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Report on Thames Floods

By A. T. DOODSON, D.Sc.
Tidal Institute, University of Liverpool.

Meteorological Conditions

associated with

High Tides in the Thames

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REPORT ON THAMES FLOODS

By A. T. DOODSON, D.Sc.

Tidal Institute, University of Liverpool.

As a result of the disastrous floods experienced in the Thames on the night of January 6–7, 1928, the Tidal Institute was requested to undertake an investigation of the causes of such floods, with a view to an answer being provided to the question: What is the reasonable probability of the recurrence of a tide of a height approximating to or exceeding that of January 6–7?

Previous experience of such problems had led us to believe that the large perturbations of sea level and tides are not necessarily locally generated, but depend upon oscillations set up in the main basins, and that full satisfaction could only come from a study of the storm surges all round the North Sea and even along the Atlantic seaboard. A more limited investigation, however, was urgently required, in order to provide a possible basis for forecasts of such effects, and therefore a preliminary investigation was suggested, dealing with the meteorological conditions which are most favourable to the production of storm effects on high water. For this, it was suggested that all storm surges for the last ten or twenty years be examined in relation to (*a*) the types of barometric pressure systems, (*b*) the position and lines of travel of cyclonic centres, (*c*) the time relations between the maxima of the storm surge and ordinary tidal oscillation.

A statistical study of the meteorological perturbations of sea-level, on the lines of one already published for Liverpool, was also suggested. Such a study is concerned primarily with the slow variations of general sea level (taken over a whole day) and *not* with the quickly-varying effects usually experienced in connexion with a storm. Such a method lends itself to the study of time relations between the variation of sea level and the variation of wind and pressure, not only locally but elsewhere, and consequently the most effective winds, and the places where they are most effective, can be deduced.

PART I—STUDY OF STORM SURGES

§1—Classification of Disturbances

Tide-gauge records had been supplied at the outset by the Port of London Authority (P.L.A.) but these were concerned only with water levels over Trinity High Water Mark (T.H.W.) and the tides were spring tides. A cursory inspection indicated that in some cases the high level was due only to the high tides and that no large meteorological effects were present. The diagrams revealed, however, that some very notable disturbances of tides[1] had occurred without the level rising above T.H.W. Generally speaking, the principal part of a storm surge may be expected to be independent of the tides, and it requires the maxima of both surge and tide to be almost simultaneous in order to produce excessively high tides; in other words, there is no specific phase relationship between them. While this is true in general, it is necessary to remember that the effects of wind on water vary with the depth and that especially in shallow seas there may be a second-order effect tending to give the phase relationship which one would not otherwise expect. Consequently, in order

[1] It is perhaps advisable to mention that this word is used in a general sense and is not restricted to high water or low water.

to determine the maximum meteorological disturbance of the tides it was necessary to consider all cases of large storm effects, whether at spring tides or neap tides, low water or high water, positive or negative. On request the P.L.A. supplied the whole of the tide-gauge records for Southend since 1911. Southend was chosen because the tides there are more easily predicted than at London Bridge, and it was desired to compare the observations hour by hour with " predictions " obtained on the tide-predicting machine. These gauge records were inspected personally, and I picked out all cases where there were obvious disturbances of the normal progression of the tides —a tide-gauge record often shows on one sheet records for a fortnight and when there are no meteorological disturbances the curves are regularly spaced and show regular variations at high water and low water. Those cases which showed irregularities were tabulated, and classified roughly (see App. I.) into :

Class A : effects with a disturbance of magnitude exceeding 6 feet.
Class B : effects with a disturbance of magnitude 4 to 6 feet.
Class C : effects with a disturbance of magnitude 2 to 4 feet.

Ordinarily Class C was ignored unless the tide exceeded T.H.W. Approximate times of greatest effects were noted.

Class A effects have been studied intensively, hourly heights having been tabulated and compared with predictions of hourly heights over a sufficiently long period in each case. The difference " observed minus predicted tide " will be referred to as the " residue."

The immediate result of this work was to reveal that many large disturbances of tides can occur ; 5 feet is quite common, 7 to 9 feet occur fairly frequently, and over 11 feet was experienced on one occasion. Obviously, if it is possible to get 11 feet superposed on high water, a most important fact was revealed, and one which would dominate the discussion concerning the raising of the defences. In January last the maximum of the storm surge (5 feet) occurred a little before high water, but in most of the cases considered the favourite time of occurrence seemed to be about 2 or 3 hours after low water. We know that on certain theories the wind has a much greater influence when the depth of water is small than when it is large, and therefore a wind blowing at low water has more effect than a similar wind blowing at high water.

