat, without moving appreciably. By its position it partially prevented the Bay winds (south-west) from penetrating beyond deltaic Bengal, thus diminishing rainfall in other parts of north-east India, but concentrating it in deltaic Bengal, where heavy rain fell until the morning of the 9th.

Also, in July, 1909, three slight depressions were formed, in different parts of the month, over the north of the Bay, and were then transmitted across northern India, the first and second to the centre of the Gangetic Plain, and the third to the western Desert. Their intensity, as measured by the departures of pressure at the centre, was small (as is usually the case in disturbances of this class); they were, however, a potent factor in depriving the north-east of India of its normal share of rainfall.

Another interesting example is provided by the storms of September, 1904. During the month the monsoon was lighter than usual over the Arabian Sea, the wind was more westerly than the average over northern India, and more northerly than usual along the west coast and over the Deccan, while the absolute humidity was less than the normal over almost the whole country. These conditions, favouring dry weather, were disturbed on three occasions by cyclonic storms which, developing over the Bay, passed inland and, drawing the monsoon currents into their circulations, occasioned much needed rain over a large part of the country.

In particular, the storm of September 10-18 was of immense economic importance, as it traversed the districts over which the rainfall of the season had been uniformly deficient and where the crops, at the time of its appearance, were in a critical condition. The storm gave widespread rain and at the same time moved very slowly during the greater part of its course, so that the districts passed over benefited in a marked degree from the disturbance. The heaviest rainfall in most cases occurred on the northern or advancing side of the storm.

Again, in September, 1905, the Arabian Sea monsoon as a rain-giving current to a great extent had failed. Except when under the influence of a storm from the Bay this current gave only scattered showers—principally to the coast districts—to the Peninsula, and never penetrated properly into north-west India. On the other hand, the Bay current was vigorous, and storms of slight or moderate intensity formed at frequent intervals over the Bay, and, travelling in some northerly direction, occasioned heavy general rainfall over parts of Burma and north-east India. This rainfall, however, was in all cases concentrated around the storm centre, the surrounding regions being but little affected.

The most important storm of the month, both from a meteorological and economic point of view, was that of the 6th to 12th. This storm formed over the north-west of the Bay, passed through Orissa and the Central Provinces, then turned north-westwards to central India, and then northward into the Punjab, finally breaking up among the Punjab Himalayas on the 12th.

The storm carried heavy to very heavy rain with it throughout its course, and the temperature, which had been exceedingly high over north-west India previous to the appearance of the storm, fell to largely below the normal as rain advanced over the country.

Numerous other examples could be given showing that these storms, though not usually barometrically "severe," can and do wield an important, and very often beneficial, influence over the rainfall and temperature of the period.

Before leaving the subject of small storms of the rains proper, some short account must be given of the character of the winds to the north and west of such storms.

We have seen that when a storm is imminent, the usual south or south-west winds of the season are suspended, and light unsteady winds prevail and the weather is often sultry and oppressive. A sudden strong onrush of monsoon wind, probably in the centre of the Bay, then gives rise to squalls of increasing frequency and intensity, and gradually a storm circulation is evolved, the centre advancing landwards under most circumstances; the subsequent history is as described above.

Thus it is clear that "the winds in the southern and eastern quadrants are the normal winds of the season, intensified locally by the cyclonic indraught" (Eliot).

The winds in the northern and western quadrants are in marked contrast, however, being abnormal winds of little or no energy, which are dragged into the storm, and shifting round to north-east, become a part of the cyclonic circulation which is under formation. These winds are generally very light and unsteady. Their main value lies in the fact that when they occur in the north-west angle of the Bay, during the monsoon months of June, July, August and the first half of September, they are an almost certain indication that a cyclonic storm is in formation or in existence in the north of the Bay.

It must also be mentioned that very dangerous, stormy weather with winds of hurricane force can occasionally be encountered during this period of small storms of the rains proper, and no account would be complete without a reference to the famous False Point Cyclone of September 19 to 23, 1885, which is one of the most intense cyclones on record. The lowest barometric reading (27·135 in.) taken at False Point Lighthouse during the passage of the storm centre over it, is said to be lower than any previously recorded *verified* barometric reading at sea level. The barogram is shown on Plate XVIII. For further details of the storm the reader is referred to pp. 238-249 in Eliot's Handbook.

During the years 1877-1912 seven storms have occurred in September, in which a wind force of 10 has been reached or exceeded. These have almost always taken place during the last fortnight of the month, that is, just prior to the setting in of the October transition period. Among other violent storms of the rainy period, that of July 1 to 7, 1887, should be mentioned. This, although of the normal monsoon type, was in the early stages unusually severe for July. Winds of hurricane violence were experienced on the 3rd, when there was also evidence of a fairly well developed calm centre to the storm, where the barometric depression was at least 0·6 in.

As is usually the case, the storm weakened considerably after its passage inland, and over the last part of its course the disturbance was of normally moderate intensity.

Heavy rain occurred on the south side of the storm track in the belt of country stretching from Orissa to lower Sind; very little rain fell on the north side.

III.—6. STORMS OF THE TRANSITION PERIODS.

In the May transition period the south-west monsoon has not yet advanced up the Bay, and hot weather conditions prevail in Bengal and at the head of the Bay; whereas in the October transition period the south-west wind is retreating down the Bay and a north-east wind is setting in over the Coromandel coast. The storms of these periods are usually very extensive and fierce, and are often generated in the south of the Bay, between the Andaman Isles and the coast. It may thus happen that the prevailing normal north-easterly winds over the north and north-west of the Bay are unaltered in direction, and merely strengthened and steadied by an extensive cyclonic circulation in the south of the Bay. In this way a north-east wind, apparently a fair weather wind, may be blowing directly into a cyclonic storm. It is therefore most important to ascertain whether, when north-east winds

prevail in the north-west angle of the Bay, they are merely the normal winds of the period, or are augmented north-east winds due to the presence of a suitably placed cyclone farther south in the Bay. If the winds are merely the normal winds of the season, they are generally light, and shift through two or three points during the day in consequence of the heating of the land.

If the strengthening of the north-east winds be due to a distant cyclone there is a tendency for the wind to veer to east as the cyclone moves up the Bay (the average direction of motion of cyclones being north-west). Also the weather continues fine and bright with the atmosphere unusually clear, so long as the centre is at a considerable distance. On the other hand the stronger north-east winds may be due to a stronger north-east monsoon than is usual on the Coromandel coast and in southern India. In this case the weather is usually showery with much rain and stormy winds in the Carnatic, and squally in the Bay of Bengal off the Coromandel coast; while pressure is often unusually high over northern India, with fine clear weather and moderate west or north-west winds over Bengal and the Gangetic Plains.

Of the eight detailed descriptions by Eliot of typical cyclones, five deal especially with north-east winds which have prevailed at the head of the Bay, during the formation and northward movement of large cyclonic storms in October and November.

Some typical storms of the transition periods which have occurred since 1900 will now be described.

1. *Storm of May 4-7, 1902.*—This storm probably began to form on the evening of the 4th a little to the north-east of the Andamans. During the previous three or four days unsteady winds, chiefly from northerly directions, had prevailed over Lower Burma and the adjacent parts of the Bay, while humid southerly winds were advancing up the centre and east of the Bay. It was almost certainly this rush of southerly winds into the area of unsteady northerly breezes that caused the cyclonic circulation. Data obtained from logs of vessels in the Bay for 8h. of May 5 indicated that, by then, the winds were generally cyclonic in direction over practically the whole of the Bay. They were not, however, strong, except in the storm area, where the ss. *Goa*, probably not more than 120 miles to the north-north-west of the centre, experienced north-east gales of force 9, and the R.I.M.S. *Elphinstone*, probably less than 70 miles from the centre, a hurricane.

The meteorological information supplied by the latter vessel is very valuable and shows that the inner area of hurricane winds was probably of small extent, and that the transition from the outer to the inner area was unusually abrupt. The vessel entered the eastern quadrant in the early morning and was apparently carried round by the force of the storm winds, through the northern and western quadrants, into the southern quadrant in less than twelve hours.

Weather was also very disturbed over the east and south-east of the Bay, almost all vessels in that area reporting heavy to hard squalls with much rain.

The observations recorded at the Lower Burma stations indicated clearly the existence of the storm. Skies were more or less thickly clouded over Lower and Central Burma, and light to moderate showers had occurred in the coast districts.

The whole of the available information, when charted, indicated that the storm was centred about latitude 14° N. and longitude $94^{\circ} 54'$ E. at 8h. of the 5th. The barometer at the centre was below 29.3 in. and the deficiency of pressure thus probably exceeded half an inch, so that the storm was of considerable intensity.

On May 6, pressure had given way over the whole of India, the decrease being brisk over the Peninsula and rapid over northern India. The fall had been very rapid in Lower Burma and the north Andaman Sea, amounting to nearly three-tenths of an inch at Rangoon and Bassein. On the other hand, pressure had risen slightly on the south Tenasserim coast. The storm centre at 8h. of the 6th was crossing the coast to the east of Diamond Island. The intensity had increased, and strong cyclonic winds were reported from the Burma coast stations. Skies were

overcast in Burma and heavy rain had fallen in front of the storm at Diamond Island and Bassein, and light showers in central Burma. Reports from ships showed that light to moderate winds prevailed over the eastern half of the Bay, except in the southern quadrant of the storm, in the immediate neighbourhood of the Pegu coast, where violent gales of force 9 to 11 were blowing.

The ss. *Lethington*, which was probably about 80 miles to the south-south-east of the centre, reported winds of almost hurricane violence (10–11). When charted, the available data showed the centre to be in latitude 16° N., longitude 95° E. at 8h. of the 6th, that is 170 miles to the north by east of its position 24 hours earlier.

Its average rate of motion had thus been 7 m.p.h. By 8h. of the 7th the storm had advanced about 300 miles in a northerly direction and the centre was a little to the west of Yamethin. Its rate of motion was thus about 13 m.p.h. from the 6th to the 7th. It had, however, filled up almost completely, and was now a small residual disturbance of little importance.

Skies were more or less heavily clouded in Burma; and heavy rain had been received in Lower Burma and Tenasserim, and light rain in central Burma. Weather over the Bay had improved very rapidly during the past day and was now fine, with winds of force 1 to 5. By May 8 pressure had increased briskly over Burma and the residual disturbance had passed completely away. The cloud amount had considerably decreased and only light rain had fallen.

The barometric changes elsewhere in the Bay were everywhere slight.

The storm under discussion was remarkable in several respects, more especially in its unusually rapid formation and growth. It was, on the whole, the most severe storm that has visited Lower Burma in the first half of May for the past 30 or 35 years; it caused the total loss of the ss. *Camorta* and the ss. *Hermol*, and did great damage to property and shipping at Rangoon.

2. *Storm of October 24–27, 1909.*—This storm was the most severe October storm since 1900. It was generated in the Andaman Sea on the 22nd, and after intensifying rapidly on the 23rd while travelling north-westwards, it became, on the 24th, a dangerous cyclone with an inner area of hurricane winds and probably a calm centre.

The ss. *Shahzada* and ss. *Bharat* ran into it on the 24th; the former was involved in the inner area for upwards of 24 hours. Both experienced a perfect hurricane, while the barometric records of the *Shahzada* indicated that on the early morning of the 25th, pressure at the centre was at least an inch below normal.

No large change occurred in the line of its advance till the morning of the 26th, when, owing to some unknown circumstance, the direction became westerly and the cyclone, travelling much faster than hitherto, struck the Madras coast a little north of Gopalpur about midnight on the 26th. According to the Gopalpur Observatory records, there was a fall in pressure of a little over an inch between midnight and 3h. on the 27th, and an equally rapid rise during the succeeding three hours. The barometer stood lowest a little after 3h., and was no less than 1·4 in. below the normal value. Winds of destructive violence were felt at the station, and caused much damage to property, the loss in the Gopalpur district alone being estimated at about 15 lakhs of rupees.

The rotary motion was, as is usual in the case of storms of low elevation, broken up speedily by the high ground to the west of Gopalpur, so that by 8 h. (that is, only five hours after its passage inland) the decrease of pressure at the centre was less than two tenths of an inch. The residual depression continued to advance westwards, and by the morning of the 29th had reached the east of the Arabian Sea. It was, however, no longer of any significance.

3. *Storm of November 29 to December 6, 1909.*—This storm appears to have been generated on November 29th over the narrow strip of sea between the Andamans and the Nicobars. From there it moved in a west-north-west direction, and by the morning of December 3 the centre had reached a position about 200 miles east of Nellore.

Winds of force 6 to 7 prevailed on that day in the eastern quadrant at a considerable distance from the centre, a circumstance which, together with the roughness of the seas on the Madras coast, would indicate that even at this stage it was a well developed depression. There was no inflow of humid air into southern India from the Arabian Sea, and it was perhaps owing chiefly to this circumstance that the storm turned round abruptly to the north or north-east during the day.

At 8h. of the 4th the centre was within 100 miles of Waltair and Calingpatam, where the barometer stood about four-tenths of an inch below the normal height and where very rough seas prevailed. The storm travelled in a north-easterly direction during the next two days; by the morning of the 6th it had reached Chittagong and Cox's Bazaar, and was speedily broken up by the action of the Chittagong Hills.

So far as can be ascertained from the available information, it is almost certain that the pressure at the centre was at least half-an-inch below normal throughout the 5th and on the morning of the 6th. According to a letter received from the Commander of the F.L.V. *Comet*, although the greatest intensity attained by the wind there was equivalent to force 8, winds of hurricane violence were experienced at the Mutla station, which is only 60 miles to the south-east; this is an indication that the inner area of the storm was of small extent.

The storm was noteworthy in several respects, but more especially for the very heavy rain it gave to Orissa and the Andamans, and for the direction of its line of advance during the last three days of its existence.

The north-easterly course followed in the present instance was unique, for storms formed over the Bay in December ordinarily travel either due north or between west and north.

III.—7. INDICATIONS OF STORMS. (See Eliot, pp. 207, etc.)

The indications of a distant cyclonic storm in the Bay of Bengal are as follows, in order of importance :—

1st. The occurrence of a succession of squalls which increase in frequency and intensity as the storm area is approached.—Whatever the causes and origin of cyclones may be, the history of all cyclones in the Bay shows that they are invariably preceded for longer or shorter periods by unsettled squally weather, and that during this period, the air over a considerable portion of the Bay is gradually given a rapid rotary motion about a definite centre. These squalls are at first very light and infrequent, but become more fierce and frequent with the gradual development of the storm, this preliminary period of unsettled squally weather lasting in some cases only a few hours, and in others extending over several days.

It must be remembered, however, that squalls occur under several sets of conditions in the Bay and that, while squally weather always precedes a cyclone, the latter is not of necessity a sequence to it.

For example, during the hot weather months of March, April and May, squalls often originate in Bengal or Orissa, near the sea coast. These are usually confined to a very small area, over which they occasion violent winds, often with heavy rain, hail, and much thunder and lightning. They are of comparatively brief existence, and die away even more rapidly than they are formed.

Also, there is always a tendency for rain-squalls to form during the south-west monsoon, and this tendency is apparently very much increased if the monsoon meet with any sudden obstruction, or if it advances towards another air-current which differs much in temperature, humidity or other characteristic features.

Therefore, such rain-squalls are frequent in May and June, in front of the advancing south-west monsoon.

The neighbourhood of the West Pegu and South Arakan coast appears to be very liable to rain squalls during the height of the monsoon; these are believed to be due to the obstructive height of the action of Arakan Hills, which are from 1,000–4,000 feet high, and divert the current from south-west to south and south-east.

2nd. Barometric Indications.—The movement of the barometer in the Bay of Bengal is in ordinary weather very regular, and is confined within narrow limits.

The total rise and fall, however, due to semi-diurnal variation, exceeds on the average a tenth of an inch in each of the six-hourly periods between maximum and minimum, so that it is not surprising that this diurnal oscillation is so rarely obscured or obliterated by changes due to cyclonic storms, since these latter changes are in the majority of storms quite small—a fall of two-tenths of an inch in 24 hours being a very rare occurrence—and even in the large intense storms the fall of pressure is never great until the inner storm area is reached.

The barograms shown on Plate XVIII illustrate this clearly.

In each of these the fall of pressure is not only slow at first, but is also such as frequently occurs during slightly unsettled weather in the Bay or in India, and has no special feature which gives any reliable indication of the approach of a depression.

In the majority of smaller storms, the fall of pressure below the normal height for the period is not large. It increases in amount from the outskirts of the depression to the centre of the storm, but even there seldom exceeds two or three tenths of an inch.

In severe cyclones the fall of pressure in the outer storm area usually does not exceed four or five tenths of an inch; in the inner storm area, usually of small diameter, the fall is exceedingly rapid until the calm centre is reached.

It is believed that the barometer stands at nearly the same height throughout the whole of this calm central area at the same instant, but that the height varies with the changes in the intensity of the storm.

The rule given by Eliot for the use of barometric variations as storm indicators is as follows :—

If the reduced barometer reading is, at any time during the cyclone season, a tenth of an inch below the normal for the time of day, the possibilities are two to one that a cyclonic storm has formed in the Bay; if the decrease below normal is 0·15 in. the probabilities are at least three to one, and if two-tenths below, it is practically certain that a cyclonic storm has formed.

It must be remembered that the barometer is frequently unusually high and steady on the outskirts of a storm in formation.

The same conditions also frequently occur in fine weather.

This fact, together with the small fall of barometer in the outer portion of the cyclone storms in the tropics accounts for the lack of warning given by the barometer (as ordinarily used by sailors) of the approach of a storm.

3rd. General Appearance of the Sky and Weather.—These will be classified for storms forming during the rainy season and for those forming during the transition periods. (See Eliot pp. 298–300.)

(a) *Indications for Storms of the Rainy Season (June 15th to September 15th) :—*

(1) Winds are very light and variable at the head of the Bay and frequently shift round to north and north-east at Saugor Island and False Point.

At sea the chief feature of the winds is their lightness and variability, in strong contrast with the normal winds of the season.

(2.) Weather is usually fine, with passing clouds, but more or less unpleasant and oppressive in consequence of the great dampness and stillness of the atmosphere. The atmosphere is frequently very clear. The rains are practically suspended in Bengal for the time being, and usually little rain beyond the light local showers falls at the head of the Bay.

(3.) Light to moderate south-west winds prevail in the south and centre of the Bay, with perhaps occasional rain-squalls. There is a strong tendency for these to increase in force.

The majority of these storms are feeble and of no great importance ; the indications of a severe storm of this period are as follows :—

- (1) A strong and squally monsoon over the south and centre of the Bay.
- (2) Rapid increase in the strength of the south-west and south winds on approaching the head of the Bay.
- (3) Rapid succession of severe rain-squalls.
- (4) Comparatively light cyclonic winds in the north-west and south-west quadrants, even at moderate distances from the centre, these giving no indication of the strength of the winds in the opposite quadrants.

As these storms occur in the midst of the south-west monsoon and usually form close to shore near the head of the Bay, the indications given by sky, swell, etc., as to the position of the centre are usually very feeble and of little use.

(b) *Indications for Storms of the Transition Periods* (May to June 15th and September 15th to December) :—

1. Winds are very light and variable in the centre of the Bay, whereas light and steady winds from north-east prevail in Bengal and at the head of the Bay.
2. Fine clear weather with smooth sea and very transparent atmosphere usually prevails over the north and centre of the Bay.
3. South-west winds prevail over the south of the Bay, tending to increase in strength and to give rain-squalls.

The following indications point to a severe storm of this period :—(1) South-west winds in the south of the Bay increase in strength, the weather becomes more squally, and the cloud amount increases and shows, by its movement, indraught to a central or cyclonic disturbance.

(2) In the area to the north and west of the storm, the sky becomes less clear and transparent and a veil of light cirrus appears and extends northwards. This veil thickens very gradually and frequently gives rise to conspicuous halos round the sun or moon. These clouds at times frequently show very dark or vivid bright red colours at sunrise or sunset.

(3) Cirro-stratus clouds soon begin to appear below the cirrus clouds, and increase and extend outwards (*i.e.*, northwards and westwards).

The humidity of the air increases and the weather becomes more sultry and oppressive, and the wind begins to shift and becomes steadier and stronger in the north of the Bay.

(4) Shortly after the above, the first indications of the cloud bank are seen low down on the horizon. This is a peculiarly dense bank of nimbus cloud which is most frequently observed in the northern quadrant in front of the cyclonic storm. Its position is sometimes shown at night by frequent, and in some cases almost continuous, lightning, which is seen by reflection from distant clouds.

This lightning and the cloud bank may be seen sometimes as early as two or three days before the approach of the storm.

(5) The winds then begin to freshen, cumulus and nimbus clouds appear on the horizon and gradually extend and cover the sky, and light drizzling rain begins to fall. Passing squalls come up with increasing intensity and frequency as the storm approaches.

(6) A heavy swell occurs in the Bay ; this swell proceeds outward in all directions from the cyclone, and is fairly regular even at great distances from the centre. This regularity is specially pronounced in the northern and western quadrants, where the winds are light and consequently the swell is little confused by them.

Hence, one of the earliest indications at the head of the Bay of the existence of a cyclonic storm to the south is often the setting in of an increasingly heavy swell.

The determination of the bearing of the Storm Centre for cyclones in the Bay of Bengal and for hurricanes and typhoons in other parts of the world is discussed in detail in Section I of the present report.

Part II.—Storms in the Arabian Sea.

A short account will now be given of the frequency and distribution of similar storms in the Arabian Sea.

These storms have been described in Cyclone Memoirs, Part IV (39), which contain an inquiry into the nature and course of storms in the Arabian Sea, and a catalogue and brief history of all recorded cyclones in that sea from 1648 to 1889. The information contained in the Memoir was compiled by W. L. Dallas, Esq., Assistant Meteorological Reporter to the Government of India, and was published by the Meteorological Department of the Government of India in 1891.

The paper is divided into two parts, the first giving the details of each storm separately in its chronological order, the second treating of the distribution and movement of the storms according to months and seasons, and giving the opinions of past meteorologists on the characteristics of the cyclonology of the Arabian Sea.

The present account proposes to supplement the information with the frequency figures for recent years—1890–1912; to give a short account of the track and character of the storms in successive months of the cyclone season, and to conclude by giving detailed descriptions of some of the more interesting storms of recent years.

This information has been collected from the *Indian Monthly Weather Review* and from the Pilot Charts of the Indian Ocean and Arabian Sea.

III.—8. MONTHLY DISTRIBUTION OF STORMS FOR THE 23 YEARS, 1890-1912.

Month.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
No. of Storms	2	—	—	2	5	11	3	—	2	10	8	2
Percentage Frequency	5	—	—	5	11	23	7	—	5	21	17	5

This table is in general agreement with the lists for the earlier years, 1648–1889, which are given on page 403 of Cyclone Memoirs, Part IV.

The main features of the distribution are the absence of storms in February, March and August, and the two well-marked maxima occurring in June and in October and November.

The tracks and places of origin of cyclones in different months will now be discussed, and, when possible, a full description will be given of a characteristic storm for each month.

These individual accounts are chosen from storms which have occurred since the report of Dallas was published. For many interesting accounts prior to that date the original report should be consulted.

In the following accounts a storm occurring at the end of one month and the beginning of the next is allocated to that month in which it has the longest duration; if the duration in each month is the same the storm is allocated to the month in which it originated.

JANUARY.

Only very fragmentary information is available with regard to the three storms reported in this month prior to the year 1890. Since that year there have been only two storms. These took place as follows:—

(1) *January* 4–6, 1892, when a disturbance, cyclonic in character, was transmitted eastwards over the Persian Gulf and North Arabian Sea from the 1st to the 4th.

The disturbance passed eastwards across Baluchistan on the 4th and entered India on the night of that day or the morning of the 5th. It was apparently of moderate intensity in Persia and the Persian Gulf, but as it approached the Sind frontier it diminished in importance and was very feeble over the North Arabian Sea and in north-western India.

(2) *December 31–January 6, 1909.*—This storm did not originate in the Arabian Sea, but in the south of the Bay of Bengal, whence it advanced due west and was shown over the Arabian Sea to the west of the Malabar coast on the morning of January 2. Winds recorded on the Malabar coast and at Minicoy show that the disturbance was broken up during the next two or three days while moving slowly westwards.

From this meagre information it is clear that the Arabian Sea is singularly free from disturbance during this month, but that there exists a slight probability of cyclones crossing over from the south-west of the Bay of Bengal, and therefore causing unsettled weather over the south of the Arabian Sea.

No storms are recorded by Dallās for February, and only two for March. Of the latter, one was a furious hurricane all over southern India, and occurred on March 26 to 28, 1853. It may not have entered the Arabian Sea. The other was a west-north-west or north-west gale in March, 1874, which lasted for two days and travelled from the Persian Gulf towards Cutch.

APRIL.

During the first half of this month the weather is as undisturbed as during March, but after the 15th the probability of the development of cyclones rapidly increases. Prior to the year 1890, seven storms are on record for this month, and all of these occurred during the latter half of the month.

From 1890 to 1912, two storms have been noticed, as follows :—

(1) *April 28–May 2, 1892.*—This storm formed over the centre of the sea, and at 6 p.m. on the 28th was centred in latitude $16^{\circ} 30' N.$, longitude $62^{\circ} E.$ It travelled approximately north-eastwards, and made land about 10 a.m. on May 1st, passing a few miles west of Mandvi in Cutch and crossing Central Rajputana. It broke up in the outer ranges of the Simla Hills during the afternoon of May 2.

The storm was of considerable intensity, winds of force 8 being felt at a distance of at least 150 miles from the centre. The most remarkable feature of the storm was its rapid increase of velocity after reaching land and its high velocity when moving over Rajputana, the average rate of motion on successive days being $6\frac{1}{2}$, 11, $14\frac{1}{2}$, and 32 miles per hour respectively. The velocity is often greater when the cyclone is filling up than at any previous stage, but the increase in this instance was more marked than in any other storm recorded in India.

(2) *April 25–May 5, 1901.*—This remarkable storm was generated on April 24 and 25, in the neighbourhood of the Maldivé Islands, in front of the first temporary advance of the south-west monsoon in the Arabian Sea. It marched in a north-westerly direction towards the Arabian coast and lay off the Kuria Muria Islands on May 2. It then recurved rapidly to north, and travelling rather quickly, passed inland across the Mekran coast, during the 3rd, near Omara. It thence moved north-eastwards, through South Baluchistan and Sind, where it absorbed a feeble depression already existing in that area. The combined depression passed during the next 24 hours into the Punjab, where it filled up at the foot of the hills during the day.

The storm gave exceptionally heavy rains to some parts of Baluchistan and the Punjab frontier districts, and this gave rise to destructive floods in many valleys. H.M.S. *Sphinx*, which passed through the inner area of the storm on the afternoon of the 3rd, experienced winds of force 11.

The greatest observed barometric depression was 0.42 inches.

The available information for this latter half of April shows that almost any part of the Arabian Sea, except the south-west, may be visited by a cyclonic storm. The majority of storms which form over the Arabian Sea itself originate in the south-east near the Maldivé Islands and travel north-westwards; they may approach the entrance of the Persian Gulf or else recurve to north and north-east. Other storms of this period originate over that portion of the sea enclosed by the African coast, Socotra and the Arabian coast.

Those storms which cross over from the Bay cross in the extreme south and take a west-north-west course.

MAY.

Five storms have formed in this month since 1890. These are as follows :—

(1) *May 27–30, 1896.*—This storm formed off the North Konkan coast and moved westwards across the sea to Arabia. The greatest recorded barometric depression was 0·11 inches, and the storm nowhere was very severe, except in the northern quadrant, where the wind reached force 10.

(2) *May 5–14, 1902.*—This was an exceptionally interesting and severe storm and an account of it will be given in some detail.

An advance of humid southerly winds was in progress over the north of the equatorial belt during the first three days of the month ; the wind system prevailing over the area lying between the parallels of 4° S. and 12° N. was complex in character, consisting of north-east winds between latitude 12° N. and 8° N., and southerly to westerly winds between the parallels of 4° N. and 4° S., with an intervening zone of light variable winds. In the meeting ground between these two opposite systems of air movement, a storm was developed with remarkable suddenness during the 24 hours preceding 8 a.m. of the 5th, its centre being apparently about 700 miles to the west of the Maldivé Islands. The depression intensified considerably during the 5th and moved very rapidly in a west-north-westerly direction, its average velocity being 18 m.p.h., an unusually high rate for a storm in the early stages of its existence.

It began to recurve slightly to northwards on the 6th and, as usually happens in the recurve, its rate of motion decreased considerably and was about 11 miles an hour, on the average, between 8 a.m. on the 6th and 8 a.m. on the 7th. It was a fully developed storm on the morning of the 7th, when it lay about 70 miles to the east of Socotra. It continued to recurve slowly during the next three days, during which its rate of motion averaged only four miles an hour. Its velocity increased again on the 10th, when the recurvature was complete, and thereafter the storm travelled in a north-easterly direction with increasing velocity to the Central Punjab, where it broke up rapidly on the 14th, its average velocity during the previous 24 hours having been as high as 27½ m.p.h.

The causes of the recurvature of the storm can only be surmised. The available data tend to show that it was due in part to the absence of humid winds in the south-west of the Arabian Sea at this time. The barometric observations indicated that pressure was lower than 28·5 in. at the centre, and hence at least an inch and a quarter below normal. The storm though of small extent, was undoubtedly a severe disturbance, and may have possessed a calm centre.

The most interesting feature of the air movement in the storm area was the contrast of intensity in the eastern and western quadrants respectively. Thus, while the “Clan Maclean,” which was about 100 miles to the east-south-east of the centre, experienced a hurricane, the “Australia,” about 200 miles to the west-north-west, experienced only light north-west winds of force 1 and 2. This was due to the fact that in the eastern quadrant the winds were the ordinary winds of the season, intensified locally by the cyclonic indraught, whereas in the western quadrant they were winds deflected from their normal direction by the storm.

The storm was hence characterised by its rapid formation, small extent, great intensity, large recurvature, very quick movement in the earlier and later stages of its existence and its almost complete disintegration on crossing the coast.

The storm did enormous damage on land in the Kurrachee districts, and at sea to numerous ships.

(3). *May 19–24, 1903.*—This was a storm of considerable intensity which originated off the south Konkan coast, advanced northwards parallel to the coast during the 22nd and 23rd, and, on the morning of the 24th, was a small concentrated disturbance with its centre about 60 miles to the west by south of Bombay. It filled up over the Gulf of Cambay during the day. The greatest observed barometric depression was 0·36 in., and hurricane winds with a very high cross sea were experienced near the centre.

(4). *May 3-9, 1909.*—This was a storm of feeble intensity, which formed over the south of the Bay of Bengal and crossed to the south-east Arabian Sea. The strongest winds reported by vessels affected by the disturbance were of force 7, and the greatest observed barometric depression 0·2 in.

(5). *May 22-27, 1911.*—This storm formed near the Laccadives on the 22nd and developed during the next three days while travelling north-westwards by noon of the 26th pressure at the centre was about an inch below normal. The storm disappeared before the morning of the 27th, probably having passed into Arabia. Hurricane winds and a dangerous confused sea were experienced by ships involved in the inner storm area, and reports indicate the existence of a central calm.

These and former investigations show that cyclones are fairly numerous during May and that, in general, they are severe (four out of the above five storms gave winds equalling or exceeding force 10).

The majority of the storms originate near the west coast of India, travel northwards parallel to that coast until they reach the latitude of Bombay, when they commence a north-westerly movement to the head of the Arabian Sea and the Mekran coast.

JUNE.

Eleven storms have been reported since 1890.

(1). *May 30 to June 6, 1890.*—A severe storm which crossed from Bombay to the Persian Gulf, and gave stormy weather, with winds of force 10 and 11, to the centre and north of the Arabian Sea.

(2). *May 31 to June 4, 1892.*—A feeble storm following the above track from Bombay west-north-westwards to the Persian Gulf. The greatest observed barometric depression was 0·20 in.

(3). *June 13-18, 1895.*—A storm of moderate intensity which travelled from the Konkan coast in a north-west direction to the Mekran coast. The greatest observed barometric depression was 0·25 in.

(4). *June 7 to 11, 1897.*—This was again a moderately intense storm, which moved from the west of the Arabian Sea northwards to Arabia, giving winds of force 6 to 9 over its track. The greatest observed barometric depression was 0·35 in.

(5). *May 31 to June 3, 1898.*—This storm originated over the centre of the Arabian Sea and moved northwards to the Gulf of Oman, giving winds of force 8 to 10 along its track. The greatest observed barometric depression was 0·32 in.

(6). *June 4 to 11, 1901.*—This was a slight storm which formed off the south Konkan coast on the 4th and moved very little during the next few days, causing a brisk fall of pressure along the west coast, especially between Bangalore and Goa. The storm remained almost stationary until the 10th, when it moved slowly northwards, the centre being in latitude 19° N. and longitude 70° E. by 8 a.m. of the 11th.

The storm was of moderate intensity, but force 8 was reached locally, and heavy rain fell over the north-east of the sea and along the west coast.

(7). *June 9-16, 1902.*—This storm was one of the most severe that has occurred in recent years in the north-east of the Arabian Sea during the month of June. It was generated slowly, on the 8th, 9th and 10th, off the Konkan coast, in front of the first great advance of the monsoon current over the east of the Arabian Sea. It developed steadily during the next three days, at the same time travelling slowly north-westwards, and on the 14th was a dangerous cyclone with a calm centre and an inner storm area of hurricane winds. It recurved slowly to north on the 15th and its rate of motion diminished from 6 to 4 m.p.h. The centre crossed the Mekran coast about 30 miles to the west of Kurrachee on the afternoon of the 16th, and passed into the broken ground of South Baluchistan, where it apparently broke up very rapidly.

It was accompanied by a storm wave, which, in conjunction with the violent winds, caused great damage to life and property in Kurrachee and its neighbourhood. It may be noted that the tide on the morning of the 16th rose 7ft. higher than usual; later in the day the chain of the tidal gauge broke, showing that the height attained then was even greater than in the morning.

This storm was remarkable for its slow movement, great intensity and small extent.

(8). *June 12–17, 1903.*—This severe storm formed in the east of the Arabian Sea on the 12th and 13th; it moved north-westwards on the 14th, and was central about 160 miles to the west by south of Verawal at 8 a.m. of the 15th. During the following two days it advanced west-north-westwards, and on the morning of the 17th lay off the Arabian coast, with its centre about 170 miles to the east by south of Ras al Had. Ships involved in the inner storm area experienced winds of force 10 to 12, a high sea and blinding rain.

During the last two days of its existence over the Arabian Sea the storm was a true cyclone with a calm centre; the greatest observed barometric depression was 0·95 in.

(9). *June 4–6, 1907.*—The storm was a development of a low pressure area which moved up the west coast of the Peninsula in front of the first advance of the monsoon winds. It proceeded northwards from about latitude 20° N., longitude 67° E. on the 4th, to a position west of Kurrachee at 8 h. of the 6th. After crossing the coast the disturbance diminished rapidly in intensity, and travelled up the valley of the Indus as a slight residual depression.

Winds of over 70 miles an hour were felt at Kurrachee during the height of the storm; over the sea, the strongest winds actually experienced by vessels, which were, however, at a great distance from the centre, were of force 8.

(10). *June 18–20, 1907.*—Like the previous storm, this originated in an area of low pressure which passed northwards up the east of the sea. It followed a different path, however, travelling from a position about 220 miles to the west of Verawal on the 18th to a position in latitude $23\frac{1}{2}^{\circ}$ N., longitude $66\frac{1}{2}^{\circ}$ E. on the 20th.

The storm was of considerable intensity and hurricane winds were experienced during the 18th near to the centre; the greatest observed barometric depression was 0·5 in.

(11). *June 15–17, 1908.*—An area of relatively low pressure moved northwards in front of the advance of the Arabian Sea monsoon, and reached the north-east of the Arabian Sea on the 13th. By the 15th it had developed into a shallow depression, which crossed the Kathiawar coast on the 17th as an irregular and ill-defined area of relatively low pressure, and then drifted in a north-easterly direction to the west of the United Provinces. It was probably of high elevation, and, in spite of its diffused character at the level of the plain stations, gave a good burst of rain over Gujarat, Rajputana, the west of the United Provinces and the east of the Punjab; it did not, however, establish the monsoon in these areas.

The storms of June have been dealt with at some length, since this is the month of greatest frequency and since most of the storms are of a severe nature.

The larger advances of the monsoon (which usually come on in this month) are frequently, if not invariably, characterised by the following features:—

- (1). Each advance usually commences in the South Arabian Sea.
- (2). A shallow depression forms immediately in front of the advancing current, usually off the Malabar coast. The weather to the south-east or east of this depression is squally with more or less heavy rain.
- (3). This depression travels northwards along the coast, and, as it were, carries the monsoon current with it. As it advances, heavy rain extends northwards along the line of the Ghats and in the west coast districts.

- (4). The depression occasionally (but not necessarily) develops into a cyclonic storm. The development usually occurs in the angle between the Kathiawar and Konkan coasts. These cyclonic storms almost invariably advance to north-westwards across the North Arabian Sea toward north-east Arabia or the entrance to the Persian Gulf.
- (5). When a storm does not form the depression advances northwards to the coast of Sind and is absorbed into the permanent low-pressure area in north-west India.

These storms occasionally originate as far south as latitude 13° N., in which case they travel northwards as far as latitude 18° N. before beginning their north-westerly movement. The points of origin are more frequently near latitude 18° N., however, and the storms when fully formed begin at once their north-westerly movement.

A few cyclones of this month have a very westerly point of origin (west of longitude 65° E.), in which case no northerly movement is developed and the track of the cyclone is directed towards the Gulf of Aden.*

JULY.

Cyclones are extremely rare during this month. Only one is reported before 1890, and since that year three have occurred as follows :—

(1) *July 10–13, 1897.*—This depression formed in front of an advance of monsoon winds along the west coast. After a prolonged break over the greater part of the interior, winds began to strengthen and rain to increase on the west coast on the 6th and following days. A wave of low pressure, similar in character to that which usually initiates the south-west monsoon in June, advanced along the west coast. Weather was very squally with strong monsoon winds off the Malabar and Konkan coasts.

The depression in the low pressure wave increased slightly with its northward movement, and when the low pressure wave approached Kathiawar, a cyclonic storm was formed between the Bombay and Kathiawar coasts on the evening of the 9th. It was displaced slowly northwards into Kathiawar and Cutch at an average rate of 90 miles per day from the 10th to the 12th (the low pressure wave itself, it might be noted, had advanced during the previous three days at an average rate of about 250 miles per day), and its centre was a little to the south of Bhuj at 8 a.m. of the 12th. It filled up rapidly during the next 24 hours. Very strong squally winds and stormy weather were experienced in the Arabian Sea off the Kathiawar and Bombay coasts on the 11th and 12th. The strongest winds experienced by vessels in that area were of force 10, and the greatest observed barometric depression 0·25 in.

(2) *July 13–17, 1903.*—This storm formed in the vicinity of the Kathiawar coast on the 13th and, drifting slowly in a north-easterly and northerly direction through Kathiawar during the next three days, disappeared over Cutch on the morning of the 17th.

The strongest winds experienced along the Sind and Kathiawar coasts were of force 7, and the greatest observed barometric depression was 0·28 in.

(3) *June 30–July 3, 1908.*—The area of relatively low pressure which was in the north-east of the Arabian Sea on the 30th June developed into a depression of slight intensity, and crossed the Kathiawar coast between Verawal and Dwarka on the evening of the 3rd ; it then drifted northwards and established monsoon conditions in north-west India.

It is seen that the infrequent storms of July have all originated in the north-east of the sea off the Kathiawar or Konkan coasts, and that they have proceeded on a north or north-easterly track.

* One of these rare and violent storms " L'ouragon de juin 1885 " is described (38) in the *Annales hydrographiques*, Paris. 1886.

AUGUST.

No cyclone has ever been recorded in the Arabian Sea during this month.

SEPTEMBER.

One storm occurred in 1819 in Cutch and Kathiawar, but there are very few details of its track, etc.

Since regular records have been available, two slight storms have been reported:—

(1) *September 7–15, 1897.*—This storm was generated in the north-west of the Bay of Bengal on the 5th and 6th. It increased slowly in intensity on the 7th and 8th, crossed the Ganjam on the 9th, and then drifted slowly west-north-westwards across the south Central Provinces and into Berar on the 11th. From there it drifted westwards, and was apparently absorbed into a depression which was in formation between the Kathiawar and Bombay coasts. The latter intensified during the next 24 hours, in consequence of the Bay storm which it has absorbed. The combined storm drifted slowly north-westwards along the coast during the next three days, and filled up near the Sind coast on the 15th. It gave moderate rain to Cutch, Kathiawar and Gujarat, and squally weather off the Kathiawar coast.

The strongest winds experienced during its existence were of force 7, and the greatest observed barometric depression 0·12 in.

(2) *September 17–21, 1902.*—A shallow depression appeared over the east Satpuras on the 17th, and was unaltered in position on the 18th. Conditions on this day were also suspicious over the Bombay coast and Kathiawar, and there were signs there of the development of a low pressure area. Rain was falling in both regions.

On the 19th, the former shallow depression had moved northwards and had coalesced with the Bombay coast "low"; the combined depression stretched from Akola in the east to Deesa in the west.

Moderate to heavy rain fell in the immediate neighbourhood of the storm, which was exceedingly shallow, however, throughout its existence. The depression extended slightly westwards on the 19th and 20th, and had practically filled up by the 21st.

OCTOBER.

Six cyclones were reported previous to the year 1890, and of these, three came from over the Bay of Bengal.

Since then ten October storms have been reported, four of which crossed over from the Bay.

These are as follows:—

(1) *October 18–21, 1892.*—This storm formed in the Andaman Sea or possibly the Gulf of Siam. On the 17th it concentrated rapidly in the Andaman Sea into a storm of small extent but considerable intensity, and passed between the Andamans and Diamond Island on the morning of the 18th. It moved across the Bay and then west-north-westwards over India. By the 21st it was of little importance, but a residual depression was transmitted westwards to the Konkan coast and the adjacent portion of the Arabian Sea during the next two days. It brought heavy thunder showers and rain to the coastal districts, and to some parts of the Poona and neighbouring districts of the west Deccan on the 23rd and 24th, after which the depression filled up.

Severe floods started in the Poona district on the evening of the 23rd, and these were responsible for most of the damage done by the storm.

(2) *October 20–26, 1894.*—This storm formed off the Malabar and Konkan coasts on the 22nd and 23rd. It moved northwards on the 24th and 25th, and then recurved to north-east and advanced towards the Gulf of Cambay on the morning of the 26th. It continued this north-easterly movement during the next 24 hours, when it broke up in Gujarat. The storm was of moderate intensity, but gave heavy and prolonged rain throughout the whole of its course.

(3) *October 19–26, 1895.*—A cyclonic circulation formed in the south Arabian Sea, and during the next few days moved in a general northerly direction, but filled up in the Central Arabian Sea on the 26th without ever having advanced beyond the initial stages of a cyclonic storm.

It occasioned very squally and rainy weather throughout the south and centre of the Sea during this period. Winds of gale force were experienced by numerous vessels during the hard squalls.

(4) *October 11–14, 1896.*—This storm, which was a concentrated disturbance of small extent, but of considerable intensity, formed in the centre of the Arabian Sea on the 10th and 11th. It drifted westwards and entered the Gulf of Aden on the 13th. It then recurved slightly, following the direction of the Gulf, and moved in a west by south direction on the 14th. Ships near the centre on this day experienced winds of hurricane force. The centre continued to move westward and passed into Abyssinia during the day. The storm resembled in some ways the Aden cyclone of June, 1885.

(5) *October 12–17, 1902.*—This storm formed in the Arabian Sea nearly midway between Socotra and the Malabar coast on the 12th and 13th, and moved west-north-westward during the next three days, being central about 300 miles to the east-south-east of the Kuria Muria Islands on the morning of the 17th. It continued to move in the same direction and passed into Arabia on the 18th.

There is very little information available, but the storm is thought to have been a very severe cyclone with a calm centre. Several ships which were involved in the inner storm area experienced winds of hurricane violence and very high seas.

The greatest observed barometric depression was 1·2 in.

(6) *October 27–November 3, 1902.*—This storm originated in the south Arabian Sea about 300 miles to the west of the Laccadive Islands on the 27th and 28th, and drifted slowly north-westwards during the next three days, being central to the north and north-east of Socotra on the morning of November 1st. By the morning of the 2nd it was about 150 miles south of the Kuria Muria Islands. It diminished rapidly in intensity during the following 24 hours, and by the 3rd approached the coast as a shallow, small disturbance. Winds of forces 6 to 9 were experienced at great distances from the storm centre; no information is available for the inner storm area.

(7) *October 20–26, 1905.*—A large area of low pressure covered the east and centre of the Arabian Sea during the period 15th to 19th, and it was within this "low" that a storm was generated on the 20th and 21st. The centre advanced west-south-westwards, and by the 25th was in latitude 15° N., and longitude $61^{\circ} 30'$ E. The storm filled up during the 26th. A whole gale (force 10) was experienced by vessels in the storm area; the greatest observed barometric fall was 0·26 in.

(8) *October 25–28, 1908.*—This depression formed near the Andaman Islands on the 14th and crossed over the south of the Bay of Bengal, passing north of Ceylon and over the extreme south of India into the Arabian Sea on the 23rd.

It moved from the Malabar coast region by a curved path over the centre of the Arabian Sea and disappeared off Kuria Muria before the morning of the 30th.

The strongest winds reported from vessels, which were not, however, near to the centre, were of force 8, and the greatest observed barometric depression was 0·36 in.

(9) *October 15–18, 1911.*—This was a storm of slight intensity (the winds never exceeding force 7) which appeared off the Coromandel coast on the 15th, and crossed westwards into the Arabian Sea near Mangalore on the 18th. Little information is available as to the subsequent path, but it is thought that the centre was somewhere between Socotra and Kuria Muria on the 21st.

(10) *October 25–31, 1912.*—This was a development of a feeble depression which originally formed over the Bay on the 20th, and, travelling across the south of the Peninsula, entered the Arabian Sea during the 22nd. It advanced westwards until the 29th, when its path changed to south-west. By the morning of the 31st the disturbance had become very diffuse. Very few ships were involved in the inner storm area, and it is therefore not possible to form an exact idea of its character. The strongest winds actually recorded did not exceed force 10.

Of the October cyclones about one-half appear to be generated in the Bay of Bengal, and the majority of these cross over from the south of the Bay by the north of Ceylon and the extreme south of the Peninsula into the south-east of the Arabian Sea, whence they move approximately north-westwards to Kuria Muria Islands, off the Arabian Coast.

Of the storms which originate in the Sea itself the majority form in the south or centre, and few in the north. No well established track can be evolved from the data to hand. There appears to be a general northerly trend until latitude 18° to 20° N. is reached, after which the storms move to north-west—occasionally to north-east as in 1894. On the other hand, certain tracks are directly westwards (as in the Aden cyclone of 1896), and others directly north-westwards, from the point of origin.

NOVEMBER.

Eleven instances of cyclones have been reported prior to 1890, and of these all but one originated near the west coast or crossed that coast from the Bay.

In recent years the following have been reported :—

(1) *November 2-3, 1891.*—The storm was generated unusually far south, between the Laccadives, the Maldives, and the Travancore coast, on the 1st and 2nd. It advanced westwards and the centre passed a little north of Minicoy about 1.30 a.m. of the 3rd. Nothing definite is known of its further history.

The storm gave a deluge of rain to Minicoy and squally weather in the Arabian Sea. The greatest observed barometric depression was 0.6 in.

(2) *November 17-22, 1896.*—This storm was generated slowly in an area of unsettled, squally weather in the south-east of the Arabian Sea from the 14th to 16th. It moved north-westwards during the 17th and 18th, but changed its direction to north-north-east on the 19th, when it was unusually intense. It continued to recurve north-eastwards during the 20th, and crossed inland to the Kathiawar coast on the 21st, during which day it filled up considerably. The residual depression passed into Baghelkhand and the adjacent districts of the Central Provinces, where it broke up on the 23rd. The storm occasioned a general burst of rain over the greater part of India, and winds of hurricane violence were experienced by vessels which came under its influence on the 19th.

(3) *November 4-12, 1898.*—This storm formed rapidly in the south-west of the Bay of Bengal on the 4th and 5th and began to travel west-north-west, crossing the coast to the south of Madras, and drifting across the Peninsula during the 7th and 8th while filling up considerably.

It passed into the Arabian Sea during the 8th as a feeble residual depression, but when it had advanced well into the open sea it re-developed rapidly and was a severe storm on the 10th and 11th. The centre was apparently in latitude 10° N. and longitude $65\frac{1}{2}^{\circ}$ E. at 8 a.m. of the 11th.

Vessels within the central area experienced winds of force 8 to 12. The storm filled up almost completely on the 12th.

(4) *November 9-13, 1907.*—A depression formed in the usual area of low pressure over the Bay of Bengal at the beginning of the month and passed westward over Ceylon into the Arabian Sea. Here it developed into a cyclonic storm, which travelled in a direction north of west to the neighbourhood of the Kuria Muria Islands off the Arabian coast, where it was broken up during the 13th.

The storm was of considerable intensity, and winds of force 9 were experienced in its vicinity.

(5) *November 22-28, 1907.*—This depression, which originated in the Andaman Sea, moved westwards over the Bay of Bengal and India, and was remarkable in that it crossed the Western Ghats and entered the Arabian Sea near Karwar on the 28th. Nothing is known of its subsequent history in the Sea.

(6) *November 23-30, 1911.*—This storm developed in an area of low barometer and rainy weather, which first showed itself to the west of Ceylon on the 20th; from there the storm moved northwards up the Malabar coast during the

next two days. From the 23rd to 28th the disturbance moved northwards parallel to the west coast of India, and on the 28th was about 200 miles west by south of Ratnagiri. A slow north-westward movement took place on the 29th and 30th, and on the latter day the depression filled up. The disturbance was nowhere of a severe nature.

(7 and 8) *November 16-22 and 18-24, 1912.*—These storms formed separately and appear to have united into a single storm in the Arabian Sea. Their interesting history is as follows :—

An extensive belt of low pressure lay on the 16th over the region between the Laccadives and the south Tenasserim coast. A small cyclonic vortex was developed within the belt on the 17th, travelled westwards, and by the morning of the 20th had reached a position in latitude $8\frac{1}{2}^{\circ}$ N. and longitude 59° E. Here its progress was arrested owing to the formation on the 18th of a second cyclonic storm at a short distance to the south-east of Ceylon, and during the next two days the former storm was displaced slightly eastwards.

The second storm advanced along a north-westerly course, passed over the south of the Peninsula, and entered the Arabian Sea near Cochin on the evening of the 19th. The storm then moved northwards and recurved to north-east on the 21st, and by the morning of the 22nd the centre was about 50 miles due west of Bombay.

It weakened rapidly after noon of that day, when it crossed the coast between Bombay and Surat, and continued to march eastwards to the Central Provinces, where it filled up.

On the 22nd, when approaching Bombay, the storm was extremely severe and did much damage in the harbour. There is no direct evidence of a central calm area there, and the strongest winds reported from vessels in the Sea—none of which were close to the centre—were only of force 9.

Of these eight storms, five originated in the Bay of Bengal and crossed over to the west coast of India and into the Arabian Sea. The track of November storms shows well marked characteristics, the majority of the storms moving in some direction between west and north-west, then in some northerly direction, after which the recurve to north-north-east or north-east takes place.

The storm of 1911, which moved northwards parallel to the coast before crossing the Sea in a north-westerly direction, is an exception and resembled the storms of earlier months.

DECEMBER.

Two storms are on record before the year 1890, and two since that year, as follows :—

(1) *December 15-19, 1896.*—This depression originated to the east and south of Ceylon on the 15th and 16th and drifted westwards into the Arabian Sea on the 17th. It lay to the south-west of the Travancore coast on the 18th but was of little importance and filled up during the next day.

It was shallow and diffuse throughout its existence.

(2) *December 6-13, 1902.*—This storm formed in the south of the Arabian Sea about 500 miles to the west of the Laccadives on the 6th and 7th. It marched slowly in a north-north-easterly direction towards the Kathiawar and Konkan coasts on the 12th. It filled up as it approached the coast during the next 36 hours. It was, throughout its course, a disturbance of moderate intensity, the strongest winds experienced during its existence being of force 9, and the greatest observed barometric depression 0·25 ins.

The majority of these infrequent storms form in the south Arabian Sea, but no general rule can be given for the track they follow.

INDIAN OCEAN.

B. CYCLONES IN THE SOUTH INDIAN OCEAN.

Severe storms in the South Indian Ocean have formed the subject of careful study from the earliest times, the pioneer work having been done by Piddington of Calcutta, in 1840, and by Thom of Mauritius, in 1845, who proved that the storms, to which Piddington gave the name "cyclones," consisted of a system of revolving winds.

In common with the American pioneer Redfield, they held the belief that the winds described a more or less perfect circle about a storm centre. Later investigations, carried out by Dr. Meldrum of Mauritius, showed that if the winds of a cyclone move in a circle about the storm centre, then the translatory movement of the storm itself must be irregular or zig-zag to account for the observed circulation.

This seemed to be quite contrary to actual conditions, and after a detailed study of the Mauritius cyclone of January 8 to 16, 1860, it was definitely established that the path of the cyclone centre is regular, and in consequence Meldrum deduced what is now an unquestioned fact, namely, that the winds incurve to the centre.

Although the Royal Alfred Observatory at Mauritius was not established until 1875, yet the island had been the centre of storm investigation for many years previously, since it is admirably placed for this purpose, being in or near the paths of the majority of cyclones, except perhaps in April and May, when the greater number pass the island far to the eastward.

Thom's investigations (49) showed that the Doldrums supplied the conditions necessary for the formation of revolving storms, and his conclusions were confirmed in 1861 by Meldrum, who said :—

"The more the hurricanes of the South Indian Ocean are studied the more evident does it become that they owe their origin and continued existence for several days to the vibrating and conflicting action of the equatorial westerly monsoon and the south-east trade wind, when the sun has southern declination."

When the trades are brisk and the equatorial calm belt is farthest north, the conditions favouring the formation of tropical cyclones are absent from the South Indian Ocean.

This was brought out clearly by the work of Meldrum, who in 1885 submitted to the British Association a report and a series of yearly charts containing information of all cyclones which occurred during the years 1856 to 1884 inclusive (46). These charts were eventually transferred to the Meteorological Office, where they are combined with other tracks which Meldrum had collected from various sources for the period 1848 to 1855, and published in January, 1891, after the tracks of 1885 had been added (48).

For this period of 38 years there was no evidence of the existence of a tropical cyclone over the Southern Ocean during the months of August and September; and for earlier years—1809 to 1847 inclusive—Piddington found record of only one cyclone occurring in September and none in August. Only five were known to have occurred in June and July during 77 years of observations (1809 to 1885), and six in October for the same period.

For more recent years—1886 to 1917—no reports have come to hand of cyclonic storms during the months June to September inclusive, and only two vague indications of cyclonic activity for the month of October. As a result of this long series of investigations (1809 to 1917) the cyclonic season of the South Indian Ocean can be quite definitely established as from November to May inclusive, since storms during any of the remaining months of the year are known to be exceedingly rare.

In southern spring the south-east Trades retreat from the equator, and the north-east monsoon of the Arabian Sea and the Bay of Bengal moves southward. Between the two, for five degrees or so on both sides of the equator, the winds become to a large extent westerly and north-westerly, and are known as the "cross" or

north-west monsoon. Between this monsoon and the trades, as the season wears on towards summer, there are frequent calms and atmospheric disturbances, as the opposing winds neutralise or eddy about each other.

In midsummer the line of calms and variable winds is farthest south, and is farther from the equator towards the coasts of Madagascar and Africa than eastward near the centre of the ocean. In fact, the western part of the ocean as far south as Mauritius is influenced in some degree by the Doldrums, the northerly winds from which bring hot, muggy weather and physical enervation.

The majority of the tropical cyclonic storms of this ocean have their points of origin in the unsettled belt between northern Madagascar and Sumatra and between 5° and 12° S. latitude; they next traverse the trade wind area and usually expend their energy in the belt of variable winds of the high pressure area over the 30th south parallel; but they occasionally enter the region of the westerly winds, where they become more and more diffused and die away, or are carried eastward as temperate cyclones of much lessened severity.

III.—9. FREQUENCY OF CYCLONES.

In the western part of the South Indian Ocean the frequency of these storms is comparatively great, and numerous frequency tables have been drawn up by different observers.

Maillard, in his notes from Réunion Isle, gives 78 cyclones from 1640–1861.

Thom (49, p. 136), Bridet (43, p. 68) and Piddington give the following seasonal distribution:—

	Jan.	Feb.	Mar.	Apr.	May	June	July	Sept.	Oct.	Nov.	Dec.	Total
Thom	10	16	17	10	1	0	0	0	0	1	3	58
Bridet (51 years) ..	9	14	10	8	4	1	0	1	1	4	4	56
Piddington (1809–1841) ..	9	13	10	8	4	0	0	1	1	4	3	53

Meldrum's list for 1848–1885 is as follows. It is to be noted that it gives no information for the years 1849, 1850 and 1853, for which no reliable data were available.

	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Total
Progressive..	0	2	12	23	52	55	40	26	8	1	1	220
Stationary ..	0	3	13	10	19	6	19	24	11	2	1	108

It must be noted that Bridet's figures include Piddington's; thus Meldrum recorded 328 storms in 35 years, Piddington 53 in 39 years, and Bridet's independent results number only three in 12 years. Accordingly the records of these earlier observers are probably very incomplete, and the true frequency is to be derived from Meldrum's data alone.

Individual South Indian storms vary from those curious whirls which, if not absolutely stationary, have little forward motion, to those which, at least for part of their course, move through more than 300 miles a day. With these variations in mind, Meldrum made the classification of stationary and progressive storms shown in the above table. These charts, as previously stated, were published in London in 1891. The Secretary of the Meteorological Office in his preface makes the following statement:—

“The cyclones styled stationary may, however, from lack of observations, include some storms which may have moved from the position in which they are shown, though it is not probable that their courses or existence were long. It is necessary, however, to draw attention to this doubt in the classification.”

A similar criticism is made by Hildebrandsson and Teisserenc de Bort (9). It will be seen later that more recent observers have not recorded any stationary cyclones.

The very marked seasonal variation in the ratio of frequency of progressive storms to those classed as stationary would be most important to seamen and airmen if it could be considered established. The knowledge that in the early and late months of the season (September to November and May to July respectively) the chances are about even that a cyclone will be stationary, and that in the height of the season the chances are very great that a cyclone will have a rapid motion, would greatly influence the handling of craft in the vicinity of a storm. Meldrum's result may correspond to a real seasonal variation in the average velocity of translation.

The frequency figures for more recent years (1886–1917) have been compiled from the numerous publications of the Mauritius Observatory. (These include the Annual Reports, Monthly Results of Meteorological Observations, Monthly Bulletins, Mauritius Blue Book, and the Transactions of the Meteorological Society of Mauritius.)

The seasonal distribution for the years 1886-1917 is as follows :—

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April	May	Total
No. of Storms	2	8	25	42	54	39	18	6	194

Combining Meldrum's list with this, the resultant distribution for the 70 years, 1848-1917, three years being omitted, is as follows :—

Month	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Total
No. of storms	0	7	33	58	113	115	98	68	25	3	2	522
Percentage Frequency	0	1	6	11	22	22	19	13	5	1	0	—

From this it is seen that 74% of the total storm activity takes place during the four months December to March.