§ 2—Types of Meteorological Phenomena

The next stage of investigation was to study the meteorological conditions as indicated by the synoptic charts issued twice daily by the Meteorological Office, and these were examined for a large number of years for all cases of A and B (see App. I. for results). The meteorological phenomena were classified into four types :

Type I : A cyclonic depression forms west of Scotland and travels to the Baltic, the winds veering from SW. to NW. or N.

Type II : A cyclonic depression travels over the Flemish Bight.

Type III : The winds are steady for a long time, the isobars running almost parallel to one another in a north-west direction over very large areas, with steady NW. winds.

Type IV : The south-westerly type corresponding roughly with Type III but with SW. winds.

In most of the cases in which very large storm surges have been experienced in the Thames, the weather conditions have obviously been of Type I. The weather conditions of January 5–8, 1928, were of this type. A number of Class A cases were considered and a chart was made showing the positions of the cyclonic centres at various times related to the time of maximum of the storm surge at Southend. It was clear that the time of maximum occurred when the centre of the disturbance was over the Baltic Sea. The south-westerly wind which characterises Type I at first is always accompanied by a fall in sea level in the Thames, followed by a rapid rise as the wind veers, but this veering is essential, for if the cyclonic system travels in such a way that the winds remain south-west the sea level remains depressed ; in fact we have the conditions of Type IV.

Steady winds (Type III) from NW. raise the sea level as a whole, perhaps for two or three days at a time ; there is a strong tidal disturbance in these cases, a marked and persistent semi-diurnal oscillation being prominent in the " residues " ; in other words there is a lag (or advance) in the times of both high water and low water. This is readily explained on dynamical grounds when a steady current has been set up ; the explanation comes under the same theory as that of the ordinary tidal shallow-water constituents. On most occasions when it has been observed the high waters are raised less than the low waters; that is, the range of tide is less when the sea-level is raised.

§ 3—Need for Investigations over wide Area

The early results of the statistical investigation tended to show that the winds operating over the Atlantic Ocean are equally important with those operating over the North Sea, as had been anticipated, and therefore it seemed unlikely that the storm surges would be associated with any single type of pressure disturbance. As has already been pointed out, most of the large surges are associated with meteorological conditions of Type I but there are certain exceptions ; for instance, the storm of January 18, 1881, with easterly winds, was responsible for a calamitous flood in the Thames ; it is unfortunate that the lack of suitable data has prevented a close study of this particular storm.

It seemed clear, therefore, that while valuable information had become available concerning the types of pressure systems likely to cause storm surges, there were grave uncertainties to be faced, and that much more precise laws governing the phenomena were required before the forecasting service could be in any way satisfactory. I therefore decided that I ought to investigate conditions a little further afield, though such work had not been contemplated as part of the preliminary investigations.

§ 4—Collection of Data and method of Reduction

The Hydrographic Department of the Admiralty had undertaken to collect information concerning tidal movements from January 4–8, 1928, from the tidal authorities in Belgium, Holland, Germany and Denmark, and the results were forwarded to the Institute for examination.

The Ordnance Survey, on request, supplied hourly heights of tide from their gauges at Dunbar and Felixstowe, not only for the January storm surge of 1928, but also for other cases.

The Institute possessed copies of a number of publications of tidal information and discussions of large storms affecting places on the continent of Europe, and with this material an attempt was made to trace the progress of some of the more important storm surges. The ideal data for study is such as we had for Southend, the " residues " of tide hour by hour. When only high and low water data are available, even if predictions are known, the " residues " are at intervals of about six hours, and the maximum of the surge cannot be accurately stated either in time or height. If there are no tidal predictions available the problem of separating the storm surge from the tidal oscillation is by no means easy, whether the data be for high and low waters only or at hourly intervals. Consequently, before use could be made of much of the tidal information, a method had to be devised for separating the meteorological disturbance from the normal tide, and, fortunately, an easy method was discovered, which has much facilitated the investigation and is likely to be of further service. This is described in App. II.

With regard to the diagrams shown, the curves of residues are exact for Southend ; information obtained from high and low water data only is indicated by a cross, circle, or square whether the " residues " are obtained from predictions or by the method of App. II, and the curves joining these points are conjectural ; the remaining curves are obtained from hourly heights by the method of App. II.

§ 5—The Storm Surge of December 30, 1921, to January 1, 1922.