III.—10. VARIATION OF YEARLY FREQUENCY.

The total number of cyclones occurring year by year is very variable. This variation is shown on Plate XIX, Fig. 1, for the years 1886-1917 inclusive. The average frequency is seven or eight storms per annum; the extreme values of 0 and 1 occurred in 1889 and 1900 respectively, and 16 in 1870, while the highest number in recent years was 13 in 1913.

No satisfactory explanation of this wide variation has yet been evolved, but it seems quite clear that the sunspot cycle does exert an appreciable effect on the cyclones of the South Indian Ocean.

In connection with the question of the probability of the occurrence of cyclones, it is interesting to note that both Meldrum and his successor Claxton have shown that the number of cyclones in the South Indian Ocean follows a cycle of about 11 years, corresponding to the sunspot cycle. Meldrum in a paper read before the British Association at Brighton in 1872 (46), gave the following table:—

<i>Year.</i>					<i>Number of Cyclones.</i>			
1854	Minimum of Sunspot Period	..	..	..	.	3	
1855	" " " "	..	..	..	..	4	
1856	" " " "	..	..	.	..	1	
1857	" " " "	..		.	..	3	
1858	" " " "	.		.	.	4		
				Total	..	15		

Year.	Number of Cyclones.							
1858 Maximum of Sunspot Period	4
1859 " " " "	5
1860 " " " "	8
1861 " " " "	8
1862 " " " "	7
Total								32
1865 Minimum of Sunspot Period	3
1866 " " " "	5
1867 " " " "	2
1868 " " " "	2
1869 " " " "	3
Total								15

and wrote: "Assuming that we have got a close approximation to the actual number of cyclones, and that the numbers fairly represent cyclonic energy, it is difficult to avoid the conclusion that the above Table points to a definite law . . ." (*Nature*, Vol. VI, p. 358).

Claxton gave the following Table in a paper entitled "The Climate of Pamplemousses in the Island of Mauritius" (44).

FREQUENCY OF CYCLONES DURING THE SUNSPOT CYCLE.

Year of Minimum Solar Activity.	Years before or after the Epoch of Minimum Solar Activity.										
	-5	-4	-3	-2	-1.	0	+1	+2	+3	+4	+5
1856 ..	2	2	?	3	2	4	4	4	5	9	6
1867 ..	4	7	5	4	6	5	7	6	5	3	9
1878 ..	7	5	5	6	4	5	5	4	4	4	3
1889 ..	4	7	3	1	6	0	3	7	6	7	8
1900 ..	3	5	3	4	1	1	7	7	—	—	—
Means ..	4.0	5.2	4.0	3.6	3.8	3.0	5.2	5.6	5.0	5.7	6.5

There is not complete agreement between these two tables, but they both agree in showing a decided increase in the number of cyclones in the South Indian Ocean about the time of maximum sunspots.

The table drawn up by Claxton includes "all cyclones which occurred within latitude 10° to 30° S. and longitude 50° to 70° E., the 20° square of which Mauritius is nearly the centre."

It should, however, be stated that violent cyclones appear to be equally probable at times both of sunspot maximum and minimum, so that there is apparently no obvious connection between the intensity of the storms and solar activity.*

III.—11. TRACKS OF CYCLONES.

The tracks of the majority of cyclones occurring between the years 1886 and 1917 are shown on Plates XX to XXIII, and the distribution of the points of origin throughout the various months of the cyclone season (for the same period of years) on Plate XIX, Fig. 2. The tracks of storms prior to 1886 can be seen by consulting the charts of Dr. Meldrum in the publication already referred to. It is seen that the majority of the cyclonic storms of this ocean follow parabolic tracks, which are approximately symmetrical for some distance on either side of the vertices.

* For more detailed accounts of this theory see the British Association Reports for the years 1872, 3, 4, and 6.

Figure 1.

VARIATION IN ANNUAL FREQUENCY OF STORMS IN THE
SOUTH INDIAN OCEAN DURING THE PERIOD 1886-1917.

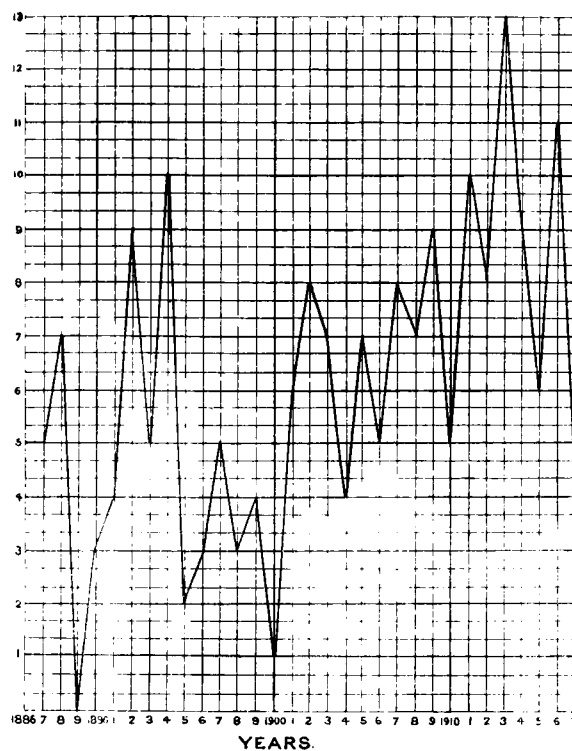
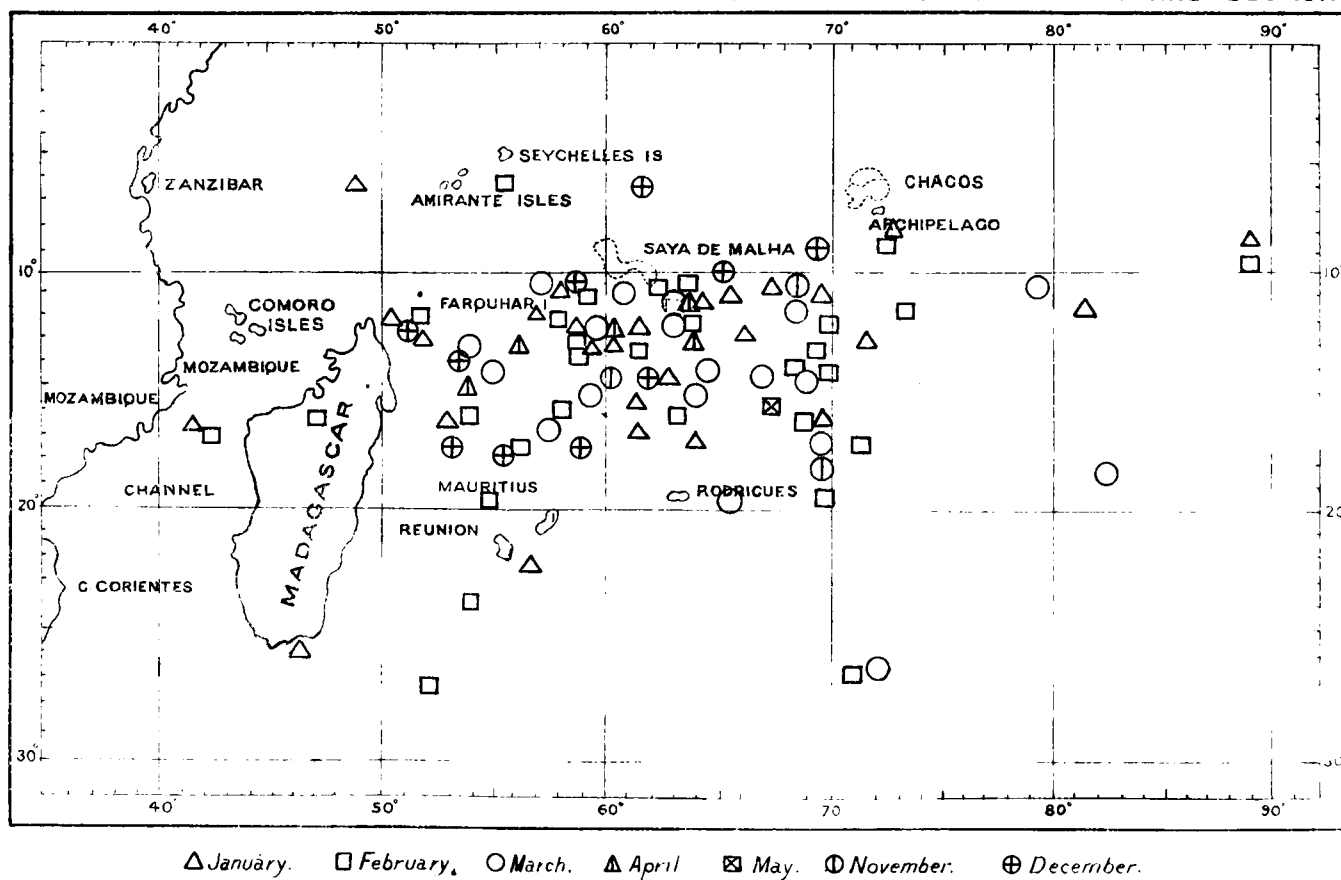
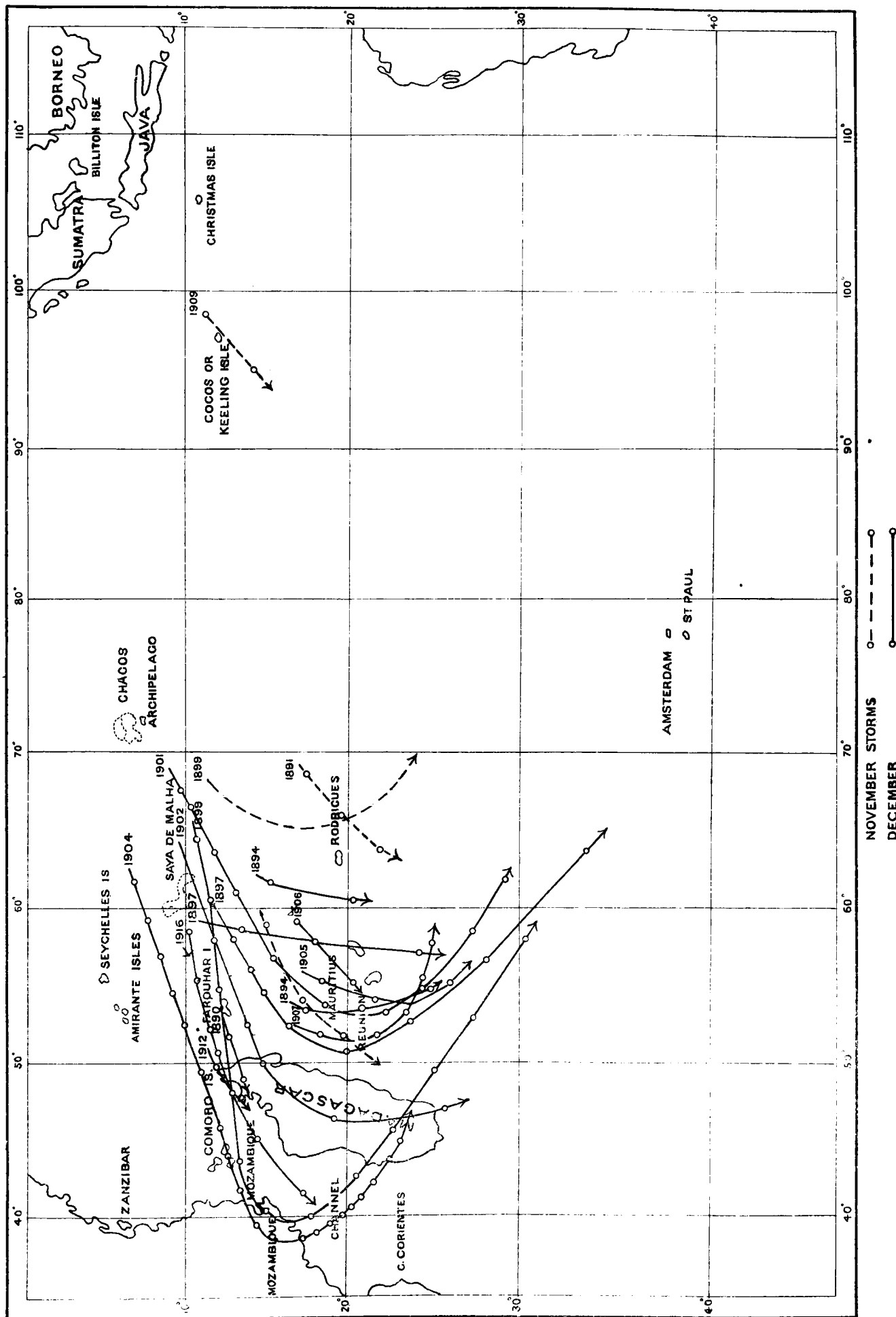


Figure 2.

CHART SHOWING DISTRIBUTION OF POINTS OF ORIGIN OF CYCLONES DURING THE YEARS 1886-1917.



TRACKS OF CYCLONES IN THE SOUTH INDIAN OCEAN DURING THE MONTHS OF NOVEMBER AND DECEMBER FROM 1886-1917.



As stated above, Thom's investigations showed that the Doldrums were the seat of origin of the majority of these storms. Here, as an atmospheric eddy resolves itself more into a storm centre, on the north the normal westerly winds of its circulation are enhanced by the prevailing direction of the monsoon, and the winds of the southern quadrants are intensified by the easterly direction of the trades. The circulation between the two once established, the storm begins to travel along its first track in a south-westerly direction.

Broadly stated, the storms usually originate between the parallels of 10° and 15° S., whence they travel south-westwards over a track that becomes more and more southerly until the vertex is attained. The average point of recurve is situated in 21° S., but the variations are wide, and, judging from the charts available, the vertex of a cyclonic storm in the South Indian Ocean may be anywhere between 8° S. and 32° S. (45).

A detailed analysis on this point was followed up by Köppen, who chose the tracks of 89 cyclones for which the recurve point was well established, and determined the mean point for each month as follows :—

	Nov.	Dec.	Jan.	Feb.	Mar.	April	May
Number of Cases	4	12	28	20	13	8	4
Mean Latitude of Recurve	$17\cdot0^{\circ}$	$17\cdot0^{\circ}$	$22\cdot2^{\circ}$	$22\cdot2^{\circ}$	$20\cdot8^{\circ}$	$15\cdot0^{\circ}$	$14\cdot0^{\circ}$
Mean Longitude of Recurve ..	$76\cdot0^{\circ}$	$67\cdot3^{\circ}$	$60\cdot0^{\circ}$	$63\cdot0^{\circ}$	$63\cdot5^{\circ}$	$74\cdot5^{\circ}$	$75\cdot0^{\circ}$

This brings out clearly the eastward retreat of the cyclones in April, May and November, which is referred to later.

After the recurve the second branch of the parabola is in some direction between south and east.

Meldrum's charts afford a few examples of storms which appear to have been first experienced by ships in close proximity to the equator ; since 1886 eight storms have originated north of 10° S., of which three were in latitude 6° S. The variation in the general tracks of these storms during successive months of the cyclone season is not so marked as in the case of hurricanes in the West Indies, and the cyclones in the Indian Ocean north of the equator. A brief summary of the tracks as the season advances is as follows (see also Plates XX to XXIII) :—

October.—In this month cyclonic storms occur at rare intervals. For the 35 years ending 1885, Meldrum reported two progressive storms and three stationary storms, making a total of five storms, with an average frequency of one every seven years.

Since 1885 there have been two indications of cyclones. The first was in 1892, when the ss. *Calcutta* encountered a violent storm in latitude 15° S., longitude 88° E. on the 17th and 18th. No further information of this storm was forthcoming, and it is not known whether it was of a cyclonic nature. The second instance was October 27, 1917, when there were marked indications of a cyclonic storm to the east of Rodrigues.

Of the earlier October storms studied by Meldrum, the majority were in the neighbourhood of Mauritius and the Seychelles. Until 1842 the Seychelles had been considered entirely outside the tropical storm belt, but the islands were visited by a cyclone on October 11 and 12 of that year.

November and December (see Plate XX).—Storms occur with increasing frequency during these months. For the 35 years ending 1885, Meldrum gives 12 progressive and 13 stationary storms : 25 storms in all during November, or approximately two storms every three years. For the 32 years ending 1917, eight storms have occurred during this month, giving an average of one every four years.

During December the frequency is somewhat higher; Meldrum reported 33 storms (23 progressive and 10 stationary) prior to 1886 (*i.e.*, roughly one storm per year), and since then 25 storms have occurred.

Most of the November and December storms originate between 5° and 15° S., and between Madagascar and longitude 70° E. On the other hand, they may occur as far east as Sumatra, especially in November, when several storms have moved from west of Sumatra to south-west of Cocos Islands. The more usual track is, however, to the east of Madagascar, over Mauritius and Rodrigues; the storms pursue the customary parabolic track, moving south-westwards, through south to south-east.

The December storms sometimes traverse the Mozambique Channel, and numerous storms have been reported in the locality both before and since 1885. These particular storms, as will be seen later, appear to pursue unusually lengthy paths.

Cyclonic eddies have sometimes been observed at the equator, but as a rule these do not travel far. An exception occurred in December, 1894, when on the 5th, a storm centre appeared near latitude 1° S., longitude 99° E. This storm pursued an unprecedented path, and instead of moving southwards, crossed the equator north-eastwards and travelled to the head of the Bay of Bengal on the 16th. Its winds, however, were nowhere severe.

Another interesting formation took place from November 28 to December 3, 1844, when two cyclones appeared at the same time on both sides of the equator, one in 6° N., 87° E., and the other in 7° S., 89° E.

January, February and March (Plates XXI, XXII and XXIII, Fig. 1).—These are the months of maximum frequency, and the tracks of the storms are, in general, very similar throughout the three months. Comparatively few originate to the east of the 90° meridian, and the majority are found considerably to westwards, the zone of maximum occurrence being to the east of Madagascar, over the islands of Mauritius, Réunion and Rodrigues. The general trend is south-westerly to the recurve, which usually takes place over or near latitude 20° S.; the storms then pass south-eastward to the south temperate regions. Occasionally, storms of January and February pass down the Mozambique Channel, but no storm has done so during recent years in March, although four have penetrated into Madagascar.

April (Plate XXIII, Fig. 2).—The storms are less frequent than in March; 50 were reported during the 35 years ending 1885, that is, an average occurrence of three storms every two years. Since then 18 storms have occurred. The majority of these have their tracks somewhat to the east of those of the three earlier months, and many of the April storms pass well to the east of Mauritius. The famous storm of April, 1892, which will be discussed in detail later, passed directly over Mauritius, and in this was most exceptional, since no severe gale had been experienced there in the latter half of April since the year 1691.

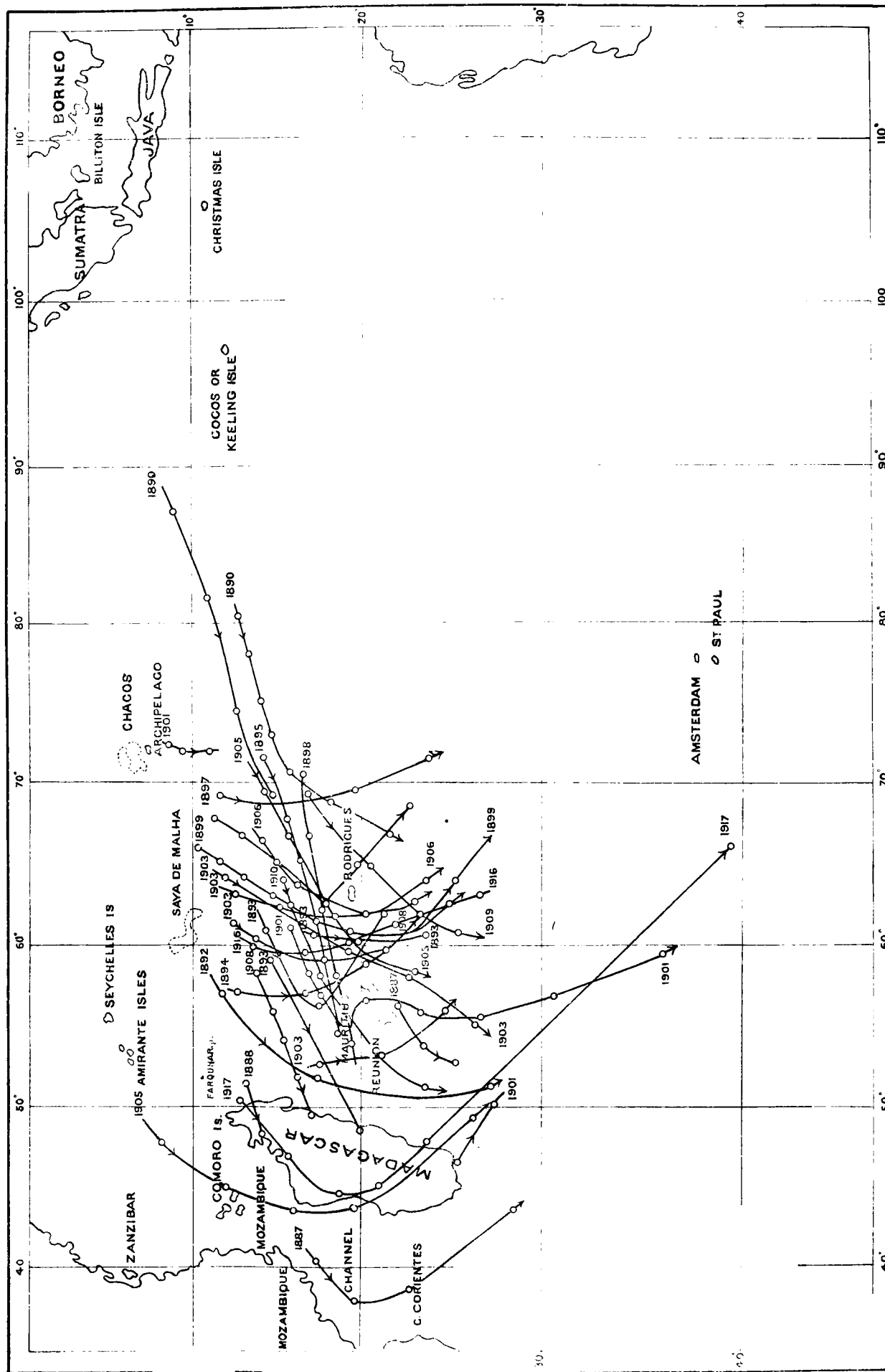
Occasional storms of this month, as in November and December, originate very far east between the 80th and 90th meridians.

May (Plate XXIII, Fig. 2).—The easterly retreat, commenced in April, is seen to continue in the storms of May. Only six storms occurred between 1885 and 1917, and only one of these travelled to the west of Rodrigues. Some stationary cyclones have been reported, but the records of such storms are so uncertain that little importance can be attached to them. The paths are curved in the way already described for the other months.

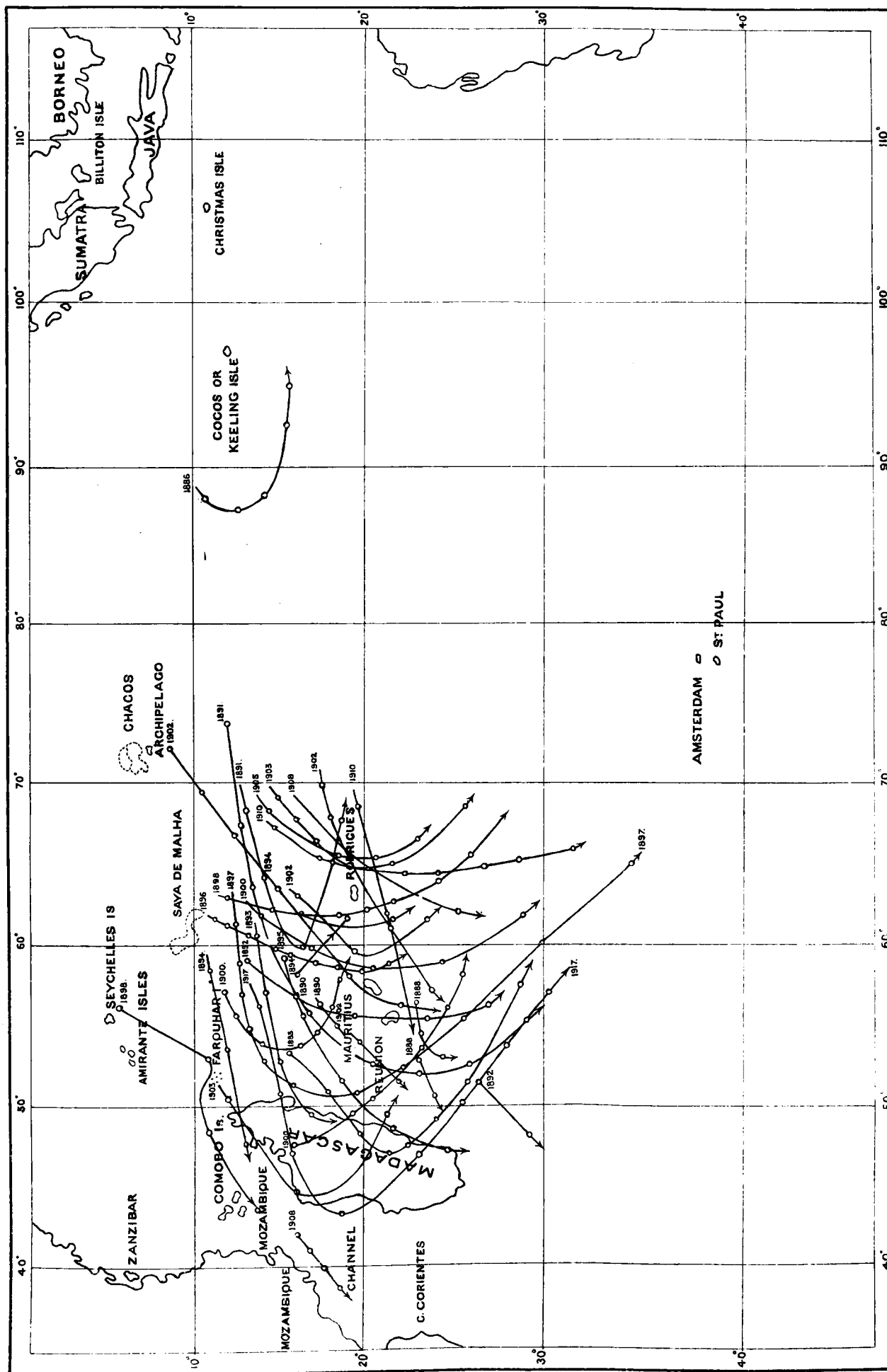
The exceptional storm occurred on May 24–28, 1916, and its track (marked *) is shown on Plate XXIII, Fig. 2. It passed 80 miles south-east of Mauritius and well to the west of Rodrigues. After its passage the barometer remained unusually low, the depression apparently remaining stationary and slowly filling up in the position noted for the 28th.

June and July.—No storm has been reported between May and October during recent years. Meldrum reported one storm in June 1859, and only one of consequence in July, this occurring from July 8–12, 1871. It formed to the south-west of Sumatra and passed to westward of the Cocos or Keeling Islands.

TRACKS OF CYCLONES IN THE SOUTH INDIAN OCEAN DURING THE MONTH OF JANUARY FROM 1886-1917.



TRACKS OF CYCLONES IN THE SOUTH INDIAN OCEAN DURING THE MONTH OF FEBRUARY FROM 1886-1917.



III.—12. RATE OF PROGRESSION.

The daily onward motion of these storms is slow and irregular throughout. Five hundred miles in 24 hours is an exceptionally rapid rate of advance for a cyclone in the South Indian Ocean, and 200 miles is a fair average rate of daily travel.

Hurd, in a short report gives the average rate of 9 or 10 miles an hour along the first branch while the storm has its south-westerly motion. At about latitude 20° S., the rate of progression decreases to five miles an hour, on the average, at about the time when the cyclone is recurving towards the south and south-east. Beyond 25° or 26° S. the rate varies, sometimes decreasing to two or three miles an hour, and sometimes showing greatly increased speed after the recurve.

Not infrequently, however, the storm field is found to move more slowly in this ocean at the beginning of its career than at any other period, even during the recurve; in this the storms differ from tropical revolving storms with recurved paths in other parts of the world.

Recent examples of this class of storm are to be found in the storm of February 1-9, 1908, in which the distances traversed on successive days were 117, 124, 129, 127, 133, 142, 147, 161 miles respectively.

Also in the storm of February 24 to March 6, 1908, the daily velocity in the first branch was 97, 96, 104, 104, 87, 82, 106 miles—an exceptionally low velocity—and in the recurve the daily velocity increased to 152 miles per day.

A detailed analysis of all the charted storms for the six years 1903-1908 gave the following results :—

Mean daily velocity in the first branch	..	..	191 miles.
„ „ „ during the recurve	..	.	164 „
„ „ „ in the second branch	..	..	181 „

This would suggest an average velocity of roughly 200 miles per day at the beginning and end of the storm path, with a slight decrease of 20 or 30 miles per day during the recurve. The individual readings, however, were most varied, the extreme values in the three cases being as follows :—

	Velocity (miles per day).	
	Highest.	Lowest.
1st Branch	401	82
Recurve	332	67
2nd Branch.. ..	400	54

The cyclone of December 10-28, 1904, originated near latitude 8° S., longitude 62° E., recurved on the African Coast in about latitude 15° S., crossed the Mozambique Channel on a south-east course, and died out in southern Madagascar; the greatest 24-hour movement, 259 miles, occurred on the 15th-16th, between Cape Amber, Madagascar, and the Comoro Islands; the lowest 24-hour rate, 54 miles, occurred on two successive days, the 21st to the 23rd, in the Channel about latitude 20° S. The whole distance travelled by this storm was about 2,100 miles.

Other storms which have travelled down the Mozambique Channel have had notably long paths, and in this connection the cyclone of December 10-16, 1899, should be mentioned. This storm originated in 6° S., 68° E., and travelled as far south as 22° S., the length of the path exceeding 3,000 miles. The average southern limit is 34° S. in January, but 18° S. in May, following the northward retreat of the sun. The January storms, however, sometimes reach the 40th parallel.

III.—13. RAINFALL.

No regular laws can be formulated with regard to either the amount or the distribution of rain during the passage of these storms. Most of the information available is from measurements and observations on the Island of Mauritius, and from an analysis of these there is one outstanding point, namely, that the rainfall is slight when the storm field passes the Island well to the eastward (51, 1902, p. 21). On the other hand, the storms which pass to the north and west of Mauritius usually bring the principal rainfall of the month, though there are numerous exceptions to this rule.

In February, 1916, two well formed cyclones passed to the east of Mauritius, but "in consequence of the absence of cyclonic storms to the north and west, rainfall was low over the entire island."

On February 16–18, 1902, a cyclone passed 200 miles to the east of Mauritius and gave very little rain to the island, the precipitation in three days being 0·160 in. at St. Louis. The velocity recorded on the 17th was 23·2 m.p.h.

Earlier in the month, however, three cyclones had occasioned extremely heavy rainfalls: 14·96 in. in 24 hours had been measured at St. Louis, and correspondingly heavy amounts over other parts of the island. These cyclones all came from the north of Mauritius, one passing within 50 miles of the island, and the third actually crossing the island. The difference cannot be attributed to difference in the distance from the centre alone. The wind force gives some indication of the intensity of the cyclone and the distance from the centre, and in the latter cyclone 6 in. fell on the 9th alone, with a maximum velocity of 27·7 m.p.h., only slightly greater than that for the storm of February 16 to 18.

The amount given by the northern storms decreases with increasing distance from the centre: e.g., in January 1901, a storm which passed from northwards, very near to Mauritius if not directly over it, gave a fall of 12·22 in. of rain in 24 hours; later in this month a storm which passed more than 100 miles to the north and north-west of Mauritius gave a fall of only 3·19 in. in four days.

One of the most remarkable falls was occasioned by the storm of February 15–21, 1896, which passed directly over the island from north to south. The greatest 24-hour fall was over 20 in., and the following total falls were measured for the four days during which the influence of the storm was felt: Pamplemousses, 26 in.; Réunion, 47 in.; la Marie, Tamarind Falls, and l'Etoile, 41 in., while falls of over 30 in. were measured in other parts of the Island.

A storm which came from the north-north-west and passed within four miles of Mauritius on December 4–7, 1897, gave from 10 to 12 in. of rain in two days at certain stations and from 4 to 7 in. at others.

In January, 1910, a storm passed within 100 miles to the north of Mauritius and gave a moderate rainfall of 5·53 in. from the 8th to the 12th.

The rainfall in storms may, however, be associated with such a deficiency in the rainfall of the ordinary days that the total rainfall of the month is below normal. For instance, in 1909 there were three storms in January, two of which passed to eastward and the third to north and west of Mauritius; the rainfall for the month was 37 per cent. below normal. In March of the same year, as many as five cyclonic storms influenced Mauritius, as follows:—

- (1) Formed to north-north-east of Mauritius on March 7 and travelled to the Madagascar coast by the 9th.
- (2) Formed due north of Mauritius, was due west of Réunion on the 13th and then curved to south and south-east by the 16th.
- (3) Formed to east-north-east of Rodrigues and passed within 100 miles of that Island on the 13th.
- (4) Formed 300 miles north by west of Mauritius on the 17th, travelled on a south by east track to a little over 200 miles south-east of Mauritius on the 22nd and then curved on a south-east track.
- (5) Formed on the 21st about 500 miles north-north-east of Mauritius and travelled on a west-south-west track to the Madagascar coast.

It is seen that four of these passed either to north or west of Mauritius; nevertheless the rainfall was 36% below normal for the month.

Figure 1. TRACKS OF CYCLONES IN THE SOUTH INDIAN OCEAN FROM 1886-1917. MARCH.

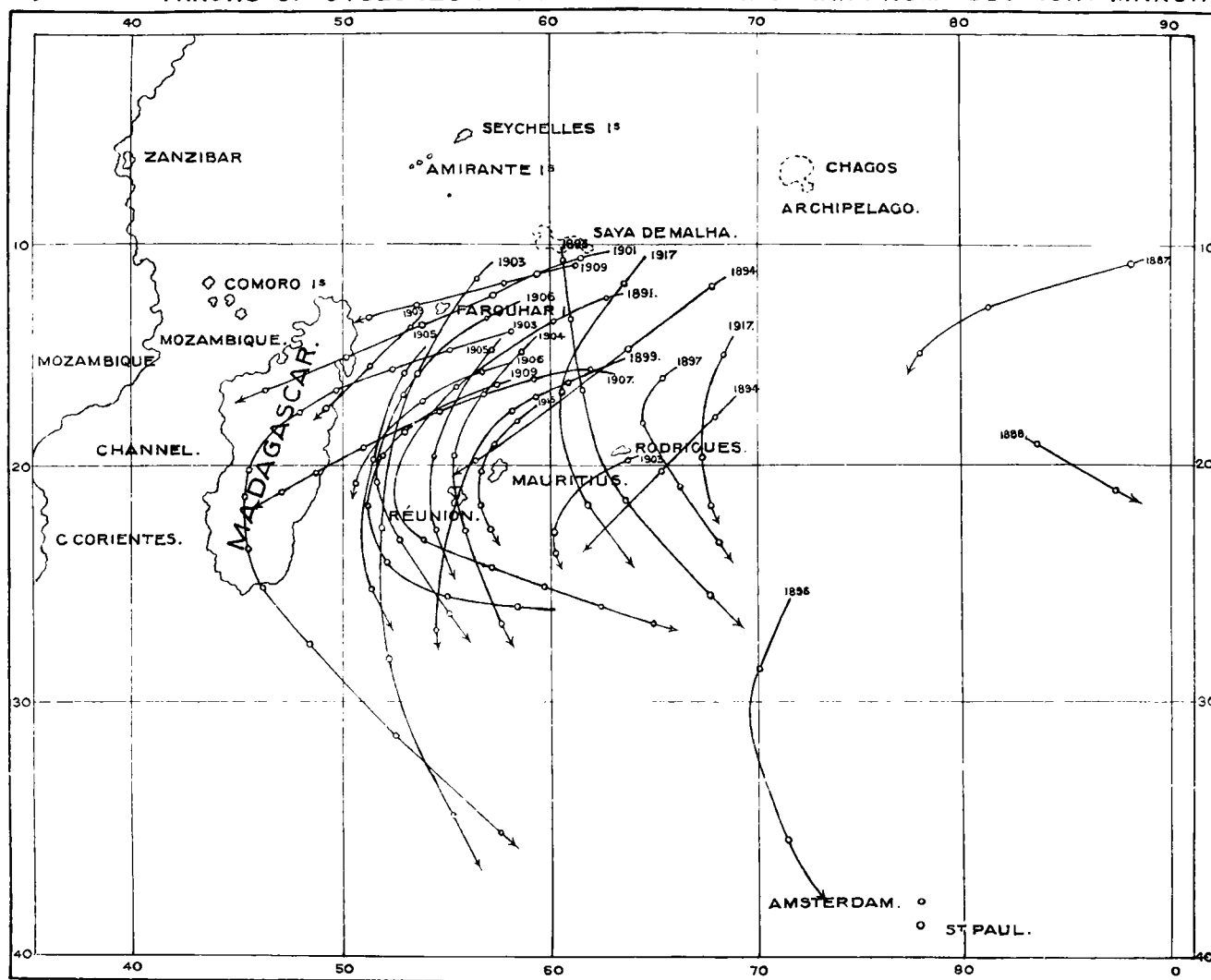
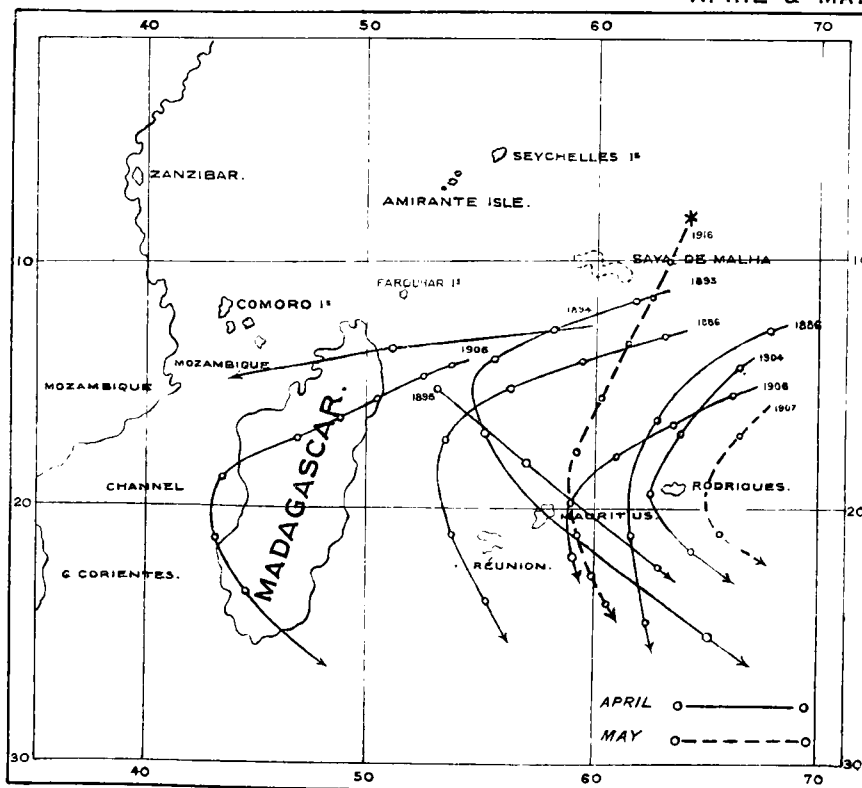


Figure 2.

APRIL & MAY.



**Records of Barometric Pressure and Wind Direction and Velocity at
the Royal Alfred Observatory during the passage of two cyclones.**

Figure 1. Cyclone of April 29, 1892.

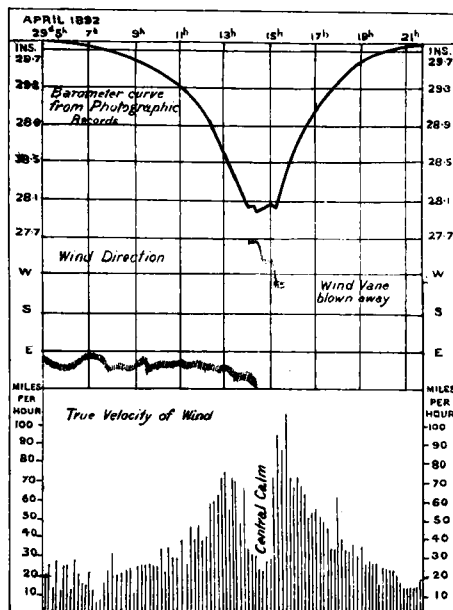
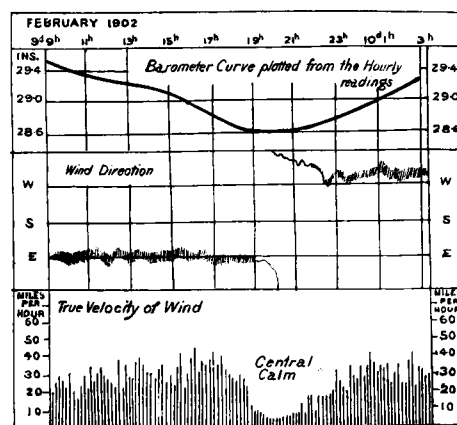
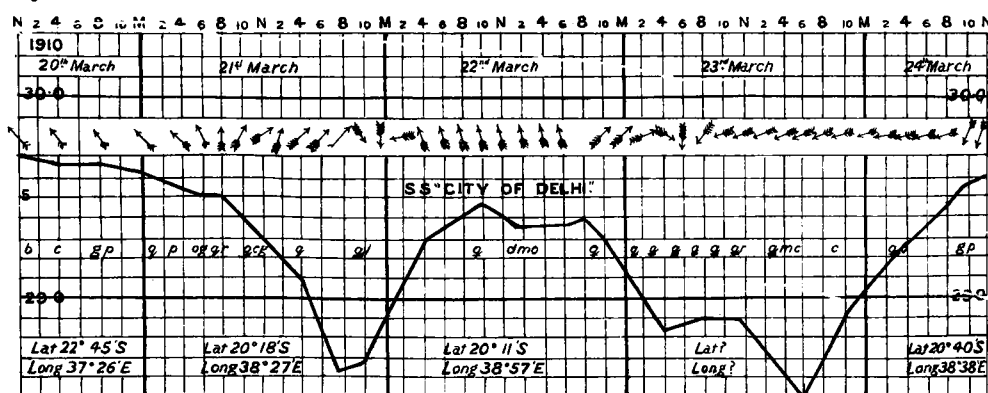


Figure 2. Cyclone of February 9-10, 1902.



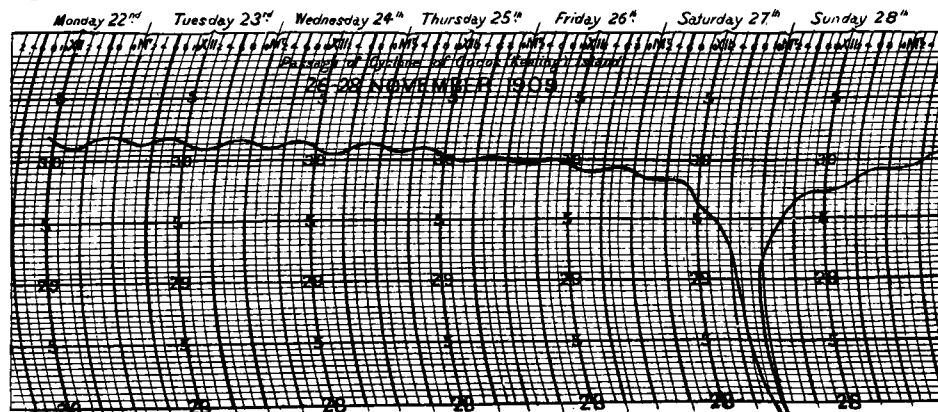
From "The Sugar Industry of Mauritius" by A. Walter.

Figure 3.



From "M.O. Monthly Meteorological Chart of the Indian Ocean, September 1910."

Figure 4.



From "M.O. Monthly Meteorological Chart of the Indian Ocean, May 1910."

III.—14. SOME PRECURSORY SIGNS OF CYCLONES.

Most of the storms of this part of the world are unaccompanied by electrical phenomena ; in occasional storms, however, thunder and lightning have been reported, and in almost all these the occurrence has been on the northern side of the storm field. It has long been a local belief, moreover, that thunder and lightning portend the cessation of a storm already in progress or the dispersal of a threatened storm : this would be the case if the thunder was on the north side of a storm moving south.

Many precursory signs are well known. Amongst them is a red coloration given to the clouds, especially at sunrise and sunset, together with the accompanying pink to crimson tints which give an unnatural appearance to all objects. Oppressive heat and a shift of wind from the customary north-westerly direction are almost unfailing signs. The heat and moisture resulting from the *distant* presence of a cyclone have a most beneficial effect on the agricultural conditions, especially on the sugar crop of the Colony. It must be remembered that these storms, unlike the storms of the rainy season that pass from the Bay of Bengal to India, are fully developed, with winds of hurricane force, and a central storm area or "eye." But they cannot be considered dangerous unless the centre approaches within 50 or 60 miles, and this near approach is heralded by a "wind velocity about 28 miles an hour (true velocity) with a falling barometer and the wind steady from any direction between south-east and east during the five months from December to the end of April." (See Report by A. Walter, Director, Mauritius Observatory.)

Daily weather Reports from Rodrigues and Réunion, Chagos and St. Brandon (and more recently from Cocos Island) are received at St. Louis, Mauritius, during the cyclone season. In spite of these and the other observable precursory signs, it is difficult to forecast the exact path of tropical storms, since so many which apparently are going to strike the island pass by on one side or the other.

The mean maximum wind velocity for the cyclones at Mauritius is estimated at 80 miles an hour. Both Mauritius and Réunion with their high ground of 3,000 to 5,000 feet above sea level act in some measure as a wedge to the trades, but it is noticed that they exert no influence in breaking up the cyclones that cross them.

If a V-shaped depression form between two anticyclones from December to May, in the neighbourhood of these islands, tropical cyclones are likely to occur, and sometimes three to five storms form in rapid succession.

The following are accounts of some noteworthy storms in this region :—

III.—15. THE HURRICANE OF APRIL 29, 1892. (See the account in the Mauritius Blue Book, 1892.)

At 9 a.m. on April 24 the barometer (reduced to sea level) read 30·063 in. and there was a light breeze from east-south-east-half-south and fine weather. Pressure gradually fell until 9 a.m. of the 27th, when the reading was 29·900 in., the weather fine, with a moderate breeze from east by south. This fall of pressure, with this direction of the wind, and the sea disturbed to northward, indicated the existence of a cyclone to the north of the Island. But as, since at least 1691, no severe gale had ever been experienced in Mauritius later than April 12, while small cyclones in the South Indian Ocean to the north of Mauritius in April and even in May were not unusual, no fear was entertained.

At 9 a.m. on the 28th the barometer read 29·905 in., slightly higher than at the same hour on the 27th with the wind from north-east-by-east at the rate of 12·3 m.p.h. ; at 9 p.m. of the same day the pressure was 29·850 in with the wind north-east-half-east at the rate of 14·5 m.p.h. There was also during the 28th, a considerable amount of thunder and lightning which had never been known to take place immediately before a hurricane.

At 9 a.m. of the 29th the pressure was 29·576 in., and had fallen 0·084 in. since 6 a.m. The wind was 40 miles an hour from east-north-east-half-north. From the backing of the wind it was evident that the storm was recurving and approaching the island, and warnings were then issued to that effect. By 11 a.m. the barometer

reading was 29.338 in. and falling, and the wind had reached 52 miles an hour from north-east-by-east. Warnings issued at this time stated that the wind would probably not exceed 56 miles an hour, but that all preparations should be made for a heavy gale.

The reasons why it was considered that the wind force would not exceed that of a strong to a whole gale were that Mauritius had not for 200 years been visited by a hurricane after the 12th April, and that the wind was from north-east, which had never been regarded as a dangerous quarter at any season of the year, no hurricane ever having passed over the Island from north-westward. After 11.30 a.m. no further warnings were possible, since all telegraphic communications had been interrupted.

The barometer continuing to fall at a great rate and the wind velocity to increase, the probability was that, contrary to long experience, the centre of the cyclone would pass over the island from the north-westward and that the wind would then come from the south-west.

The centre, however, did not pass over the observatory. The wind there backed from north-east to north, west-north-west, west and west-south-west, increasing to an average velocity of 88.9 miles an hour from north-east between 0.30 and 1.30 p.m., decreasing to 56.1 m.p.h. from north between 1.30 and 2.30 p.m., increasing a few miles per hour from west-north-west between 2.30 and 3.30 p.m., and then increasing rapidly to 103.3 m.p.h. from west-south-west between 3.30 and 4.30 p.m., after which it decreased. There was a lull but no calm, and at no time during the lull was the rate of the wind less than 34 miles an hour. The anemometer was blown down between 3.40 and 4 p.m., and the greatest recorded velocity was 122 miles an hour. From calculations afterwards made it reached the rate of 177 miles an hour* according to the account of the storm in A. Walter's *The Sugar Industry of Mauritius*. See Plate XXIV, Fig. 1.

From noon to 2 p.m. the barometer fell from 29.062 in. to 27.990 in., and from 3 to 5 p.m. it rose from 28.028 in. to 29.073 in., the mercury oscillating considerably between 1.30 and 3.30 p.m. The lowest reading as shown by the barogram in Plate XXIV, Fig. 1, was 27.956 in. at 2.12 p.m.; this is the lowest reading on record at Mauritius.

After 5 p.m. the wind diminished rapidly, and by 9 p.m. its velocity was only 26 m.p.h., the barometer reading being then 29.718 inches, the weather fine and the stars shining brightly. When the centre was over Mauritius the barometric gradient was exceedingly steep, since simultaneous readings at Mauritius and St. Denis (only 120 miles to west-south-west) were 28.028 in. and 29.437 in., respectively.

This cyclone was unprecedented in Mauritius with regard to time of year, direction and force of wind, and the suddenness, rapidity and extent of the changes which took place. Nearly all the loss of life and property took place in less than two hours.

The yearly sugar crop for 1892 was much reduced by the destructive action of this storm. The yield was about 69 millions of kilograms, whereas the usual yield is from 120 to 130 million kilograms.

The second figure on Plate XXIV gives the barogram, sequence of weather, etc., during the cyclone of February 9-10, 1902, which also passed over Mauritius. A comparison of figures 1 and 2 exemplifies the very different conditions which may obtain in different, though equally near, cyclones.

III.—16. STORM IN THE MOZAMBIQUE CHANNEL, MARCH 20-24, 1910.

One of the records of storms in the Channel is available from an account furnished by the ss. *City of Delhi*, which left Delagoa Bay on March 18, 1910. By noon of the 20th she was in 22° 45' S., 37° 26' E., the wind was fresh from south-east, and the weather sunny and generally of the normal type pertaining to that part of the world.

* It was found in 1905 that the Robinson records of wind velocity at Mauritius were systematically too high. Each of these velocities should probably be reduced by about 20 per cent. to get the true velocity.

Towards 4 p.m., however, the sky became overcast and the wind began to increase in strength, and by 8 a.m. of the 21st there was every evidence of a cyclonic storm in the proximity of the steamer.

During the afternoon of the 21st the wind continued to strengthen, the sea became dangerously high, and terrific squalls with rain prevailed. The wind shifted from east by north to south-east, and by 5 p.m. was blowing with hurricane force. At 7.30 p.m. the ship approached closely to the centre of the storm and the wind and sea went down nearly instantaneously although the "roar of the storm" could be heard all around. The sea at the centre "was almost calm with a confused swell, but with no broken water; the wind was very light and shifting rapidly, and at times the smoke from the ship's funnel rose vertically."

The ship crossed the centre, steering north-east, and then drifted west-south-west. At 9 a.m. of the 22nd the wind moderated and the steamer was eventually put on a north-east-by-east course with her engines going at full speed. By 9 a.m. of the 22nd both wind and sea were increasing; fierce squalls were frequent, and by next morning, the 23rd, the conditions of wind, weather and sea were still more unfavourable. At 11 a.m. the squalls were terrific, the sea high and dangerous, and heavy rain was falling.

Five hours later the winds had again reached hurricane force, the sea was mountainous, and heavy dark clouds were drifting across the sky at a low altitude; there was also a dense haze. The steamer was again nearing the storm centre. At 6 p.m. on the 23rd the lowest barometric reading, 28.50 in., was reached; the ship was then on the eastern verge of the central area. The wind and sea again subsided, and there was a lull for about half-an-hour. Soon after 7 p.m. the wind again increased suddenly and its force was very high; the sea, however, was less dangerous, and the clouds more detached; the barometer, as seen from the diagram of Plate XXIV, Fig. 3, had begun to rise. The wind increased in force from east-north-east until about 6.30 a.m. of the 24th. The ship steered at full speed on a northerly course and by 8.20 a.m. had left the disturbance behind her.

By noon she was in latitude $20^{\circ} 40' S.$, $38^{\circ} 38' E.$ (See Plate XXIV, Fig. 3). Throughout the storm the clouds were of a dull, leaden hue, heavy and dark, torn, and in piled up masses on the outer circle. It became hazy as the centre was approached and the clouds seemed to get lower and lower until they were apparently only a little higher than the ship's mastheads, while the haze became denser. On the inner circle the radius of vision was small, but in the vortex itself it was wonderfully clear.

The diameter of the vortex, estimated by combining the speeds of the ship and cyclone, was about 20 miles; the speed of the storm centre itself was about 6 miles an hour, $S.35^{\circ} W$ (The rate of travel of most storms through this channel is comparatively small, say 5 miles an hour.) Lightning was only reported once, on the night of the 21st, when the centre was crossed.

III.—17. CYCLONE AT COCOS ISLANDS (KEELING GROUP), NOVEMBER, 1909.

A severe cyclone visited these islands on November 27, 1910. The wind began to blow strongly from south-south-east in the morning and the barometer to go down steadily; precautions were therefore taken in case of a further increase of wind.

Later in the day the barometer still continued to fall and towards evening the wind force was exceedingly strong, and there was also a high sea running. Shortly after 7.30 p.m. the barometer reading fell rapidly, the wind increased to a terrific hurricane, and the rain fell in torrents. At 8.15 p.m. all instruments in the Office were vibrating sharply and it was impossible to read on any of the circuits. Perth, Rodrigues and Batavia were advised and the cables put to earth.

The wind continued to blow with cyclonic force, but at 10 p.m. there was a distinct lull in the storm, and the moon, which had previously been obscured, became visible. The barometer was exceedingly low (27.96 in. corrected), and it is probable

that the centre of the storm passed overhead shortly after 10 p.m. The cyclone recommenced, with tremendous violence, the wind coming as anticipated from the north-west; the hurricane force continued until about 12.30 a.m., after which it abated but continued to blow strongly all night; the barometer reading at 6 a.m. was 28.97 in.

The barogram is shown on Plate XXIV, Fig. 4.

The Orient Line R.M.S. *Otway*, outward bound to Australia, passed south-eastward, west of the Islands, on the evening of November 26, and experienced squally, rainy weather with a freshening of the Trade during the succeeding night. From midnight 26th to noon 27th she had south-south-east to south-east wind, force 7 to 8.

The disturbance seems to have approached the group from east-north-east, the centre passing slowly over the Cocos Islands just after 10 p.m. 27th; by that time the *Otway* was in latitude 16° S., with a rising barometer and less disturbed sea.

SECTION IV.—PACIFIC OCEAN.

A.—TYPHOONS IN THE WEST OF THE NORTH PACIFIC OCEAN.

The typhoon of the western Pacific Ocean is in many respects the counterpart of the West Indian hurricane of the Atlantic. Both classes of storm have their origin in the vicinity of groups of tropical islands and under similar barometric conditions; both undergo the same slow development and exhibit the same tendency to recurve upon reaching the northern limit of the north-east trades. (See Section II A.)

In a report on *Typhoons in East Asiatic Waters*, issued on numerous Pilot Charts of the U.S.A. Hydrographic Office, the following description appears:—“A typhoon or tropical cyclonic storm of the Pacific is due primarily to the appearance—generally within the sea enclosed by the Philippines, the Western Carolines, and the Mariana Islands, or within the China Sea—of a local area of low barometer, brought about by the inequalities in the temperature conditions of the atmosphere. In its incipient stages, the deficiency of atmospheric pressure throughout this area may be slight, amounting to only a few hundredths of an inch.

“According to varying conditions, such a depression either may be dissipated, or may deepen and ultimately develop into a well-defined storm centre, giving rise to winds of hurricane force. At the centre and during the height of the storm the barometric pressure may fall as low as 28.50 in. The space, however, over which this exceedingly low barometer prevails, is generally small, sometimes not more than a few miles in extent.

“Around this central low, which constitutes the heart of the storm, the winds circulate in a direction contrary to the motions of the hands of a watch, not in circles, however, but in spirals, which continually approach the centre, the curve described by the air being similar in many respects to the familiar path followed by the water escaping from a circular basin by a central opening in the bottom.

“To the north of the storm centre we thus have easterly and north-easterly winds; to the south, westerly and south-westerly; to the east, south-easterly and southerly; and to the west, northerly and north-westerly winds.

“The strength of the wind diminishes as we go outward, the winds of typhoon force rarely extending farther than 300 miles from the storm centre.

“If the storm centre remained stationary, a vessel hove-to under storm canvas would experience no steady shift of wind, but would simply feel the force of the gale increase until its full violence was attained, after which it would gradually blow itself out all from one quarter. Such, however, is never the case. In addition

to the movement of the air around the storm centre there is a progressive movement of the centre itself, carrying with it the circulating system of winds. In low latitudes, the direction of this motion for all typhoons has a westerly component, some storms continuing this course until they enter the mainland of Cochin China. Others recurve towards the north-east and skirt the shores of Japan. Omitting those typhoons which recurve in the China Sea, the Middle Dog Lighthouse, at the northern entrance to the Formosa Coast, is the centre of the region of recurvature."

These intense and frequent storms are discussed in great detail in publications of the Philippine Weather Bureau, the Hong Kong and Shanghai Observatories, the Tokio and Zikawei Observatories, the Pilot Charts of the North Pacific Ocean, published by the U.S.A. Hydrographic Office, and the Pilot Charts of the Indian Ocean, published by the London Meteorological Office.

Numerous books have been written on these typhoons and, of these, the best known and most comprehensive is *Cyclones of the Far East* (53) by the Reverend Father Algué, who has been for many years Director of the well equipped observatory at Manila, and who has made a detailed study of the storms at first hand.

In the present account numerous passages will be given verbatim from Algué's second report, published in 1904, but accounts of individual storms will be limited to those which have occurred since 1904. (For accounts of earlier storms see the original report or any of the above mentioned publications.)

The tracks of the storms are shown on monthly charts (Plates XXVI-XXVIII), and these also only give the tracks of storms occurring during recent years, since those of earlier years are charted in Algué's report.

IV.—1. FREQUENCY OF TYPHOONS.

Numerous frequency Tables have been compiled by different observers, and the following are amongst the most noteworthy :—

1. TABLES OF STORMS IN THE NORTH PACIFIC occurring during the years 1855-1887, collected from the works of several authors by Captain SCHUCK (57).

1855-1887.

Storms originating	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Above lat. 20°N	—	—	—	—	1	4	18	18	19	6	2	1
Below lat. 20°N	1	—	1	2	4	4	8	12	17	10	7	3

2. TABLE COMPILED BY DR. W. DOBERCK, Director of the Hong-Kong Observatory. This Table covers the 13 years 1884-1896, and includes 244 typhoons in all.

The monthly distribution is as follows :—

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
No. of storms	1	0	1	4	10	24	45	43	57	31	22	6

3. ALGUÉ'S TABLE, which includes "those cyclones which have appeared in this Archipelago, either crossing it, or passing through it for a greater or less distance and whose trajectory this Observatory has been able to discover."

The observations include 468 cyclones, and the period is from 1880-1901, inclusive.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
No. of storms	9	2	5	10	25	41	74	74	88	65	51	24

This gives a general yearly average of 21.3 cyclones; the average would be greater for the last 10 years of the series, as, on account of the larger number and better quality of the data, it has been difficult for any typhoon to occur in these seas without being recorded. The extreme numbers of storms for this period were 34 typhoons in 1894, and 11 in 1880, 1882, and 1885.

February is the one month which is practically immune from the storms; it may be noted that the two recorded in the above table both occurred in the last year of the series, 1901.

4. THE FREQUENCY TABLE FOR RECENT YEARS, embracing the period 1902-1918, has been compiled from the Monthly Bulletins of the Philippine Weather Bureau.

The Table is given in yearly detail, since it has hitherto not been published.

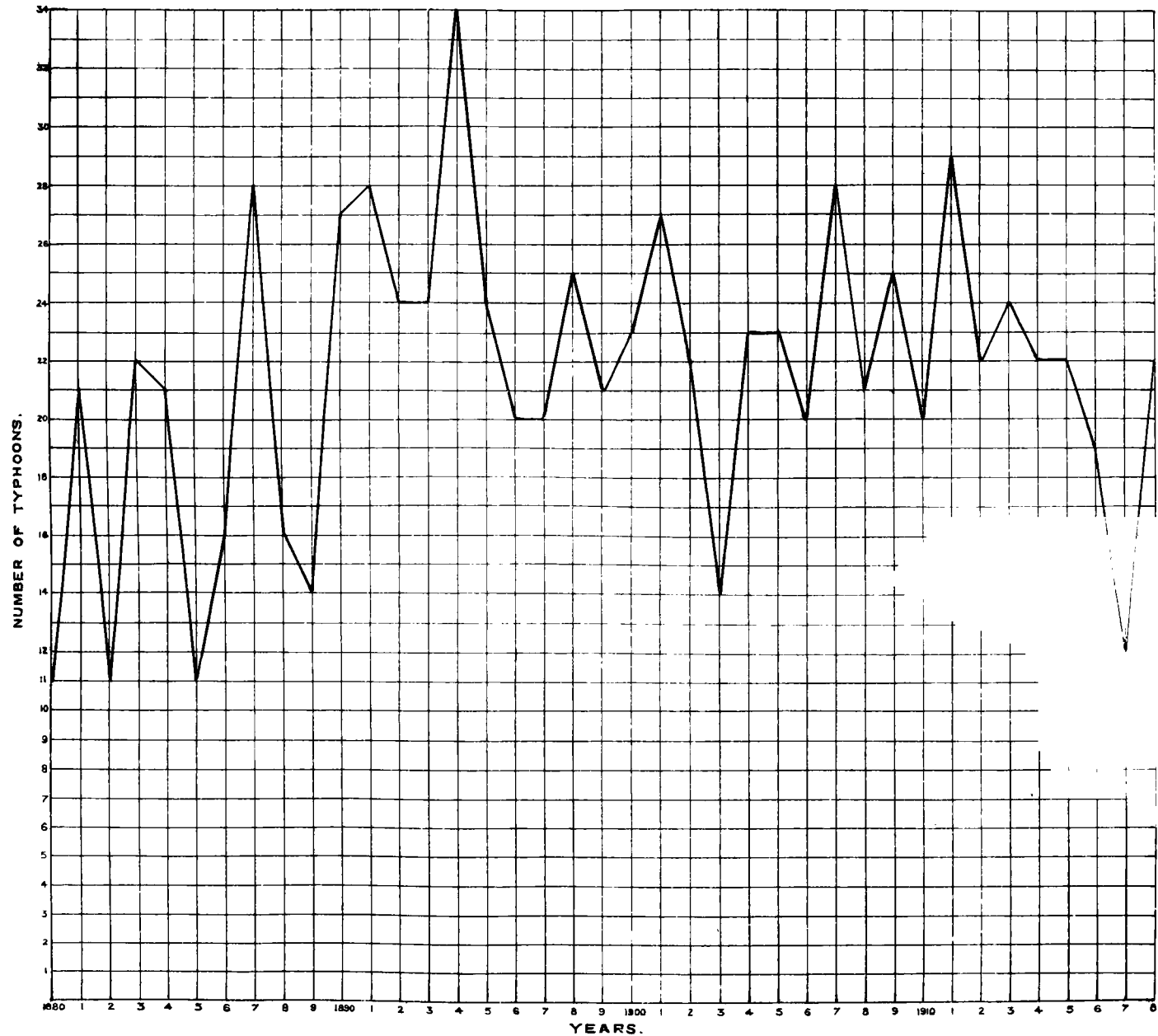
Year.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total.
1902 ..	1	—	—	—	1	2	4	3	6	3	1	1	22
1903 ..	1	—	1	—	—	1	2	3	1	2	1	2	14
1904 ..	1	—	—	2	1	2	4	5	4	3	1	—	23
1905 ..	1	1	—	1	2	3	2	4	3	2	2	2	23
1906 ..	—	—	—	2	2	—	3	2	5	3	2	1	20
1907 ..	1	1	1	1	1	2	4	5	5	2	2	3	28
1908 ..	—	—	1	1	2	1	1	4	5	3	2	1	21
1909 ..	—	—	1	—	—	1	3	4	5	7	2	2	25
1910 ..	—	1	1	—	4	2	3	2	4	2	—	1	20
1911 ..	—	—	1	1	1	1	6	8	7	2	1	1	29
1912 ..	—	—	—	1	—	—	2	4	4	4	5	2	22
1913 ..	—	—	—	—	1	—	3	6	6	5	2	1	24
1914 ..	—	—	—	—	2	2	4	5	6	1	1	1	22
1915 ..	1	2	—	—	—	—	1	6	4	4	3	1	22
1916 ..	3	—	—	1	2	—	1	4	5	—	2	1	19
1917 ..	—	—	—	—	—	—	2	4	5	1	—	—	12
1918 ..	—	—	—	1	1	1	4	5	5	3	—	2	22
Total	9	5	6	11	20	18	49	74	80	47	27	22	368

The average yearly frequency for this period is 21.7; the extreme values of 29 and 12 storms occurred in 1911 and 1917 respectively.

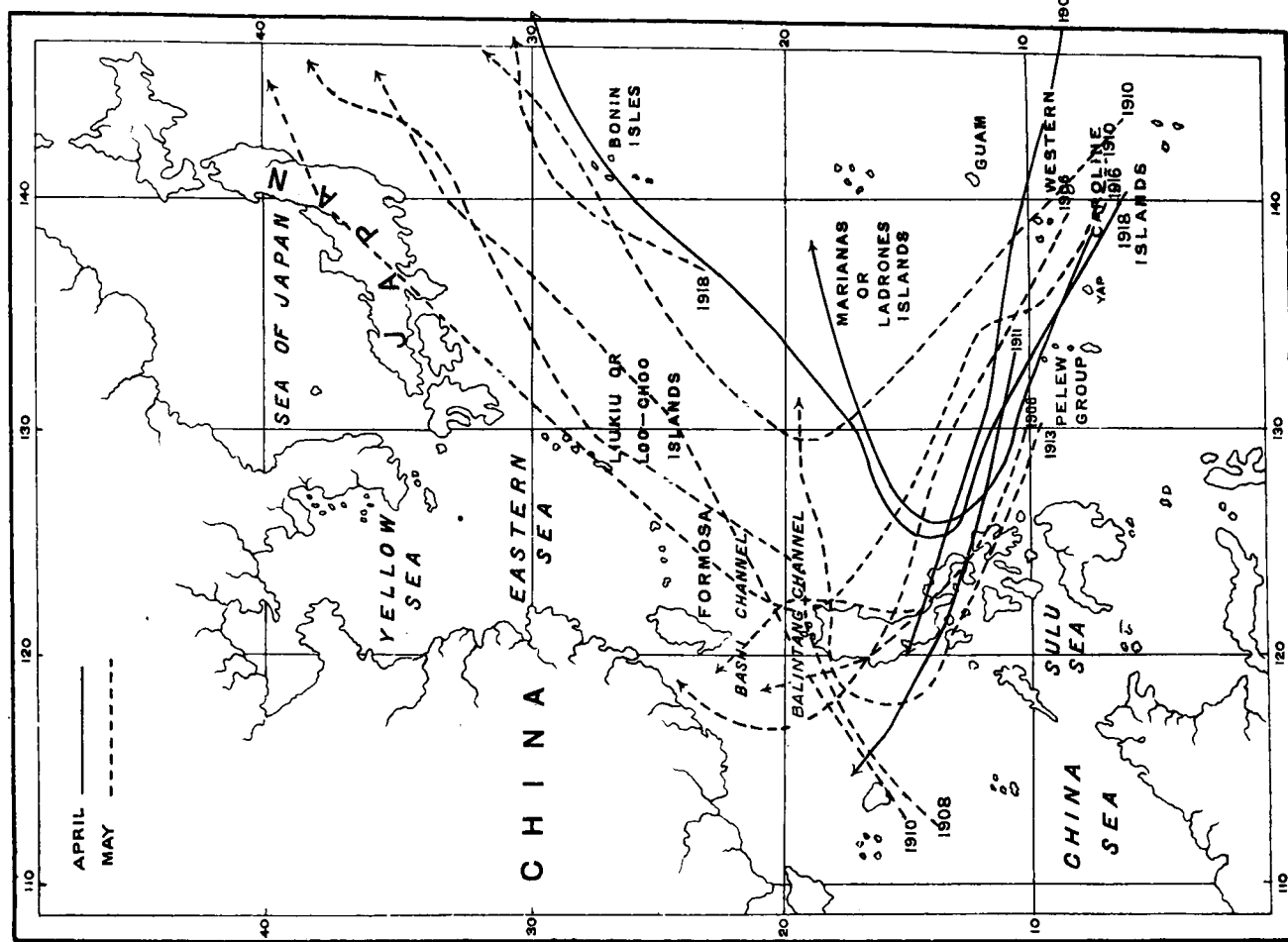
The variation in the yearly frequency between 1880 and 1918 is shown graphically on Plate XXV.

Of the five storms reported for the month of February, four were felt only in Japan, and did not affect the weather of the Philippine Archipelago. The remaining one occurred on February 9-11, 1907, and formed as a depression to the east of Formosa, from which it moved north-north-east or north-east to the north of Liukiu Islands and along the south coast of Japan. Hurricane winds were experienced in its eastern quadrant.

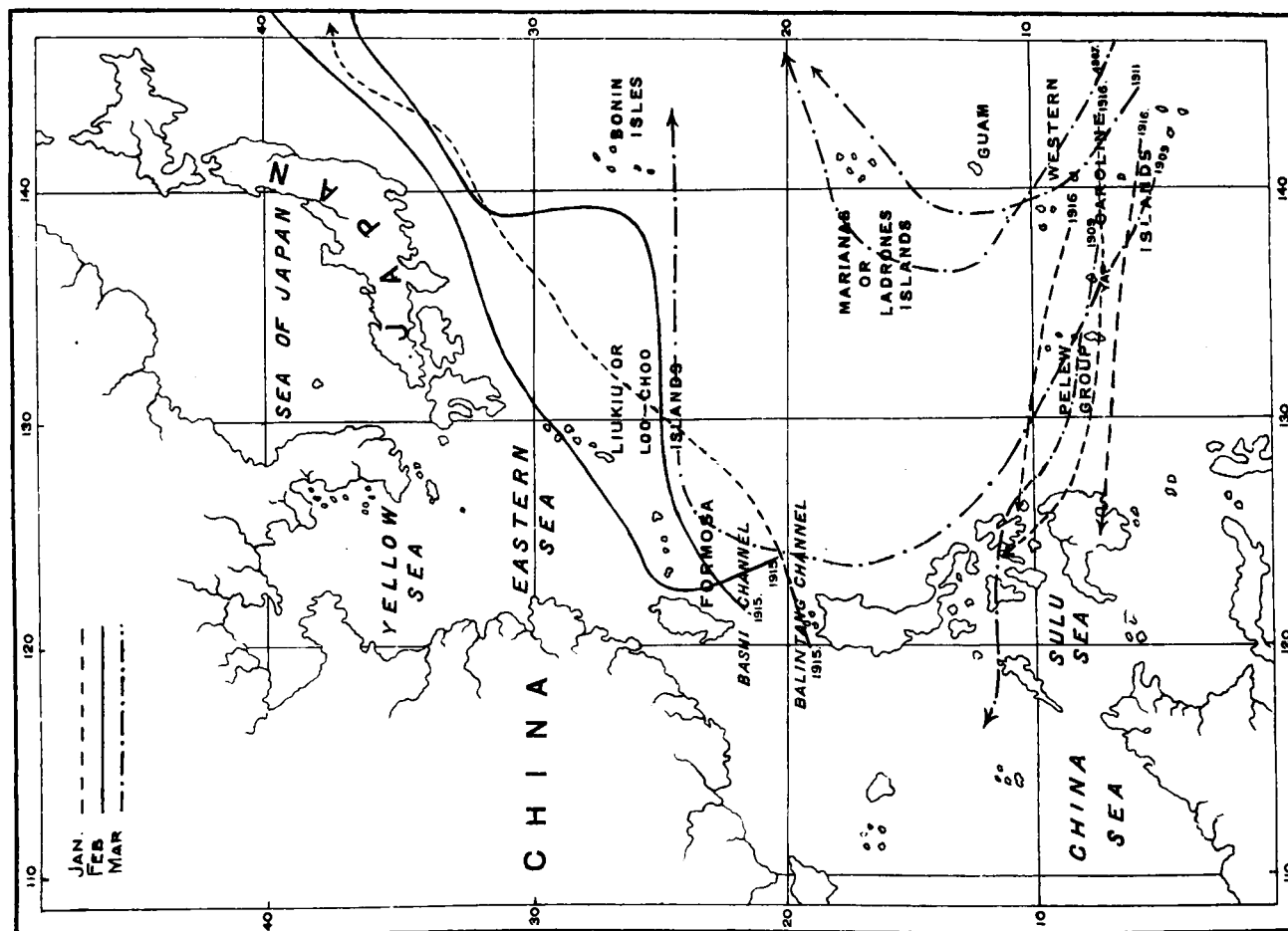
VARIATION IN YEARLY FREQUENCY OF TYPHOONS IN THE N. PACIFIC OCEAN.



TRACKS OF TYPHOONS DURING RECENT YEARS FOR
THE MONTHS OF APRIL AND MAY.



TRACKS OF TYPHOONS DURING RECENT YEARS FOR
THE MONTHS OF JANUARY FEBRUARY AND MARCH.



IV.—2. ZONES OF ORIGIN OF TROPICAL CYCLONES IN THE FAR EAST.

For the purpose of investigating the zones of origin of these storms, Algué (53, p. 22) has classified the months into three groups as follows :—

- (1). December, January, February and March constitute the first, or winter group.
- (2). April, May, October and November constitute the second, or transitional group.
- (3). June, July, August and September constitute the third, or summer group.

The prevalent zones of formation of cyclones originating east of the Philippines he gives as follows :—

First Group.—The greater part of the typhoons which develop during these months are formed in latitudes lower than 10° , but the region of formation is displaced in the beginning of December and at the end of March, moving somewhat further to the north, so that, generally speaking, the region of formation for this group is circumscribed by the parallels 12° N. and 5° N., and the meridians 145° E. and 143° E.

Second Group.—The region of formation of the typhoons of the second group is more extensive than that of the first ; it extends from 17° N. to 6° N. and from 142° E. to 129° E. Cyclones originating east of the Marianas, and therefore dangerous for those islands, usually occur in April and October.

Third Group.—The region for the third group lies between 20° N. and 8° N. and between 139° E. and 126° E.

It is worthy of note that during the month following each group there may appear typhoons that have the characteristics of those of the preceding group. Algué also gives the following information with regard to cyclones formed within the China Sea :—

The number of these baguios or cyclones is relatively insignificant when compared to the many which are formed in the Pacific, and therefore we will briefly say of them that the zone of their formation may be limited by the parallels of 5° N. and 20° N. and the meridians 112° E. and 120° E. It is to be noted, however, that those formed between the parallels 5° N. and 14° N. are few in number, the great majority originating between 14° N. and 20° N., to the west or north-west of Luzon, and almost always at a distance from Manila greater than 120 miles.

IV.—3. TRACKS OF THE PACIFIC CYCLONES.

From the charts it is evident that the paths of these storms go through a regular displacement during the course of the year.

The Pacific cyclones are now redefined as those which do not cross the meridian of 124° E. The seasonal variation of these tracks is as follows (53, p. 79) :—

Group of Months.	Mean Inclination of the 1st Branch.	Latitude of the Vertex.	Mean Inclination of the 2nd Branch.
December to March (1st Group) ..	NNW	15° — 19°	NNE
April, May, October and November (2nd Group)	NW	16° — 21°	NE
June to September (3rd Group) ..	NW by N	21° — 25°	NE by N

Pacific Cyclones of the Winter Group.—The tracks of these lie along the zone of depression between the two areas of high pressure then existing, the one in the interior of the Asiatic continent, the other over the Pacific Ocean, and the tracks are directed towards the Polar centre of low pressure which occupies part of the Behring Sea.

Pacific Cyclones of the Transitional Group.—During April and May the cyclones move in a zone bounded by the extreme isobars of the two centres of high pressure lying over the Pacific Ocean and the Asiatic Continent.

During October the tracks lie in the immense region between the Philippine Archipelago and the edge of the Pacific high pressure area. During November this zone is somewhat narrowed by reason of the development of the Asiatic centre of maximum pressure.

During all the months of the second group, the Pacific typhoons move towards the Polar depression.

Pacific Cyclones of the Summer Group. During this period the high pressure area disappears from the neighbourhood of the eastern coast of Asia, and hence the cyclones are able to penetrate into higher latitudes. The same circumstance also explains why some of these cyclones recurve as far west as 124° E. In general the storms recurve much nearer to the Philippines than do those of the first and second group. This does not apply to the latter half of September, when the majority of the vertices are between 129° and 132° E., but during the rest of the period, almost all of the tracks recurve west of 129° E. All the Pacific typhoons of this group move towards the northern area of depression.

IV.—4. TRACKS AND VELOCITY OF TRANSLATION OF THE CHINA SEA CYCLONES.

These are now redefined as those which, during part or the whole of their course, are west of 124° E. Their trajectories are quite different from those detailed above.

Tracks during the First Group.—No cyclone at this time of year follows a parabolic track, unless the recurve takes place in the interior of the Asiatic Continent (an occurrence which appears possible, but has not yet been conclusively established). Cyclones of this group retain their original direction, west by north, in the south of the China Sea; the storm centres of December and January reach the mainland in Cochin China or in South Annam; those of February and March somewhat farther to the north, and therefore almost exclusively in Annam.

The China Sea typhoons of this period travel through the lower latitudes, which, under normal conditions, are occupied by the outermost isobars belonging to the Siberian high pressure area. It must be remarked that from January to March, as the area of high pressure moves back into the interior of Asia, it loses its intensity; and furthermore, as the outermost isobars advance northwards, the typhoon tracks become broader and approach the centre of low pressure which has been travelling north ever since January.

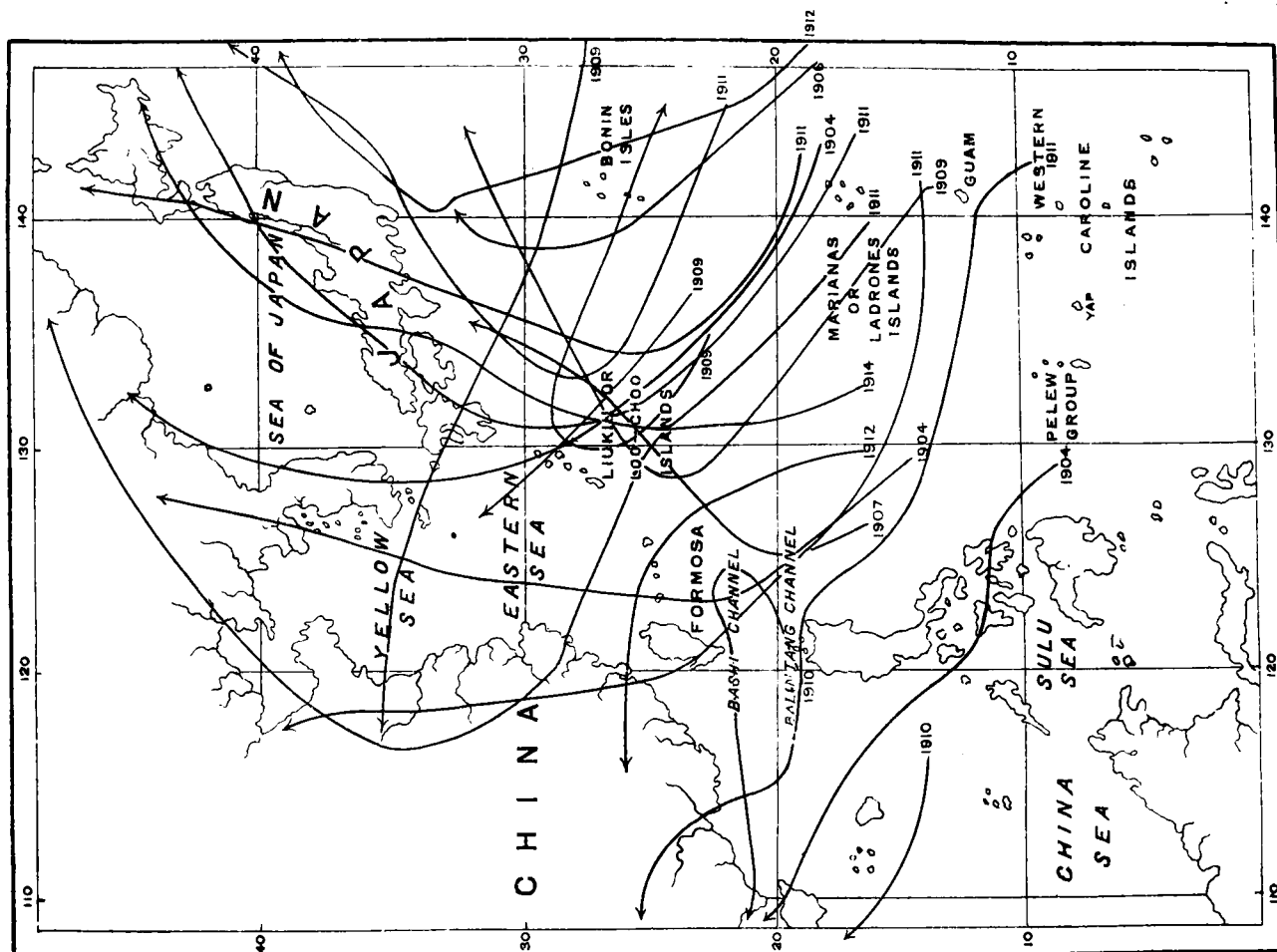
Tracks during the Second Group.—The mean direction of motion of the China Sea typhoons during April and May is north-west by west. Those of April reach the continent to the north of Annam, those of May pass over the Gulf of Tonkin and the Straits of Hainan; but towards the end of the month some of them strike the coast between Macao and the Straits of Hainan.

The October storms, especially those of the first days, reach as far north as Hong Kong; the remainder strike the coast—in accordance with the advance of the season—farther south, so that some of them reach Asia to the south of the Gulf of Tonkin. The original direction of the cyclones in October is west-north-west; the November storms have from the first a direction west by north, and reach the coast of Annam; most probably no cyclone has ever reached North China during November. The April and May cyclones have their trajectories to the south of the region corresponding to the 760 millimetre (29.92 inches) isobar of the inner Asiatic centre of high pressure.

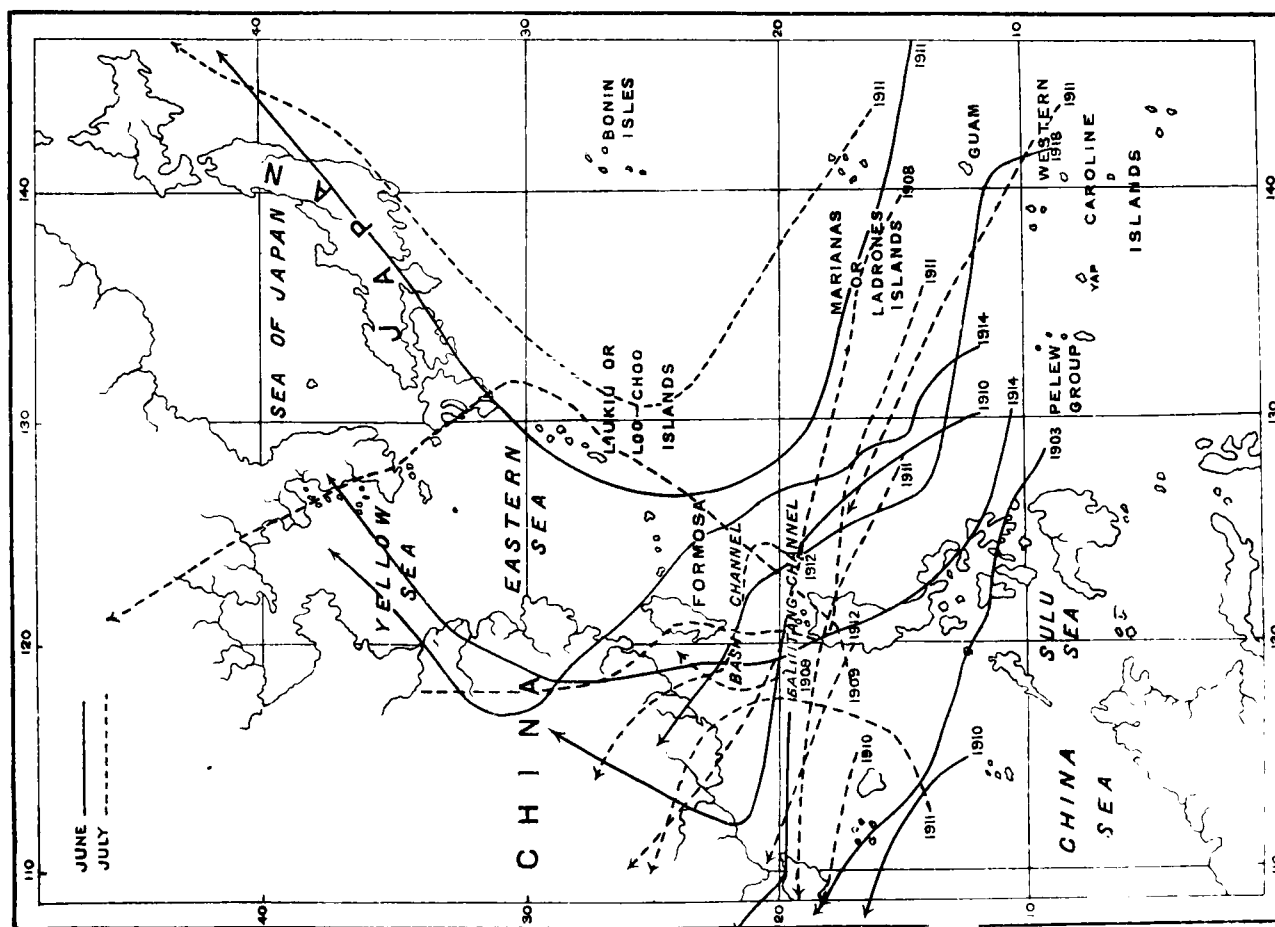
As the Asiatic high pressure area develops from October to November, the typhoons of the China Sea follow more and more southerly tracks, their trajectories, however, always being influenced by changes in the distribution of pressure over India.

Tracks during the Third Group.—The cyclones of June move toward north-west; they reach the continent generally on the south coast of China, from Breaker Point to the Straits of Hainan; some recurve south of the Formosa Channel. The cyclones

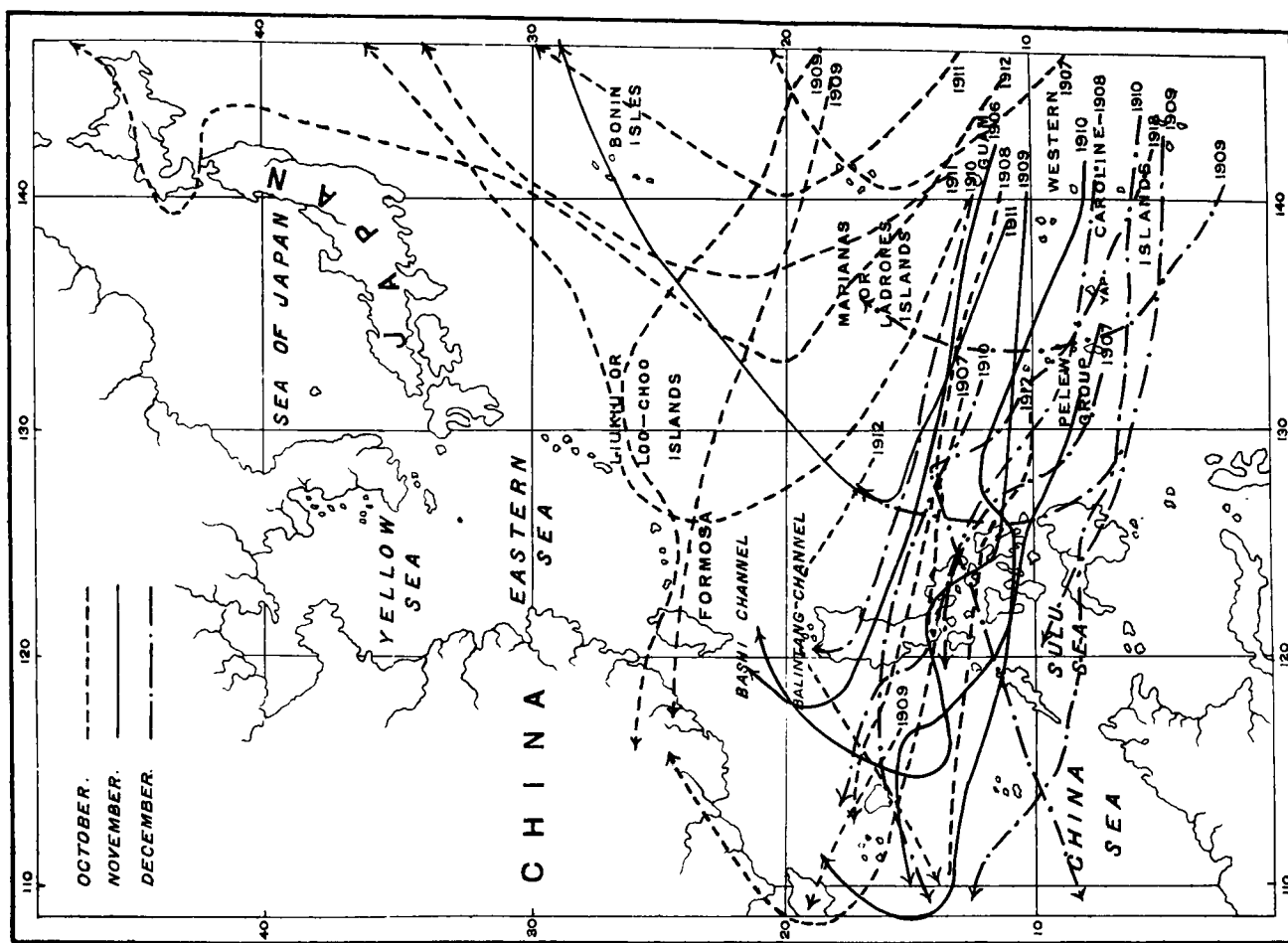
TRACKS OF TYPHOONS DURING RECENT YEARS FOR
THE MONTH OF AUGUST.



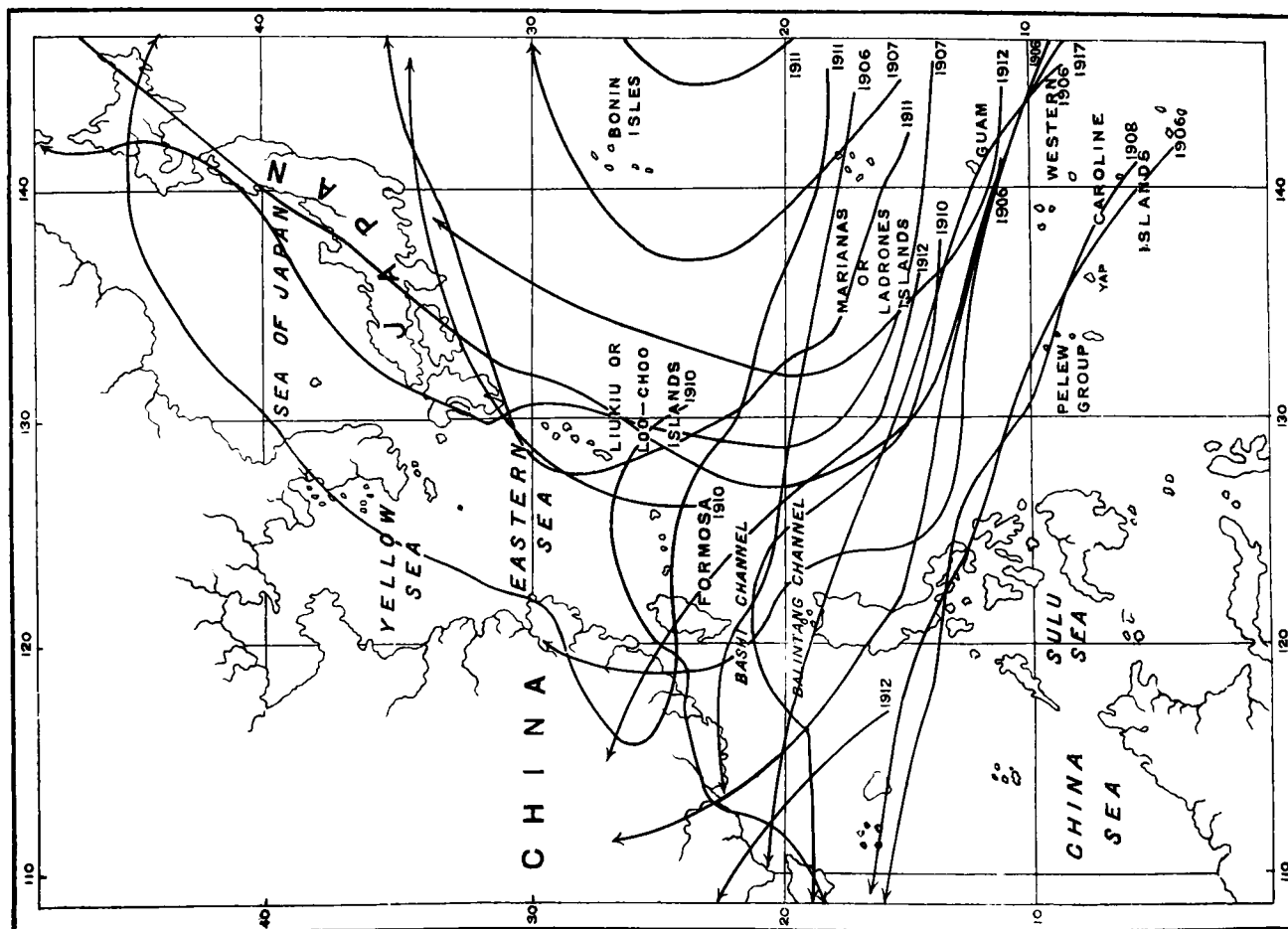
TRACKS OF TYPHOONS DURING RECENT YEARS FOR
THE MONTHS OF JUNE AND JULY.



TRACKS OF TYPHOONS DURING RECENT YEARS FOR
THE MONTHS OF OCTOBER, NOVEMBER & DECEMBER.



TRACKS OF TYPHOONS DURING RECENT YEARS FOR
THE MONTH OF SEPTEMBER.



of July have also a north-westerly track at first. They fall into three classes: those of the first, like June storms, enter the continent by the south of China; those of the second travel along the coast between Amoy and Shanghai, from whence certain storms taking a north-north-eastern direction, recurve into the Yellow Sea; those of the third group recurve abreast of Formosa and then move in the direction of the Japan Sea.

The August cyclones have a north-westerly direction from their beginning. Generally speaking they may be considered as belonging to the July class.

The typhoons of September, which originally move towards north-west by west, usually belong to the first or third class of July cyclones.

Furthermore, in proportion as the continental centre of low pressure recedes towards the north, the northerly inclination of these tracks increases, reaching its maximum at the end of August and the beginning of September. During the second half of September the depression advances again into lower latitudes, and to this movement corresponds a diminution of the northern inclination of the typhoon trajectories, which inclination attains its minimum during the months of the first group.

The fact that some of the cyclones of July recurve along a trajectory which has a strong inclination towards the north, and reach the Yellow Sea, may find its explanation in the presence of a very small area of low pressure in Siberia, and this agrees with the well-known statement that "cyclones turn toward the areas of depression."

Recapitulating what has been said with regard to the trajectories of the China Sea typhoons, we find that the zone of origin in December, January, February and March lies between 5° N. and 20° N.; they reach the mainland between 8° N. and 15° N.

The zone of origin for typhoons of the months of the second group lies between 6° N. and 17° N.; they land on the Asiatic coast between 12° N. and 23° N.

For the third group the zone of origin is between 8° N. and 20° N.; they strike the continent between 18° N. and 30° N.

For further details as to tracks, etc., see Chapter VIII of Algué's work (53).

Velocity of Translation of Cyclones.—Cyclones may be divided, according to the velocity of their progressive movement, into rapid, regularly progressive, slow and stationary. This classification, however, is not a general or absolute one, but relative and particular for each region, because the same cyclone may move slowly while forming or while remaining in lower latitudes until its recurve point is reached; during the recurve the storm may be practically stationary, or move with a very small velocity, while on the second branch of the track there is a systematic increase of velocity with latitude.

A typhoon is said to move rapidly in the Philippines if its velocity exceeds 12 nautical miles an hour; it moves with a regular velocity when travelling from 6 to 12 miles an hour, and its progress is slow if the rate is below six miles an hour.

Of typhoons which have been studied up to date, 180 have crossed the Archipelago or the adjoining region of the ocean with regular velocity, 40 with rapid and 30 with small speed, while a few remained stationary for several days (53, p. 92).

IV—5. THE CLASSIFICATION OF CYCLONES.

Hitherto the main classification has been that of Pacific and China Sea typhoons. These classes include many different types of storm, and admit of further sub-division.

(a) *The cyclones of the Pacific* include:—

- (1) The cyclones of Japan, which originate in the Pacific and recurve before reaching 124° E. longitude, after which they traverse the islands of Japan; they develop from June to November inclusive.
- (2) Cyclones of the Magallanes, which originate and recurve in the Pacific, and generally cross the region of the Magalhaes or Magallanes Archipelago, a scattered group of islands to the north of the Mariana Islands. These storms develop from December to May and in October and November.

(b) *The cyclones of the China Sea* include :—

- (1) Typhoons of Mindanao, which pass over this island from December to March.
- (2) Typhoons of the Visayas, which cross the central Philippines in a north-westerly direction and generally occur during the months of the 2nd group—especially in April and May, and sometimes in December.
- (3) Typhoons of Luzon, which pass over this island or very close to the north of it in a north-westerly direction. They belong to the months of the 3rd group, but also appear in October and November.
- (4) Typhoons of Formosa, which pass in a north-westerly direction over Formosa. They usually reach the mainland, but may recurve southwards into the middle of the China Sea.

(c) Occasionally typhoons originate and run their course entirely within the China Sea itself, being usually formed north of 10° N. latitude. These must form a separate class and are known as typhoons which belong entirely to the China Sea.

(d) A fourth main section should be known as “cyclones of the Philippines,” strictly speaking.

This section includes the typhoons of the Visayas and of Luzon that do not reach the Asiatic continent or recurve in the China Sea in order to reach the Archipelago again. They may recurve in the interior of the Archipelago itself.

In his final classification Algué reduces the paths of all these cyclones to eleven principal types, and gives a graphic representation of the veering and intensity of the winds which are to be expected in Manila with cyclones of each one of these types. These charts are shown on Plates XVII and XVIII of his book, and short descriptions can be seen on page 92.

The following table gives the months of occurrence of storms of the above types :—

----	Months of Occurrence.
A1. Cyclones of Japan	June to November.
A2. Cyclones of the Magallanes	Groups 1 and 2, especially December and January.
B1. Cyclones of Mindanao	Groups 1 and 2.
B2. Cyclones of the Visayas	Groups 1 and 2.
B3. Cyclones of Luzon.. .. .	Group 3, and sometimes October and November.
B4. Cyclones of Formosa	Almost confined to September.
C. Cyclones confined to the China Sea	Group 3.
D. Cyclones of the Philippines strictly speaking	July to November.

IV.—6. RAIN AND CLOUD AREAS IN TYPHOONS.

The amount of rain is dependent on the degree of saturation with moisture of the converging air, and this in turn is greatly influenced by local conditions. The velocity of the cyclonic winds also has a very great influence, as is clearly shown by comparing the rainfall in cyclones which pass to the north of Manila with those passing to the south.

It is well known that the latter, even when nearer to the city than the north-passing storms, are of a much less violent nature, both with regard to wind and precipitation. The reason for this is clear when it is remembered that with a north-passing storm the backing of the wind is from north-north-west or north to north-west, south-west, and sometimes perhaps to south-east, and that these winds come almost directly from the China Sea and meet with very few obstacles. Consequently they arrive on the shores of the Archipelago saturated with aqueous vapour and give copious precipitation of water.

On the other hand, the south-passing storms cause the wind to veer from north-east to north-north-east, east-south-east and south, which winds are practically all land winds; in addition, the first three have crossed the mountain range which runs through Luzon from north to south, and, in the case of the south wind, the mountain range of Sungay.

The following tables have been prepared by Algué for all the cyclones which are on record as having been observed to pass near to Manila. The wind direction and corresponding quantities of rain were observed every three hours. Expressing the quantity of rain belonging to each direction of wind in percentages of the whole amount, Father Algué finds the following results. The great preponderance of rain brought by south-south-west to west-north-west winds is clearly illustrated by the first table. Cyclones passing on the south side give currents which have all passed over mountains before reaching Manila, and hence there is less variation in the rainfall from the different quarters.

TYPHOONS PASSING NORTH OF MANILA.

Direction of the wind.	Percentage of rain.
NNW.—NW.—WNW.	1·3
WNW.—W.—WSW.	32·5
WSW.—SW.—SSW.	57·9
SSW.—S.—SSE.	6·2
SE.	2·1

TYPHOONS PASSING SOUTH OF MANILA.

Direction of the wind.	Percentage of rain.
NW.—NNW.	34·3
N.	15·2
NNE.	11·8
NE.	3·5
ENE.	2·4
E.	20·3
ESE.	4·9
SE.—SSW.	7·6

Father Algué does not indicate whether in the first table half the rain brought by the west-north-west wind is recorded in the first line and the other half in the second, but the trend of the records is independent of this ambiguity.

The Form and Extension of the Rain and Cloud Areas.—"These regions do not always strictly coincide with one another nor are they concentric with the area of low pressure. In the tropics the vortex sometimes lies behind the centre of the zone of clouds and rain, while on the contrary these centres may fall behind the vortex. In shape these areas are not circular, but nearly always elliptical. In general, the cloud zone, although it is in some manner concentric with the rain area, is not co-extensive with it, but is much larger.

" The extension of the cloud zone is sometimes extraordinarily large; nevertheless it seldom stretches over a greater distance than 500 miles from the centre. The average length of the major axis of the elliptical cloud zone may be taken as being 700 nautical miles. . . . The area of central calm is generally free from rain and even from clouds." (53, p. 56.)

IV.—7. PRECURSORY SIGNS OF TYPHOONS.

The first barometric indication of the approach of a typhoon is the disturbance of the diurnal range. In these low latitudes the barometer, during settled weather, shows decided maxima about 10 a.m. and 10 p.m., with corresponding minima at 4 p.m. and 4 a.m.

If the forenoon maximum is appreciably below its normal reading (29.85 in.), or if the descent between this and the afternoon minimum is markedly greater than one-tenth of an inch, the weather should be watched with great care. Several successive days of light variable winds and calms; a period of hot, sultry weather, increasing moisture of the atmosphere, shown by the diminishing difference between the wet and dry-bulb thermometer; increasing amount of cloud and an ominous heaving of the sea,—all of these are conditions forerunning the occurrence of a typhoon.

The direction of translation and the intensity of a typhoon are difficult to determine from observations at a single station. This uncertainty arises from the fact that, when the vortex is so far away that only the outermost isobars reach the station, there is no way of determining definitely its depth and intensity. It may be far away and of great depth, or near by and of comparatively gentle gradient. The angular elevation of the distant cloud bank and the rate of increase in the velocity of the winds are of great help in this connection, above all when the distant storm is well developed; but they do not altogether eliminate the uncertainty.

The difficulty lies ultimately in the geographical position of the Philippines. The islands are but a small group, having on their east a wide expanse of ocean reaching to the Ladrões, within which area the typhoons originate. Thus, while the Philippines form a secure outpost for the China coasts, they themselves cannot be so well guarded on the east. The new stations of Guam and Yap have added some security, and it is hoped that soon there will be a line of stations east through the Carolines and also northwards through the Ladrões to Bonin Island and Japan. Such stations would furnish valuable information as to the origin and formation of typhoons.

Typical and noteworthy typhoons which have occurred during recent years will now be described, the accounts and plates having been collected and summarised, in most cases, from the *Monthly Bulletin of the Philippines Weather Bureau*.

IV.—8. "THE CAPIZ TYPHOON." JUNE 2-7, 1903.

This typhoon is so-called because it was the town and province of Capiz which suffered the greatest ravages from its violence.

This depression, which crossed the Visayas Islands on the 2nd and 3rd with a high velocity, has placed once more in evidence the great danger to which small craft are exposed in crossing inter-island seas after the middle of May, since this is the beginning of the period when those rapidly moving typhoons of small diameter, but perfect development, usually spring up.

Origin and Formation.—From the end of May to the 5th of June an extensive area of low pressure lay over the southern part of the Archipelago; the low area was without any well-determined nucleus, and was slightly fluctuating in its character, being very little affected by the passing of the typhoon on the 2nd and 3rd. This suggests that the said typhoon was nothing more than a secondary centre, which took its origin in the extreme eastern portion of the large area of low pressure in the same way that tornadoes are formed in the outer zones of large depressions.

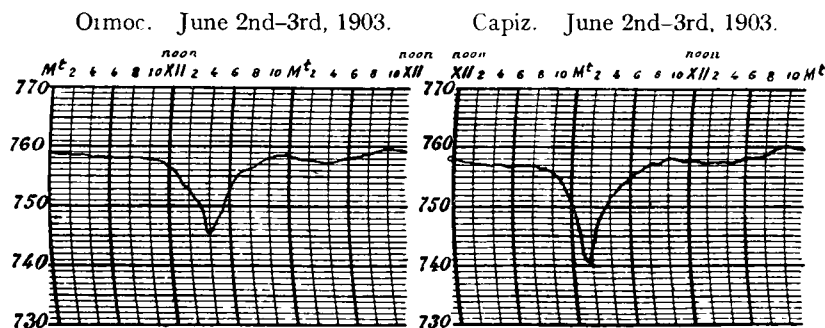
The smallness of diameter of this typhoon, its velocity and terrible violence, gave it much of the nature of a tornado; although considering the length of the path over which it preserved its energy, crossing the China Sea and renewing in Tonkin on the 7th the ravages committed in the Visayas on the 2nd, it was endowed likewise with the character of a well-developed typhoon.

Path.—The typhoon probably formed to the east of Surigao on the afternoon of June 1st. Between 10 and 11 a.m. on the 2nd the centre was found to be north-north-east of Surigao; its direction of movement at this time was west-north-west. It afterwards cut the Island of Leyte almost midway, then the extreme northern part of Zebu, and finally swept across the whole of northern Panay. At midday on the 3rd it was near the meridian 120° E., entering the China Sea in latitude 13° 30' N.

Once in the China Sea it inclined slowly northwards until it struck Tonkin in latitude 20° N. ; thus, after passing the Paracels its direction must already have been north-west. It is not known whether it touched the south-western part of Hanan.

The storm entered Tonkin on the morning of the 7th, when the north-west winds began to blow with increasing force until midday, then, after a short calm, the winds started from south-west, with such fury that the whole town of Nam-dinh was laid in ruins. Over 2,000 deaths occurred in Western Tonkin.

The barograms* of Ormoc and Capiz are shown below:—



Velocity of Translation.—In passing between Surigao and Sama the velocity could not have been much below 13 miles an hour ; in passing over the Island of Leyte the velocity seems to have decreased, since in passing over the 115 miles which separate Capiz and Ormoc, it occupied between 9 and 10 hours, which gives a velocity of a little over 11 miles an hour. The speed diminished still further in the China Sea, especially during the northward recurve ; it did not reach the Asiatic continent until the 7th, thus taking four days in making a distance of 950 miles, the average velocity being therefore 10 m.p.h.

Body of the Storm.—Judging from the veering of the winds, both to the north and south of the trajectory, and from the barograms of Capiz and Ormoc, the body of the storm was of modest dimensions and small diameter, and the barometric gradient in the interior must have been very sharp. The curve of Capiz shows that when the typhoon passed that point the gradient was greater in front of the storm than in the rear, as if the isobars, by their onward movement, were compressed anteriorly while broadening out to the rear. The vortex did not actually pass over Capiz, but crossed very near it to the south, as is shown by the fact that the force of the wind did not decrease during the veering of the currents, but was maintained with increasing power, as the winds swung from north-west to east and from south-east to south-south-west.

This typhoon gives another example of the great importance of cirrus and cirro-stratus cloud observations as precursory signs. At Zebu, Iliolo and Tacloban convergence of the clouds was observed to east-south-east before either barometer or winds gave any reliable indication of the storm.

From observations from various stations it can be seen that the storm or rain area of the typhoon was generally distributed around the centre within a radius of a little over 120 miles. The rains that resulted from the passage of the typhoon lasted from ten to twelve hours at the stations nearest to the trajectory ; at those situated beyond the above radius there was no rain at all, or, if it rained, it was only as a result of some local thunderstorm, as was the case at Manila.

IV.—9. TYPHOON OF APRIL 20-30, 1905.

According to a communication from Ponapi, the largest of the Eastern Carolines, these islands suffered a terrible visitation from this cyclone on April 20th. At noon of that day the storm broke over Ponapi with tremendous fury, and of the 2,150 houses on the island only one remained standing.

* From the *Monthly Bulletin of the Philippines Weather Bureau*.

When the cyclone visited Ponapi it was already well developed, for it had caused great destruction in Kursal Island, which is 300 miles east-south-east of Ponapi, in Pingelap Island also to the east-south-east, and in Mokil, 90 miles to the east by south-east.

This storm was most exceptional on account of its extreme easterly point of origin, since the majority of the Carolines storms form much farther to westwards, usually between West and East Carolines.

After its destructive course through the East Carolines, the cyclone was next met with by the transport *Thomas*, bound for Manila from San Francisco. The ship's barometer began to fall on April 22nd, when the vortex must have been 500 miles distant. The wind grew stronger from the north-east at noon on the 25th, and the barometer registered 755·21 mm. (29·73 in.) The ship's position was 138° 16' E., 13° 51' N. At 4.30 p.m. of the same day the barometer reading was 754·21 mm. (29·70 in.)

At midday of the 26th (133° 05' E., 13° 39' N.) the barometer read 752·51 mm. (29·63 in.), and the wind continued strong from north-east, with severe squalls; the wind force reached force 8 during the afternoon.

From the 26th to the 27th the wind veered to east-south-east, and blew with force 10 from that direction at noon of the 27th. The squalls became more frequent and more violent. Shortly after midnight of the 27th the ship was at its minimum distance from the vortex, which was to west-south-west. The barometer reached 746·51 mm. (29·39 in.) at 4.30 a.m. of the 28th, and the wind changed to south-south-east, force 10, with violent squalls.

In Guam (West Carolines) the squalls began on April 23, and the cyclone passed south of this station on the same day, at a distance of 210 miles. The advance isobars of the cyclone entered the Archipelago during the night of April 26, and its progress is seen from the notices and warnings issued:—

28th at 11 a.m.—“The barometers continued to fall, especially in south-east Luzon and the East Visayas.”

5 p.m. same day.—“The typhoon has entered the south-east extremity of Luzon and is now to be found probably between Albay and Nueva Caceres, moving west-north-west.”

29th, 11 a.m.—“The barometer is falling in Luzon and rising in the eastern Visayas. The typhoon is in Tayabas, and drawing near to the capital.”

29th, 11.50 a.m.—“Typhoon will pass Manila to north, at a short distance.”

29th, 3.30 p.m.—“Crossing Luzon through the provinces of Nueva Ecija, Tailac and Zambales. . . . It is probable that when the centre reaches the China Sea it will recurve north towards Formosa or the Balington Channel.”

29th, 4 p.m. (Cable to Hong-Kong, Shanghai, etc.).—“The typhoon crossing Luzon north of Manila and will reach China Sea near parallel 16° to-night.”

All these warnings were confirmed by observations made at different points in the Archipelago.

In Caraga, which is the most eastern station of the Islands, and entirely open to the Pacific, the sea began to change on the 26th, thus giving the first indications of the cyclone, then more than 500 miles away.

In Borogan, the most easterly station of the Visayas, the barometer began to fall on the afternoon of the 26th and the sea changed so rapidly that by morning of the 27th it was already heavy and boisterous with a strong swell. Squalls were frequent, and the winds had been first from north-east and later from south-east or south-south-east. At noon on the 28th the vortex passed the meridian of this station.

From a table of observations at various stations (see p. 126 of the April Bulletin) several important deductions can be made:—

(1) That the time of minimum pressure does not always correspond to that of minimum distance from the vortex, for even during the passage of the depression the ordinary atmospheric undulations often exert an influence on the barometric height. The value of these variations must be kept in order to estimate exactly the lowering of pressure due to the cyclone itself.

(2) The typhoon was deeper before the vortex touched the Archipelago than afterwards. The energy of the storm must have fallen off notably in crossing Luzon; it is known to have been very violent when it passed Baler, and comparatively weak on leaving the Island and in the China Sea.

(3) The force of the wind was most variable around the vortex and at equal distances from it; it reached hurricane force only in the immediate vicinity.

The Cyclonic Swell.—Observations made in the harbour of Gubat, a town on the eastern coast of Sorsogon, open to the Pacific, showed that on the morning of April 27th, when the barometer began to fall, the winds blew first from the north, then from north-north-west and north-west successively; the swell came from the north-east as early as 8 a.m., when the vortex must have been more than 400 miles distant.

It was of the utmost importance to know whether the approaching cyclone would pass on the north or on the south; this could not be determined from the fall of the barometer, nor from the direction of the winds, nor from the movement of the lower clouds, but only from the change of direction of the swell, since in a sea so open to the east as that of Gubat, the cyclonic swell could advance unimpeded from the vortex, and hence the latter must have been in the direction of the first quadrant from Gubat on the 27th. This cyclonic swell is so reliable and so valuable as a precursory sign to seamen who have to visit the eastern coasts of Luzon, Samai, Leyte, Bohol, Dinagat and Mindanao that it is impossible to exaggerate its importance.

In the above observations at Gubat it was noticed that the swell gradually changed its direction with the fall of the barometer, turning to north-north-east and ultimately to north (when the cyclone passed to north), which confirms what has often been stated in the publications of the Observatory (53, pp. 164-8).

Rain area of the Storm.—The storm brought copious rains, which began at the more easterly stations as early as April 26. The rainfall was very unequally distributed round the centre. When the centre penetrated the Archipelago the rain area spread out greatly in front and less towards the south; whereas when the centre was well within the Island of Luzon, and when it emerged upon the China Sea the rain area became smaller in front and more extended towards the south.

Velocity of the Storm.—The velocity decreased steadily along the course, as in the case of the storm of June 2-7, 1903. Thus:—

From the 25th to 26th the velocity was 12·1 miles an hour.

„	„	26th	„	27th	„	„	11·5	„	„
„	„	27th	„	28th	„	„	10·0	„	„
„	„	28th	„	29th	„	„	8·8	„	„

and finally, in crossing Luzon from the 29th to 30th, the velocity was only 7·1 miles an hour.

There is very little information available about the path of the storm in the China Sea and afterwards.

IV.—10. STORM OF DECEMBER 15-18, 1905.

During December 15, pressure began to rise slowly, especially in the east and south of the Archipelago; but early next morning the stations along the east registered a slight fall of pressure, which proved to be the advanced isobars of a Guam depression. On the 17th the fall was more general and more marked, revealing at the same time a gradient towards the south-east. Judging from the form of the first isobars the path of the storm centre seemed to be well inclined towards the west; hence the observers of the stations to east and south were promptly warned, while the storm was still far out in the Pacific.

Next morning the storm was east of Luzon, and before noon it was evident that the centre was passing north of the parallel of Manila; as its approach to Luzon was very slow its course must have been north-west, probably turning northwards.

Here again the element of uncertainty which enters into the forecasting of typhoons advancing from the distant Pacific made it impossible to say from the movement whether it would touch Luzon or not.

IV.—11. THE TYPHOON OF JANUARY 9–11, 1907.

It is well known that true typhoons during January are exceedingly rare. A still rarer occurrence is that a January storm should enter the Islands further north than the tenth parallel.

The storm to be discussed was a very striking one owing to the violence with which it raged in the Visayas on the 9th, 10th and 11th. The typhoon was formed to the south of Guam and south-east of Yap on January 3 and 4. During the morning of the 5th it had already passed south of Yap, moving in a west by north direction.

Remarkably low pressure persisted at Guam and Yap on the 6th, 7th, and 8th, and since on these days pressure was also low in the southern part of the Archipelago it was clear that in the exterior part of this typhoon a widespread area of low pressure simultaneously covered the whole extent of the Pacific Ocean between the Philippines and the western Carolines. Within this area another cyclonic centre formed on the 9th, and on the 10th this lay near Samar, tending to cross the Visayas along the 12th parallel.

The cyclonic vortex penetrated into the Archipelago at noon of January 10, south of, and very near to, Borongan, where the barometer fell to 739·24 millimetres (29·10 in.). This minimum was registered at 12·15 p.m., with hurricane winds from north by east, which, after a relative calm of about five minutes, during which the sky cleared, shifted over to south-east.

An interesting account of the storm was sent by the ship *Liscum*, which was anchored at Santa Rita. Here the barometric minimum was still lower, being 735·6 millimetres (28·96 in.) at 3 p.m., with hurricane winds from north-north-east. Special attention is called to the fact that a heavy hailstorm occurred some two hours previous to the passing of the vortex.

After having passed Santa Rita, the typhoon resumed its westerly direction, as is proved by the fact that it passed Ormoc at a much greater distance than it did Tacloban.

It is difficult to follow the course of the typhoon from the north of Negros to the Jolo Sea, and still more so from the latter to the China Sea.

On Plate XXIX a dotted line indicates its probable path in these parts. The same plate also exhibits the great deformation which the storm had undergone up to 6 a.m. of the 11th, which deformation was augmented considerably by 2 p.m. of the same day, as is shown by the isobars for that hour. There is no information indicating that the winds attained hurricane force in any part of the Island of Panay; nevertheless it is not thought that the typhoon filled up within the Archipelago, but that it penetrated into the China Sea, since reports from Cullion gave, for the 12th, unsettled weather with fresh east-north-east winds in the morning and east-south-east in the afternoon.

It is thought that after passing the north of Negros the disturbance did not regain the form of a real typhoon, but pursued its course as a depression of no great importance.

IV.—12. TYPHOON OF NORTH-WESTERN LUZON, AUGUST 19TH–28TH, 1907.

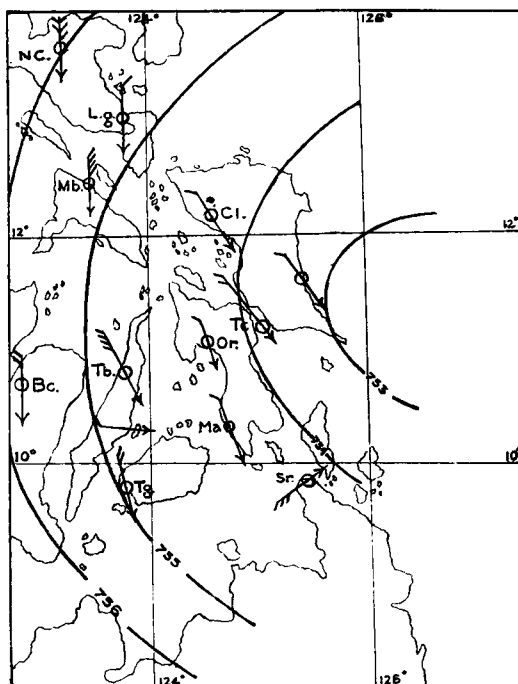
On the 19th two centres of low pressure were clearly discernible, one in the Pacific, east of the Balington Channel, the other in the China Sea to the west of northern Luzon. This latter storm was the most important for the Philippines and will be briefly discussed. The daily weather notes of the Observatory contained the following references to the storm :—

August 20, 11.50 a.m.—“The depression in the China Sea to the west of North Luzon seems to move northward.”

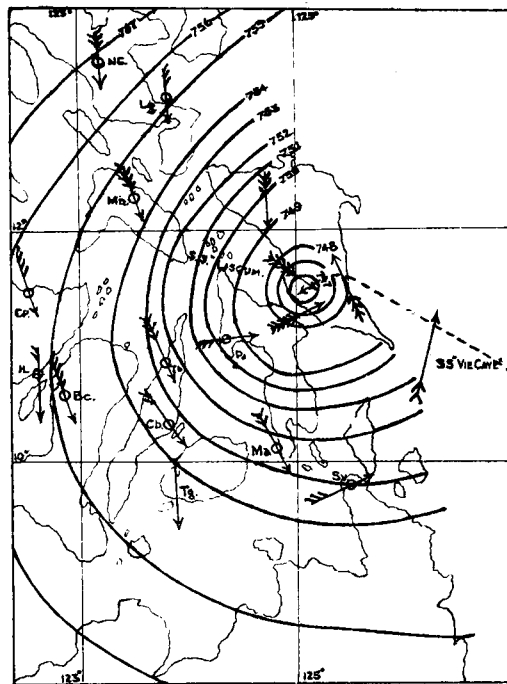
August 21, 11.50 a.m.—“The typhoon in the China Sea is increasing in intensity. It appears to move slowly north or north-north-east.”

August 22, 11.50 a.m.—“Pressure is still falling in Formosa and in northern Luzon owing to the north-north-east movement of the typhoon. The centre now lies west-north-west of Aparri, at a distance of about 150 miles, moving very slowly.”

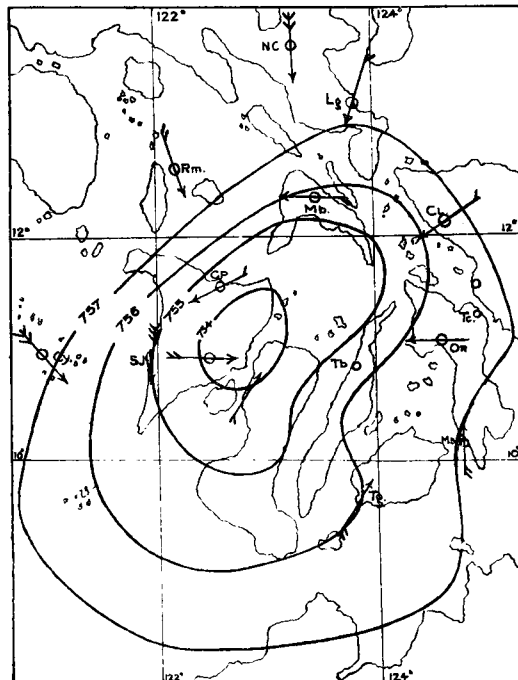
JANUARY 9th, 1907, 2 p.m.



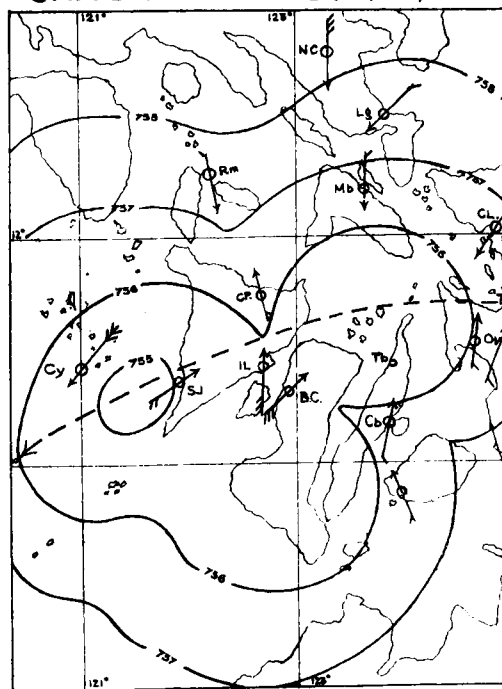
JANUARY 10th, 1907, 2 p.m.



JANUARY 11th, 1907, 6 a.m.



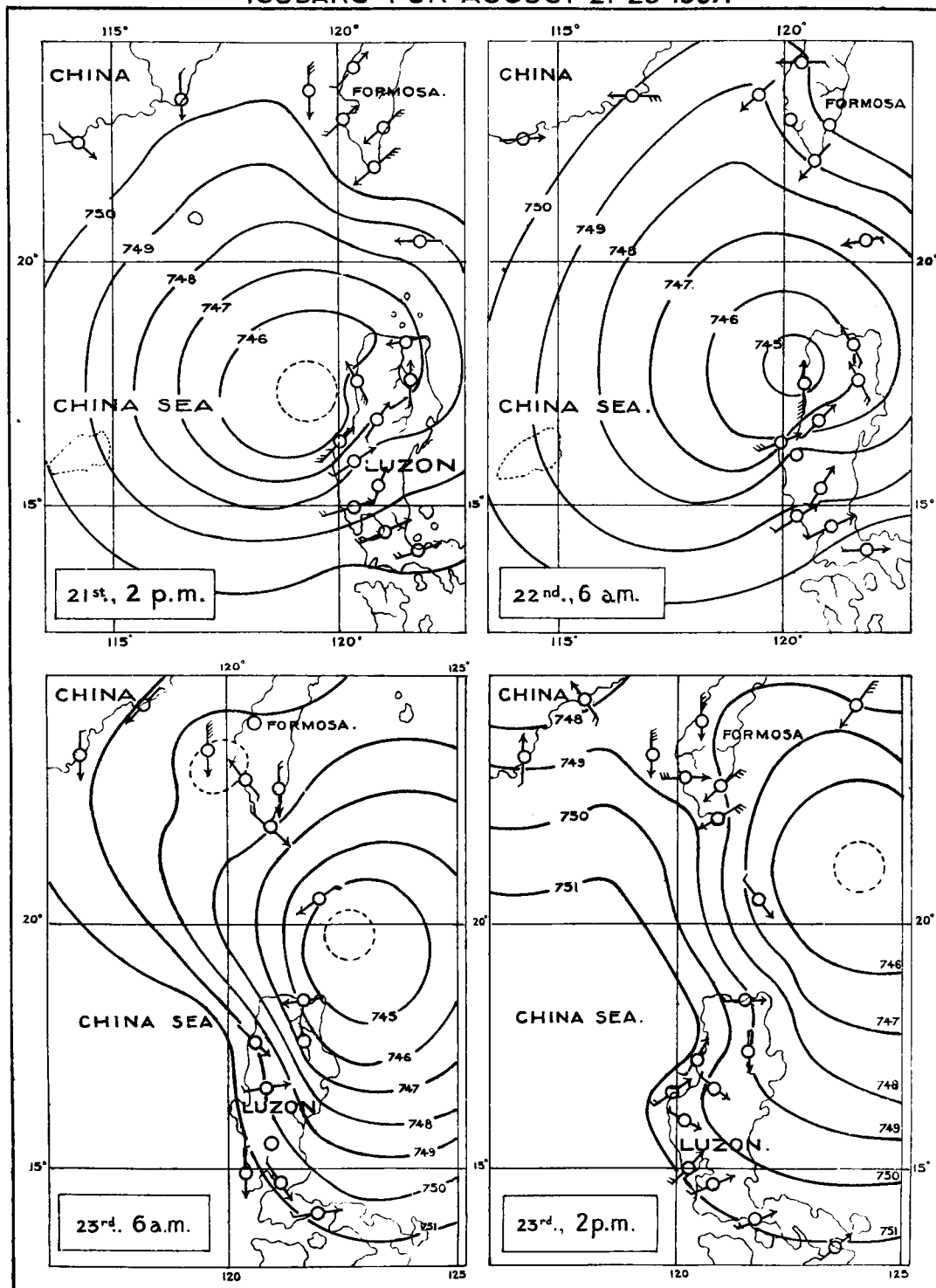
JANUARY 11th, 1907, 2 p.m.



ISOBARS OF JANUARY 9 TO 11 1907.

From "The Philippine Monthly Bulletin" January, 1907.

ISOBARS FOR AUGUST 21-23 1907.



From "The Philippine Monthly Bulletin" August 1907.

Plate XXX shows the isobars and approximate position of the cyclonic centre at 2 p.m. of the 21st, 6 a.m. of the 22nd, 6 a.m. and 2 p.m. of the 23rd.

At Vigan the south-south-east, south and south-south-west winds were of hurricane force and did enormous damage. The lowest barometer reading was 743.3 millimetres (29.26 in.) and occurred at 5 a.m. of August 22.

The typhoon advanced in a north-easterly direction and passed north-west of Aparri on the evening of August 22. At the latter station the absolute minimum was 744.6 millimetres (29.32 in.).

The minimum at Aparri differed from that at Vigan by only 1.3 millimetres. It is very remarkable that at the former station the winds acquired very little force, while at the latter they attained destructive violence.

B.—REVOLVING STORMS OF THE SOUTH PACIFIC OCEAN.

The revolving storms occurring in the South Pacific have not been so fully described as those in other oceans. They are of comparatively rare occurrence, except between Australia and the Paumotu Islands. East of these Islands, towards the west coast of America, true cyclonic storms are almost unknown south of the equator.

The storms of the South Pacific Ocean fall into two main classes. The first comprises those of the Islands of Polynesia, and the other the Australian hurricanes, which again fall into two sub-divisions :—

- (1). Those of the Coral Sea, between Queensland and the Fiji Islands.
- (2). Those of north-west Australia which, strictly speaking, belong to the South Indian Ocean, but which will be discussed here together with those of north-east Australia.

The inter-island hurricanes are experienced in great severity among the Fiji, Tonga and Samoa groups and also among the New Hebrides.

In a short treatise published by E. Knipping (60), formerly Director of the Meteorological Observatory at Tokyo, Japan, it is stated that of 125 cyclonic storms of which particulars had been obtained, the tracks of 74 passed through the Samoa, Fiji and Tonga groups, 40 passed westward of that area, through the Coral Sea and towards north-east Australia, and only 11 passed eastwards of the groups. In discussing the origin of these cyclones, Knipping states that the south-east Trade winds prevail over the entire South Pacific, from Australia to South America, during the southern winter.

In the southern summer—November to April—the winds of the western half of the ocean are quite different from those of the eastern half. Over the former, the steady south-east trades are disturbed, and north-east and north-west monsoon winds alternate with south-east trades and calms. To the east of the Paumotu Islands the conditions are undisturbed and cyclones are there unknown.

Approximately six-sevenths of all these inter-island hurricanes begin near the larger islands; the zone of origin is a band of length 350 nautical miles, running south-east to north-east, and situated between a line drawn from the south cape of New Caledonia through Tutiulea to 14° 19' S., 172° 57' W., and another passing by the New Hebrides to Rotumah Island (12° 31' S., 174° 45' E.).

One hundred and thirty-eight of these hurricanes occurring between the years 1789 to 1891 are discussed individually at the end of the treatise, the majority of the discussions being exceedingly brief, owing to the scarcity of observations. Two charts are given, one of which gives the number of cyclones met with in each square of 5 deg. and the other the tracks of 55 of the total number of cyclones, these tracks being the only ones which have been determined with sufficient accuracy. It will be noticed that most of the squares from which many storms have been reported include inhabited islands, and it is possible that with more observations storms would be reported in many squares in which no storm has yet been observed.

The charts are shown on Plate XXXI.

The seasonal and geographical distribution of 125 storms occurring during this period is given as follows :—

	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total.
N. E. Australia	—	—	—	—	2	—	3	1	—	6
Solomon Isles	—	—	—	1	1	—	2	—	—	4
New Caledonia and New Hebrides	1	1	1	1	11	9	6	—	—	30
Fiji Isles	—	—	—	4	7	6	10	1	—	28
Tonga Isles	—	—	2	1	2	4	5	2	1	17
Samoa Isles	—	—	1	7	10	1	8	2	—	29
Cook's Isles	—	—	—	—	1	—	—	—	—	1
Tubuai or Austral Isles ..	—	—	—	1	—	1	1	2	—	5
Society Isles	—	—	—	1	2	—	—	—	—	3
Paumotu Isles or Low Archipelago	1	—	—	—	—	1	—	—	—	2
Totals	2	1	4	16	36	22	35	8	1	125

From this it is seen that the hurricane season is really from December to April inclusive—some writers make it definitely from November 15–April 15—and that the months of maximum frequency are January and March. The islands over which the majority of the storms pass are New Caledonia and the New Hebrides, the Samoa, Fiji and Tonga or Friendly Isles; receding from these, whether to west or east, the frequency falls rapidly, and only two storms have been reported in the Paumotu Islands, which can be regarded as the eastern limit of the storm area.

Many of the tracks are approximately parabolic, as seen from Plate XXXI, but there are a few abnormal tracks, some of which do not recurve at all, but move in a south-easterly direction throughout their entire course. The most abnormal path (marked * on the plate) is that of a hurricane whose track was concave to the west instead of to the east; that is, its direction was south-east through south to south-west, instead of the customary south-west, through south to south-east.

Of these latter normal trajectories, Knipping investigated the recurve point whenever possible and found that the latitude of the recurve varied throughout the months as follows :—

S. Latitude ..	November. 19° (1)	December. 16·7° (2)	January. 18·5° (5)	February. 19·3° (3)	March. 20·2° (10)	April. 29° (1)
S. Latitude ..	—	December to February. 18·4° (10)			March. 20·2° (10)	—

The small figures in brackets give the number of cases analysed.

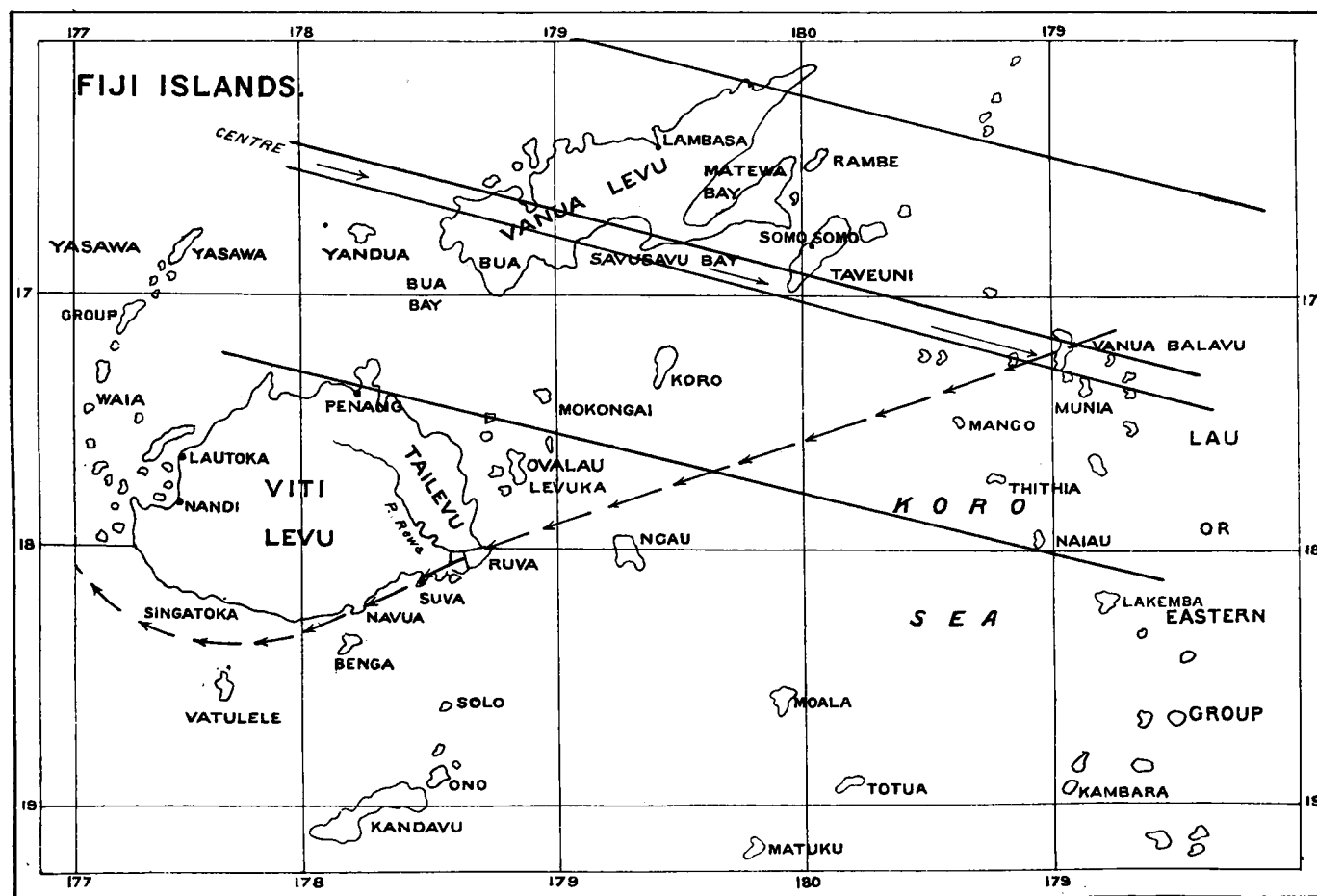
Comparing the 20 cases occurring from December to March, there would seem to be a slight southerly shift in the point of recurve as the season advances, but more observations are necessary before this can be definitely established.

IV.—13. THE NEW HEBRIDES.

Information on the subject of hurricanes is both scanty and unsatisfactory, as, owing to the practice of reporting every gale as a hurricane, whether of a rotary character or not, these destructive storms appear to be of more frequent occurrence than is really the case.

From enquiries made of those who have spent many years in the New Hebrides, it appears that the only months in which hurricanes have been known to occur are January, February and March; but it is prudent to be prepared for them, in addition, as early as the end of December and as late as the beginning of April.

TRACKS OF THE HURRICANE OF MARCH 23-25TH. 1910,
AND OF THE STORM OF JANUARY 28-29TH. 1912.



TRACK OF HURRICANE OF MARCH 23-25TH. 1910. ———→
STORM OF JANUARY 28-29TH. 1912. —————

On February 11, 1891, a hurricane was reported to have crossed the southern part of the New Hebrides, passing to the coasts of New Caledonia, Aneityum Island, apparently experiencing its greatest force.

Another hurricane was encountered between New Caledonia and the coast of Australia on March 9–12, 1891.

A steam vessel proceeding from Sydney to Noumea reported as follows :—" A falling barometer with freshening wind and rising sea warned us to prepare for bad weather, and on the following day it blew a hard gale from east-south-east with a high sea from north-east to south-east.

March 8, 10 p.m.—Barometer 1009mb (29·8 in.), heavy gale from east-south-east with high sea and overcast sky.

March 10, noon.—Barometer 997mb (29·4 in.), south-east gale with heavy sea and rain.

March 11, noon.—Barometer 987mb (29·2 in.), wind east with heavy sea and rain.

March 11, 3 p.m.—Barometer 982mb (29·0 in.), vessel apparently in centre of disturbance with wind blowing in terrific squalls from east and then from north-east.

March 12, 6 a.m.—Barometer 996mb (29·4 in.), gale shows signs of abating.

March 12, noon.—Barometer 1002mb (29·6 in.), blowing a fresh northerly breeze, with clear sky and moderate sea.

The normal pressure in the group in March is 1010·0mb.

Other hurricanes have been reported as follows :—

1867.—March 7 the rear part of a hurricane passed over Futuna and a severe gale was felt at Efáte.

1868.—On January 30, during a hurricane, the wind shifted round by north and abated at west.

1869.—January 11, a hurricane at Futuna which was felt at Fiji.

1871.—March 17–22, the rear part of a hurricane passed over Futuna and was felt severely at Fiji, being preceded by a heavy sea from the eastward.

1872.—February 17, a hurricane occurred, preceded by a heavy fall of rain; the lowest reading of the barometer was 1004mb (29·7 in.). The normal pressure in February is 1008·3mb, the extremes recorded at Futuna (62, p. 624) being 991mb and 1014mb.

1873.—On January 6, a hurricane blew from north-west and north-north-west, and on January 10th a heavy sea occurred, caused by a hurricane, to the northward.

1892.—February 14 and 18, a hurricane caused considerable damage.

IV.—14. THE FIJI GROUP.

From December to March is the hurricane season; storms at this period are sometimes attended by a storm wave, which has been known to rise as much as ten feet above the ordinary sea level, inundating the low islands and districts exposed to its force and spreading devastation in its path. These storms are cyclonic and occur on an average once a year, being most severely felt at the western end of the group.

They appear generally to approach from the north-eastward, recurve round the western portion of the group and thence travel to the south-eastward, the chief force of a storm being felt at Yasawa Island, Nandi and Kandavu, while Levuka feels only a strong northerly gale and Lau is not influenced by the gyration.

Exceptional storms have been felt equally over all the group. Between the years 1848 and 1910, 34 cyclones have been recorded, which have affected the whole or a portion of the group, those of extreme violence occurring at intervals of some years.

The lowest recorded height of barometer was 933mb (27·6 in.) at Bua Bay, in March, 1886.

There is no reliable evidence of much damage ever having been effected in the Eastern Group or at Taveuni by cyclones, only the eastern edge of storms being felt there, and that rarely.

In Fiji, the semidiurnal variation in the atmospheric pressure is very well marked, with maxima at about 10 a.m. and 10 p.m., and minima about 4 a.m. and 4 p.m. When the atmosphere is in a normal condition this rise and fall is regular whether the pressure is above or below the average.

During the hurricane season a regular rise from 4 a.m. to 10 a.m., or 4 p.m. to 10 p.m., is a safe indication that no storm is to be expected within 12 hours. On the other hand, a fall within these intervals is a definite warning of the approach of a storm.

The following is a summary of the available information concerning hurricanes which have visited the Fiji Islands since the year 1908. This information has been compiled from the Annual Reports of Agriculture, published by the Legislative Council, Fiji.

1908.—(1) January 9. Observations of the direction of the wind at various places and times served to show the general track of the hurricane, which entered the group from the north-west and travelled south-east, passing over Vanua, Levu, Taveuni and the Lau groups; the centre passed over Suvasuva Bay and near to Somosomo. A small coasting steamer and several cutters were blown ashore. A tidal wave swept along the beach at Loma Loma and carried up many tons of stone sand, and so on. Coconut palms suffered, the estimates of the damage varying from 5–50% of the crop of nuts. Breadfruit trees, which usually suffer loss of branches, were bodily uprooted in Vanua Bavalu, owing, it is suggested, to the heavy rains loosening the soil. The crops of oranges, breadfruit and shaddocks were blown off and the bananas practically destroyed. Very many Fijian houses suffered severely, especially about the ridge-poles.

(2) March 23. This storm was preceded by a fall of the barometer, starting about 9 a.m., and becoming steadily more rapid. The lowest point was reached at 8.15 p.m. The fall before 10 a.m. gave an indication of its approach. The hurricane on this day approached the group from north-west and travelled to the south-east, as in the case of the earlier one. It struck the island of Viti Levu in the Nandi district, crossed this island toward Suva, and then passed over the island of Kandavu.

The barometric indications were more remarkable for the speed at which the pressure fell and rose again than for the great depression. At 9 a.m. the reduced reading was 29.802 in. and the pressure fell to 29.317 in. at 7.45 p.m., rising very quickly to 29.747 in. by 9 a.m. next morning.

The damage was severe, except on the north-west side of the island.

1909. (1) March 25.—A hurricane visited the group and did considerable damage to crops and to several stations.

1910. (1) March 24–25.—A special report concerning this storm was published by the Colonial Office. A brief summary of the chief facts is as follows :—

A hurricane visited Fiji, passing through the group from the Lau Islands, travelling westwards across Viti Levu. The track of the storm is shown on Plate XXXII.

The disturbance first appeared over the northern end of the Lau group, at about noon on March 24; it was then centred over the island of Vanua Balavu, on which is the Government station of Loma Loma, where the wind reached its greatest force. The barometer reached its lowest at about 5 p.m., at which hour a tidal wave, whose greatest height was about 8 ft., and which exhibited an extraordinary phosphorescence, carried away the sea wall and flooded the Government station.

The wind diminished from hurricane force before midnight on the 24th.

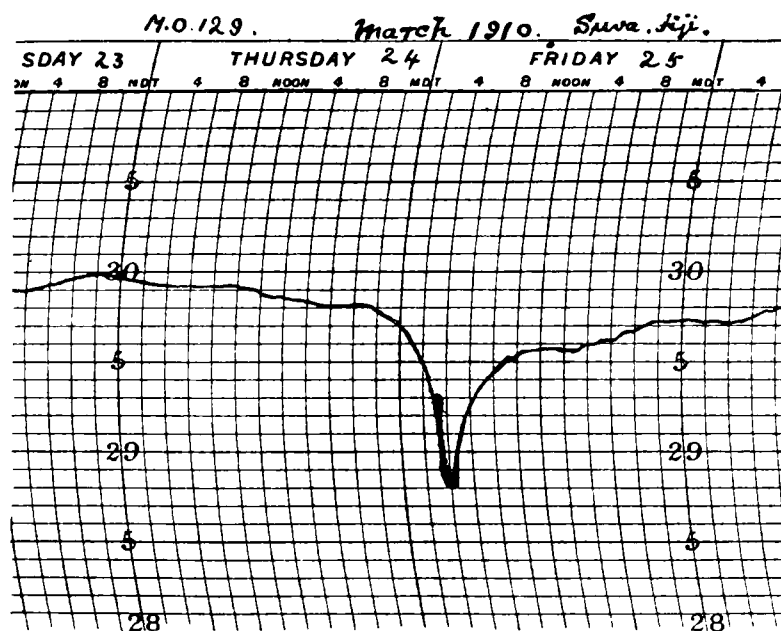
The track of the storm as it passed over Loma Loma was not wide, and little or no damage was done at the Island of Lakemba, some 60 to 70 miles to the south, and at Taveuni, a similar distance to the north-west, it is certain that the wind did not approach hurricane force. Subsequent information showed that the track of the storm through the entire group was everywhere comparatively narrow.

From the northern end of the Lau group the disturbance passed west by south, travelling at an average rate of 10 miles an hour (the average speed of the circular movement of the wind seems to have been about 85 miles an hour), between the islands of Koro and Ngau, its northern edge just touching Ovalau. About 12 hours after its first appearance over Lau the centre struck the island of Bau, with great force, and then passed successively over the district of Tailevu, over the delta of the Rewa River, where its activity was very great, over Suva, and then with diminishing force over Navua and Singatoka, after which it recurved round the south-west of Viti Levu and passed out to sea in a north-westerly direction to the south of the Yasawa Group.

The damage done on Vanua Levu, Taveuni and the northern portions of the Group and on the north coast of Viti Levu was not severe; the full force was experienced in the Rewa and Suva districts.

In the present storm the morning of the 24th opened clear and bright, with a fresh south-east wind. These conditions continued more or less all day.

A copy of the barographic chart (for Suva) is shown below, and from this it will be seen that no pronounced warning was given up to 6 p.m.



No rise in the barometric pressure occurred, but there was nothing to indicate the rapid approach of a storm, for no further fall took place until about 10 p.m., when pressure began to decrease quickly and the storm followed almost immediately.

The wind blew in gusts of increasing violence, and soon after midnight the full strength was experienced.

The minimum pressure occurred about 4.10 a.m.

A Robinson wind-gauge at Suva recorded 721.3 miles from 9 a.m. on the 24th to 9 a.m. on the 25th, corresponding to an average speed of 53 m.p.h.

In the Australian Monthly Weather Report for March, 1910, this hurricane is again described briefly, and its complete path followed out. It is said to have originated near Samoa, wrecked districts in Fiji, in the Loyalty Islands and Noumea, and damaged Norfolk Island and the north-east of New Zealand.

1911. (1) December 22.—The wind changes indicated a storm passing southwards and well to the east of the group. The lowest barometer reading was 29.568 in. The gales did much damage to the banana crops.

1912. (1) January 28.—A severe hurricane detailed below.

The phenomena preceding this storm were different in many respects from those associated with the storms of 1908 and 1910. In the latter storms pressure was above the average for several days immediately before and on the morning of the storm; the decrease when it began was very rapid, and the storms broke a few hours after the commencement of the fall. In the present storm there was a gradual fall of pressure for several days, a condition which was very general throughout the group. The prevailing winds during December and January were from between north and east.

The highest pressure (29.955 in.) at Suva during January was on the 15th; after that day the fall was gradual until the 24th, when the reading was 29.77 in.

The readings for the following days were:—

					Inches.
25th	..	..	..	..	29.598
26th	..	..	..	..	29.550
27th	..	..	..	..	29.432

and the storm passed over Suva at about 3.4 a.m. on the 28th, when the lowest pressure was 29.10 in. At 9 a.m. of the same day the reading was 29.228 in., after which the pressure gradually rose to normal.

The wind at Suva reached 9 or 10 on the Beaufort Scale.

The characteristic calm, due to the passage of the centre, was reported from the Lau Group. At Suva, which was a considerable distance from the direct path of the centre, "pumping" of the barometer to the extent of 0.05 in. was observed during the passage of the centre. The storm track is shown on Plate XXXII.

The storm appears to have travelled more slowly over land than over sea. Between Bua and Munia, a distance of 180 miles, the rate was approximately 11 miles an hour. The only portion of Viti Levu which suffered severe damage was the district round Penang, and, including this in the storm area, the diameter of the latter would be approximately 95–100 miles. Assuming a velocity of translation of 11 miles an hour, a storm of this diameter would take 9 or 10 hours to pass a definite point; this duration agrees with the observed duration at Manila.

The lull of $1\frac{1}{2}$ hours at that station indicates that the diameter of the calm or central eye of the storm was about 16 miles.

The belt shown on the map indicates the area over which the greatest damage was recorded.

The following is a list of the observations of minimum pressure at different stations in the Group.

Station.	Pressure. Ins.	Time.	Day.	Wind, etc.
Lautoka	28.79	8.0 p.m.	Jan. 27	NE., max. from SE., then SW.
Ba	29.08	8.40 p.m.	" 27	—
Penang	28.76	12.55 a.m.	" 28	—
Bua	—	1.10 a.m.	—	NE., lull $\frac{1}{2}$ hour, then SW.
Delanasur, Bua	27.25	1.15 a.m.	" 28	Strongest from W.
Navua	29.28	2.30 a.m.	" 28	E., then SE. to S. & SW.
Suva	29.10	3.30 a.m.	" 28	Shifted from NE. to E., SES. to SW.
Dreketi	27.15	4.5 a.m.	" 28	N. and NNE.
Levuka	28.24	4.30 a.m.	" 28	NE. by E. to SE. & SSE.
Savusavu Bay	27.95	8.0 a.m.	" 28	NNE. through N. to W. or WNW.
Lambasa	28.28	6.30 a.m.	" 28	—
Taneuni	28.13	11.15 a.m.	" 28	WNW., then NW.
Bavatu	27.40	3.30 p.m.	" 28	NE., then SW. (?)
Loma Loma	27.30	4.0 p.m.	" 28	NW., then SW.; lull of $1\frac{3}{4}$ hours between.
Munia, Lau	28.01	5–6.15 a.m.	" 28	N., N. by E., calm then SE., S. & SW.

1913. (1) March 18.—A hurricane visited the islands on this date. Its track was very narrow, and practically confined to the south-east coast of Viti Levu. Damage was done chiefly to the tall banana plants in Lower Rewa, Suva and the surrounding coast, and lower Vavua. Cane nearing maturity suffered rather severely on the lower Rewa and at Navua.

The lowest barometric reading at Suva was 28·861 inches at 9.40 a.m. on March 18.

The storm showed all the typical characteristics of a hurricane, but was of small diameter and short duration.

1914. (1) December 24.—In December, after a period of particularly high pressure, with a maxima of 30·028 in. on the 13th and of 30·024 in. on the 20th, a sudden fall took place, pressure reaching 29·517 in. on the 24th. A storm passed over the group on this day, entering somewhere in the neighbourhood of the Yasawa group to the north-west, and passing over the northern coast of Viti Levu, Ovalau and Makogai and then to Lakemba. The storm was of medium width, but not of great severity. The lowest pressure at Lautoka was recorded at 8.30 a.m. on the 24th, and at Lakemba at 3.45 a.m. on the 25th.

This gives the storm centre a rate of travel of about 11 miles an hour.

The hurricane was accompanied by heavy rain, and the high floods that resulted in all the large rivers in this island caused nearly as much damage as the wind.

1915. No hurricane was reported from the Fiji Islands during this year.

1916. The year was free from storms affecting the group, but on January 9 a hurricane of considerable severity passed towards the south-west at an estimated distance of about 500 miles. The depression which accompanied the passage of this storm had a minimum at Suva of 29.445 in. at 3.30 p.m. on January 9. The wind at Suva blew hardest from the north.

1917. The year passed without any storm affecting the group, but warnings were received from Australia of the presence of depressions likely to lead to storms in the vicinity of the group. All of them fortunately passed south of the group without affecting it in any way.

1918. There were no storms of a serious nature during the year.

1919. Two severe storms occurred during this year, and were the subject of a special report issued by the Legislative Council of Fiji in June, 1919. A summary of the information is as follows:—

(1) *The Storm of February 8 and 9.*—In Suva pressure was low at the beginning of February, but was rising from a minimum of 29·518 in. reached on January 31. The pressure rose to 29·886 in. on the 7th, when it began to fall. The wind continued unaltered in direction, and the approach of a violent storm was not evident at Suva. The wind during all the hot weather had been south-east, a departure from the normal which will be referred to later.

From the following observations at Lambasa and Taveuni, to the south-east of Suva, it will be seen that the depression began to show itself in this part of the group on February 7. The pressure readings quoted are those of 9 a.m. unless otherwise stated. The barometric heights are in inches.

	Feb. 5	Feb. 6	Feb. 7	Feb. 8	Feb. 9	Feb. 10
Suva	29·876	29·882	29·886	29·829	29·630	29·899
Taveuni	·849	·867	·703	·697	·676	·949
Lambasa	·825	·828	—	·698	—	·950

Although the storm began to affect the pressure at Lambasa and Taveuni at 9 a.m. on the 7th, no change in the wind was recorded (Lambasa having only gentle south-east breezes), until the 8th, when Taveuni was having easterly gusts reaching force 8-9, which gradually increased in violence as the day passed.

From observations of minimum pressures it is seen that the centre passed nearer to Lambasa than to Taveuni, and since the strong winds were south-east, east and north-east, it is evident that the centre passed north of the group.

The lowest pressure, 28.50 in., was recorded in the Yasawa group, to the north-west of Viti Levu. Since the most serious damage was done here, it appears that the centre of the storm came nearer to the Yasawa group than to any other part of Fiji, and that its track had therefore a south-westerly direction.

(2) *The Storm of March 28.*—During the latter part of the hot season the weather conditions were similar to those of the earlier parts, *i.e.*, south-east breezes of the nature of Trade winds, with fairly high pressure and temperatures not far removed from the normal.

The approach of this storm affected the pressure at Lambasa and Taveuni at 9 a.m. on the 26th, and at Suva later in the day.

The south-east wind experienced at the two former stations showed the storm to be in a north-easterly direction, and as the wind at Suva remained steady from the south-east it was assumed that the storm would finally reach Viti Levu, and therefore hurricane signals were accordingly issued.

Minimum pressures occurred as below :—

Station.	Time.	Pressure.
Lambasa	March 28th 2.15 a.m.	29.154 in. Standard barometer.
Taveuni	„ 2.30 a.m.	28.904 „ „ „
Suva	„ 3.45 p.m.	29.557 „ „ „
Munia (Lau)	„ 6.0 p.m.	29.53 „ Aneroid „

It will be seen that the Lambasa and Taveuni minimum pressures occurred nearly at the same time, which shows that the track was at right angles to the line adjoining these two places, and therefore confirms the track of the storm as from the north-east.

Since the storm did not reach Viti Levu it cannot have continued in a straight line when passing Taveuni, and the Munia observation shows that it curved south and then south-west.

From the times of occurrence of the Taveuni, Suva and Munia Minima, it seems probable that the storm travelled at a quicker rate between Taveuni and Suva than between Suva and Munia, and it is probable that the storm was at the height of its violence near Taveuni, after which it died away both in intensity and in velocity.

Extensive damage was done to breadfruit, coconut and other crops, and small boats were wrecked.

IV.—15. GENERAL REMARKS ON FIJI HURRICANES.

From the above brief notes for the years 1908–1919 it is seen that the average frequency of these storms is one per annum, and that most of them have occurred in December, January or late March. The popular idea has existed that hurricanes never visit the group in February. Most of the violent storms have certainly happened either at the beginning or end of January, or at the end of March, and this indicates that about these times the conditions for the formation of great storms are most favourable. As January advances into February, the conditions become less favourable, so that during this month storms are so rare as to have given rise to the idea above, that they cannot form. The storm of February 8, 1919, must dispel any such idea, as it was certainly a hurricane. It is probable that no particular day can be regarded as the beginning or end of the hurricane season, and that during the season—which is defined as being from mid-November to mid-April—no day or period of days can safely be regarded as free from the possibility of a storm.

During the hot weather light northerly winds with calms are so frequently experienced in Fiji that they may be regarded as usual features of the weather during this season. During 1919, however, they were the exception, south-easterly winds, practically of the nature of trade winds being general for the whole period.

The occurrence of two storms in one year, although fortunately neither of them approached in violence the great storms which have inflicted widespread damage, is, in itself, worthy of more than passing note, and, coming as they did, after a period of unseasonable south-east winds, affords some confirmation of the theory that storms are liable to be formed in the belt where the cooler winds from the south meet the hot ones from the north, heavily charged with water vapour.

When northerly winds are blowing over the Fiji Islands, the belt where they meet the cold south winds is south of the group, and cyclones formed at the boundary travel south and away from the islands; but when southerly winds are blowing, the danger zone is to the north of the group, and storms formed there can include the group in their tracks.

It is to be understood, however, that even when the group is having the seasonal north winds they may be limited in extent, and elsewhere south winds may prevail which may give rise to storms, the tracks of which may include the group.

In the hot season of 1919 the south-east winds were so regular and strong as to give the impression that they were general throughout this part of the Pacific.

In neither of the storms were warnings received from the Australian Weather Bureau, which indicates that they were both of small extent and of short duration.

IV.—16. NEW CALEDONIA (from the Admiralty Pacific Sailing Directions).

During the whole of the wet season, but principally in January and February, New Caledonia is exposed to hurricanes; as in March, 1890, when a very violent hurricane swept over the northern part of the island and did great damage to agriculture and shipping. They are, in some instances, preceded by cloudy, gloomy weather and oppressive heat, their approach being indicated only by a falling barometer a few hours previously. In general, however, they occur after some days of squally weather, accompanied by abundant rain, with a sky uniformly grey; if the sky is crossed by banks of copper-coloured clouds and the barometer stands at about 1000mb, a hurricane may be expected.

The area of these rotary storms is generally small, as those which cross the centre of the island are not always felt at the extremities; their rotation is clockwise (southern hemisphere), and their translatory movement is, in the early stages, south-west, passing through south to south-east. All parts of the island are subject to these cyclonic storms. The great extent of elevated land in New Caledonia often modifies the direction which these storms might otherwise take. In general, when the storm centre encounters the land at the northern part of the island it is deflected according to the trend of the high land, and advances from the north-westward towards the south-eastward.

It is generally supposed that hurricanes rarely pass to the southward of the Isle of Pines.

IV.—17. BANKS GROUP OF ISLANDS.

The winds about Banks Islands are governed by the same laws as those at the New Hebrides, only that the hurricanes which are experienced in the southern part of the latter archipelago are seldom felt in the former.

IV.—18. TONGA OR FRIENDLY ISLANDS.

Between November and the end of March the weather is often bad. Hurricanes are liable to occur between the above months (one has occurred in May) and are more frequent in the neighbourhood of Haapai and Vanau. These storms begin with strong winds from the north-west, veering to northward and eastward and ending at south-east. If the full fury of the storm be felt at Vanau, Tongatábu generally escapes, and vice versa, but Haapai, being situated between the two places, generally suffers in any case.

On January 30, 1912, a hurricane visited the group, and during the night of February 9, 1913, the islands were visited by a very heavy gale amounting to a hurricane, during which the barometer fell to 943mb. Great damage was done to the coconut trees, especially in the district of Haapai.

IV.—19. SAMOA ISLANDS.

Hurricanes occur from January to March and occasionally during the first half of April; they commence with a violent north-east wind, which passes through north and west to south west. These hurricanes are formed at the boundary between the conflict of the north-west winds with the trade winds, and their beginning and end are accompanied by frequent electrical phenomena.

Such storms are very frequent between Samoa and Tonga, and scarcely a season passes without one.

In April, 1850, in January, 1870, and again in March, 1883, Upolu Island was devastated. In these years, the coconut, banana and breadfruit crops were completely destroyed, reducing the natives to the verge of starvation for several weeks.

IV.—20. AUSTRALIAN HURRICANES.*

These destructive storms are known as typhoons, hurricanes or willy-willies, and occur both on the north-west and on the north-east coasts.

Those of the former class belong, strictly speaking, to the South Indian Ocean section, and many of them include the Cocos or Keeling group of islands in their track. The idea—very prevalent until recently—that cyclonic storms never occur on the eastern side of an ocean, is effectively disproved by the existence of these West Australian hurricanes, on the most easterly edge of the South Indian Ocean.

The two hurricane regions extend from Derby to Onslow on the north-west coast, that is, from latitudes of 17° S. to 22° S. respectively; and from Cooktown to Mackay on the Queensland coast, that is from latitudes 16° S. to 21° S.

The following tables give the frequency, locality, and other details of storms recorded between 1877 and 1912.

WEST AUSTRALIAN HURRICANES.

Year.	Date.	Chief Locality.	Max. ¹ Rain.	Barometer ² Inches.	Losses.
1877	Feb. 15—18 ..	Lacepede Islands (off Broome)	—	29.49	—
1878	Dec. 24	" "	—	29.52	—
1879	Jan. 25	Roeburne	—	28.92	<i>Sulina</i> and <i>Manfred</i> .
1880	Jan. 9	Yasnadarra	—	—	<i>Adalia</i> .
1881	Jan. 7	Cossack	—	27.0	Many luggers
1882	Mar. 7	Roeburne	6.5	28.1	—
1887	Feb. 12	Cossack	8.5	29.2	—
1887	Apr. 22	Wallal	—	—	Over 200 lives.
1888	Jan. 7	Derby	17.0	29.13	—
1888	Apr. 22	90 Mile Beach	—	—	114 men lost.
1889	Mar. 1	Roeburne	6.0	—	3 boats wrecked.
1890	Jan. 27	Wyndham	11.6	29.36	—
1897	Dec. 26	Onslow	6.5	28.57	Wrecked Onslow.
1898	Apr. 2	Cossack	36.0	27.8	All Cossack boats lost.
1899	Jan. 12	Wyndham	9.0	—	Tangiers record.
1900	Mar. 5	Cossack	13.0	29.34	—
1901	Jan. 30	South of Java	—	29.36	Australian record.
1901	Feb. 7	Cossack	13.0	28.78	" "
1902	Feb. 9	Cossack	7.0	29.03	—
1903	Jan. 10	East Kimberley	25.0	29.6	—
1904	Apr. 17	Broome	8.0	—	<i>Star of East</i> lost.
1905	Feb. 8	Onslow	7.0	29.11	Some loss of life.
1907	Jan. 8	La Grange	8.4	29.5	—
1907	Mar. 13	Cossack	13.5	29.2	<i>Mildura</i> lost.
1908	Apr. 26	La Grange	8.5	29.5	Fleet and 50 lives lost.
1908	Dec. 10	La Grange	8.5	—	<i>Cutty Sark</i> lost.
1909	Jan. 19	Onslow	8.8	28.9	4 luggers and 24 men.
1909	Apr. 6	Onslow	6.0	29.2	—

¹ Heaviest record in the vicinity.

² Occasionally 9 a.m. and not the lowest reading.

* From "*Australian Meteorology*," by Griffith Taylor (61), pp. 208-216.

WEST AUSTRALIAN HURRICANES—*continued*.

Year.	Date.	Chief Locality.	Max. ¹ Rain.	Barometer ² Inches.	Losses.
1910	Nov. 19	Broome	11·0	28·64	26 luggers and 40 lives.
1911	Feb. 7	Onslow	6·0	28·8	<i>Glenbank</i> and all crew.
1912	Mar. 6	Broome	8·7	29·3	—
1912	Mar. 21	Cossack	9·0	28·86	<i>Koombana</i> and all crew.
1915	Feb. 26	Perth	—	29·13	Too far south to be typical.
1917	Jan. 7	Broome	14·0	29·42	Not destructive. ³
1917	Mar. 14	Onslow	—	28·9	—
1917	Mar. 27	Fortescue	—	—	Wrecked buildings.
1917	Dec. 17	La Grange	37·6	29·12	Not destructive.

¹ Heaviest record in the vicinity.² Occasionally 9 a.m. and not the lowest reading.³ Affected outlying regions chiefly.

QUEENSLAND HURRICANES.

Year.	Date.	Chief Locality.	Rain. ¹	Barometer. ²	Losses.
1870	Jan. 30	Bowen	—	—	Houses blown down.
1870	Feb. 20	Townsville	—	—	Town nearly levelled.
1878	Mar. 8	Cairns	—	—	—
1884	Jan. 30	Bowen	—	—	Town unroofed.
1890	Mar. 24	Townsville	—	—	—
1896	Jan. 26	Townsville	17·2	29·27	<i>Sigma</i> gale.
1898	Feb. 4	Mackay	—	—	—
1899	Mar. 5	Bathurst Bay	—	—	Pearling fleet and 300 men.
1903	Mar. 9	Townsville	—	28·5	—
1906	Jan. 28	Cairns	—	—	Town devastated.
1906	Mar. 4	Croydon	—	—	Town devastated.
1907	Jan. 19	Cooktown	—	—	Town devastated.
1908	Mar. 12	St. Lawrence	7·1	29·27	Damage to north.
1911	Mar. 16	Pt. Douglas	12·0	29·6	Town levelled.
1911	Mar. 24	Flat Top	—	29·7	<i>Tongala</i> lost.
1912	Apr. 6	Innisfal	32·6	29·8	—
1913	Jan. 30	Cairns	8·2	29·1	<i>Innaminka</i> wrecked.
1915	Feb. 6	Mackay	11·5	29·38	Curved off shore.
1916	Dec. 27	Townsville	12·8	29·6	61 drowned at Clermont.
1918	Jan. 20	Mackay	24·7	27·5	Town largely wrecked, 20 lives lost.
1918	Mar. 9	Innisfal	16·6	27·8	Town wrecked, 18 lives lost.

¹ Heaviest rain recorded.² Occasionally 9 a.m. and not lowest reading.

Frequency.—From the above tables it is seen that the monthly frequency is as follows :—

	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
West Australia	1	4	10	7	8	6
Queensland	0	1	7	3	9	1

Hence it is obvious that they are practically confined to the hottest months, January being the favourite on the west coast and March on the east coast.

Some of the more important storm-tracks are plotted, on Plate XXXIII, Fig. 1. They all seem to originate near latitude 10° S., and then move to the south-west.

The Port Douglas hurricane (March 16, 1911) is an exception, its initial movement being to the south-east, followed by a most peculiar recurve.

Between latitudes 15° and 24° S. they almost all curve round in a parabolic path and then proceed to the south-east. Here again there are a few exceptions, as in the Port Douglas storm and the Bathurst Bay storm (March 5, 1899). Both of these (in North Queensland) passed to the west.

The violent phase of the storms often lasts for hours, and the storms themselves occasionally last for days.

In conclusion the *Koombana* hurricane of March 21, 1912, will be described in detail, the account being taken from the *Australian Monthly Weather Report* for March, 1912.

"Not much more than a fortnight earlier (on the 6th) a 'Willy-Willy' had visited Broome (see list of hurricanes above).

The second 'Willy-Willy' was much more destructive to shipping and property, and caused the loss of the ss. *Koombana*, with the whole of the passengers and crew. The first indications of the storm were shown on the 16th off Port Darwin (see Plate XXXIII, Fig. 3), the barometer there reading 29.55 in. with a light easterly wind. From that date to the 21st it can be traced, passing in a south-westerly direction, some distance off the coast. At 9 a.m. on the 21st a fresh easterly gale was blowing at Cossack, and the barometer stood at 29.576 in. At 11.30 a.m. it began to fall suddenly and continued falling until 11.30 p.m., reaching 28.866 in., after which it remained stationary until 2 a.m. on the 22nd, when it began to rise, and at 9 a.m. stood at 29.458 in. with a strong west wind.

More damage to property was caused at Whim Creek and at Balla Balla, 40 miles to the east, than at Cossack. The rainfall was very heavy and ranged from 6 to 13 in. between Cossack and Fortescue River, and it extended inland in a south-easterly direction. The most remote rain stations, Ethel Creek and Balfour Downs, about 200 miles from the coast, registered 5.59 in. and 3.46 in. respectively. Light falls were reported over the north-east of the goldfields, and the storm lingered over the tropics till the end of the month" (see Plate XXXIII, Fig. 2).

The following account published in the *Hedland Advocate* may be of interest :

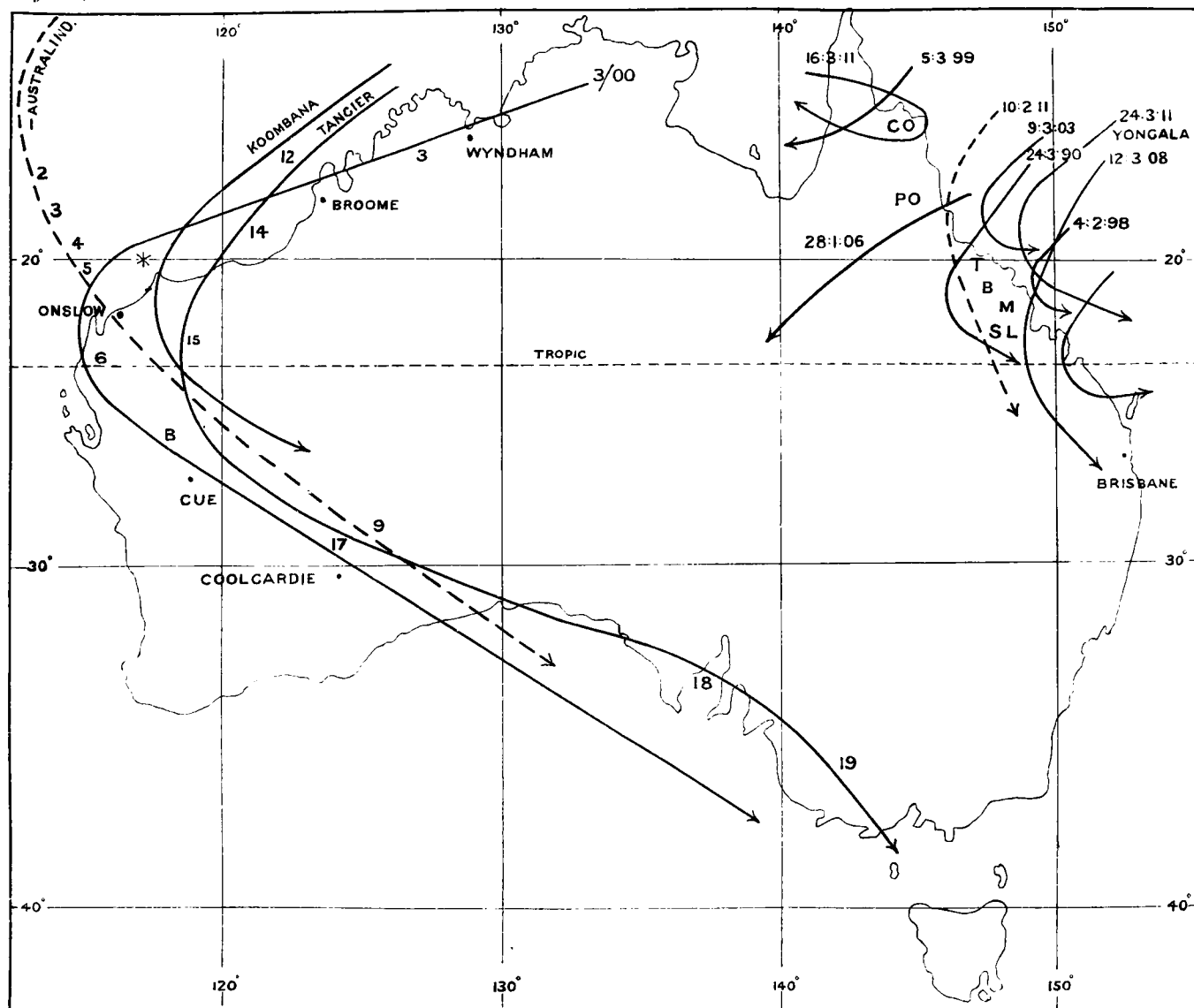
"Judging from all available information, historical and traditional, relating to 'Willy-Willies' on this coast, it would appear that the one just past (March 20-23) is without a parallel in its extraordinary characteristics of violence and destruction. There is no account of any 'Willy' equalling this in its various phenomena of suddenness and severity of power.

It was preceded by hot, stifling days. On Monday, the 18th, several divers, who have been years on the coast, warned their masters that there were sudden changes of hot and cold water below, with a ground swell, which they declared indicated the approach of a blow, although the surface of the sea was calm and the glass good. (A similar warning was given by divers two days before the disastrous Broome blow.) Quite suddenly on Tuesday night a violent thunderstorm blew up from the east, followed by moderate winds and a little rain. On Wednesday, the 20th, the wind slightly shifted to the south, increasing in its strength, and by midday it was again blowing from the east, always blowing in gusts, accompanied by occasional showers. By the time the *Koombana* and *Bullarra* had left Hedland, at 10.30 a.m. and 11.30 a.m. respectively, it began to excite alarm ; luggers moved up the creeks, and people bolted up their houses. Two or three layers of swiftly moving clouds could frequently be seen through the prevailing mist. It blew with terrific force whenever the wind shifted its course, but the *Bullarra* struck its fury three hours out, and the *Koombana* must have struck it earlier.

The hurricane was moving southward, and its centre was not far out to sea, as the *Bullarra* experienced half-an-hour's dead calm (in which it was possible to keep a match alight), in the middle of the hurricane. Officers of the ships *Moir* and *Bullarra* say that the rapidity of the storm was indescribable, the wind driving from the raging and foaming sea spray like a snowstorm, which mingled with the clouds.

As the *Koombana* left the port she was so light that her propeller was partly out of the water ; in the small swell at the entrance it was racing. Once outside, the captain had no other course open but that which led his ship right into the vortex of the tremendous elemental strife that prevailed at sea."

Figure 1.

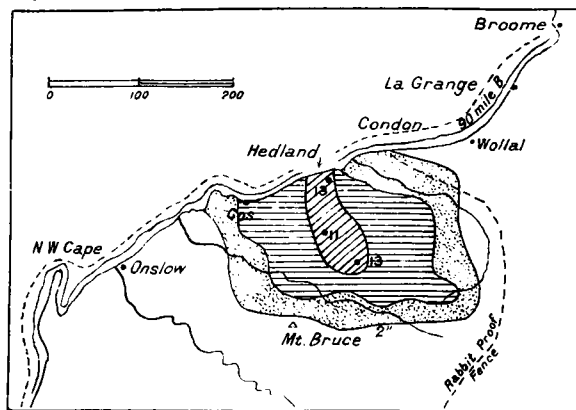


SOME AUSTRALIAN HURRICANES. THEY LOSE THEIR VIOLENCE SOUTH OF THE TROPIC. INITIALS IN QUEENSLAND INDICATE COOKTOWN, PORT DOUGLAS, CAIRNS, INNISFAIL, TOWNSVILLE BOWEN, MACKEY AND SAINT LAURENCE.

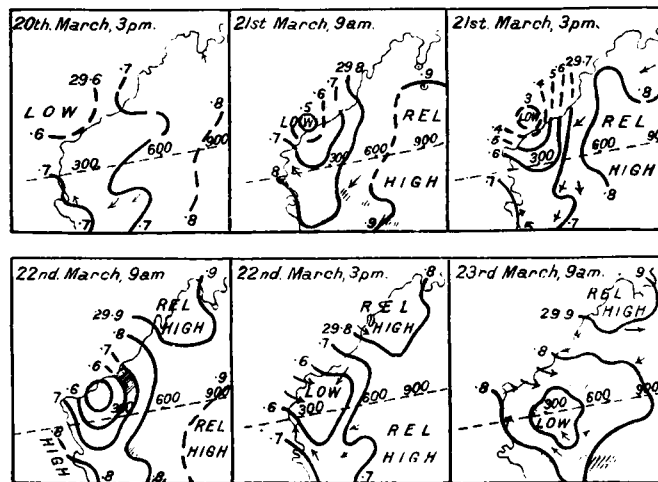
(From Griffith Taylor's "Australian Meteorology.")

Figure 3

Figure 2.



HEAVY RAIN ASSOCIATED WITH THE "KOOMBANA" HURRICANE OF MARCH 1912. TWO, FIVE, AND TEN-INCH ISOHYETS SHOWN.



Approximate distance in miles shown thus 300 600 900
WEATHER CHARTS FOR THE "KOOMBANA" HURRICANE OF MARCH 1912. (From the Australian M.W.R.)

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