This remarkable storm led to an elevation of tide over 11 feet above that normally expected. Fig. 1a shows the residues for the three days. Early on Dec. 30 the sea level[2] began to fall until about 7 p.m. it was nearly 4 feet below its normal tidal level. After this time a rapid rise set in, culminating at 11 feet about 9 a.m. on Dec. 31 and then a rapid fall was experienced until about 11 a.m. on Jan. 1, after which the level began to rise again. The diagram also shows the time of high water by the marks H. Thus the maximum elevation occurred about 2 hours after low water. The same diagram shows the residues for Dunbar, indicating a storm surge of maximum 3 feet about 1 a.m.

A study of storm surges at Liverpool had been commenced a few years ago, and in the upper part of Fig. 1b is shown the errors of prediction of high and low water for Dec. 29, 1921, to Jan. 2, 1922. These indicate that a large storm surge occurred there on Dec. 30, with a maximum of 5 feet about 8 p.m.

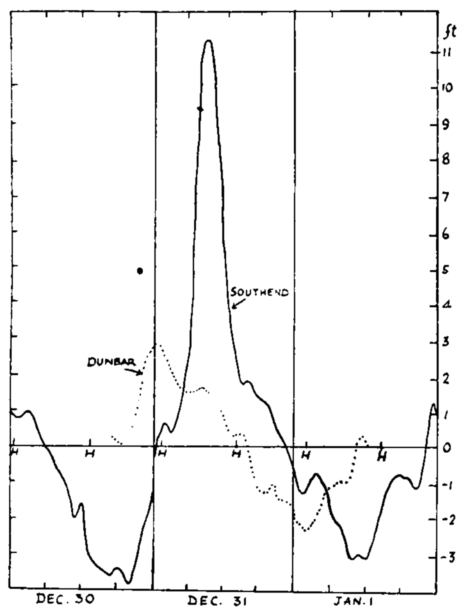


Fig. 1a. Storm Surges of Dec. 30, 1921, to Jan. 2, 1922, at Dunbar and Southend.

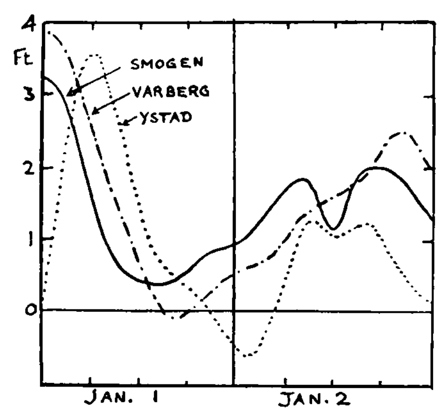


Fig. 1c. Storm Surges of Dec. 30, 1921, to Jan. 2, 1922, in the Kattegat and the Baltic Sea.

The only other information available is for the Kattegat and the Baltic Sea,[3] comprising elevations of sea-level at intervals of 4 hours during 1922, and, previously to this year, the values of maximum and minimum levels. It is clear from the maxima and minima that no large storm effects were in evidence during Dec. 30, and that a large elevation was experienced at Smögen during Dec. 31, but the data for Jan. 1 readily show that this maximum value must have been experienced about midnight (G.M.T.). Further, the progression of surge from Smögen in the Kattegat to Ystad in the Baltic is clearly revealed by Fig 1c.

Of course we must not say that a surge travelled from Liverpool, as we have no evidence for a progression from that place northward through the North Channel, but there is definite evidence that the meteorological condition over a wide area set up surges in the Atlantic Ocean, the maximum effects of which were experienced at Liverpool (5 feet) on Dec. 30 about 8 p.m. and at Dunbar (3 feet) about 1 a.m. the next day, and that this surge travelled southwards, attaining maximum effects at Southend (11 feet) about 9 hours later, and finally the surge, having travelled round the North Sea, spent itself in the Baltic on Jan. 1.

[2] By this, of course is meant, the level upon which the tidal motion is superposed, and it does not refer to the surface, the rise and fall of which is compounded of the tidal motion and the meteorological variation of 'sea level.'

[3] *Stockholm : Met.-Hydrog. Anst. Medd.* **2**, No. 4, 1925 and *Årsbok* **4**, 1922 (1924).

The lower part of Fig 1b gives meteorological information. Barometric pressures are measured in millibars and the curve gives the local pressure at Liverpool, with the east and north gradients (E. and N.) of the pressure system, measured in millibars per 500 miles. An east gradient corresponds roughly to a south wind, and a north gradient to an east wind. The principal point to notice is the rapid changes in the barometer and in the wind direction. It is quite likely that the rapidity of the change is an essential factor in the mechanism of the action. The changes in the wind are those coming under Type I.

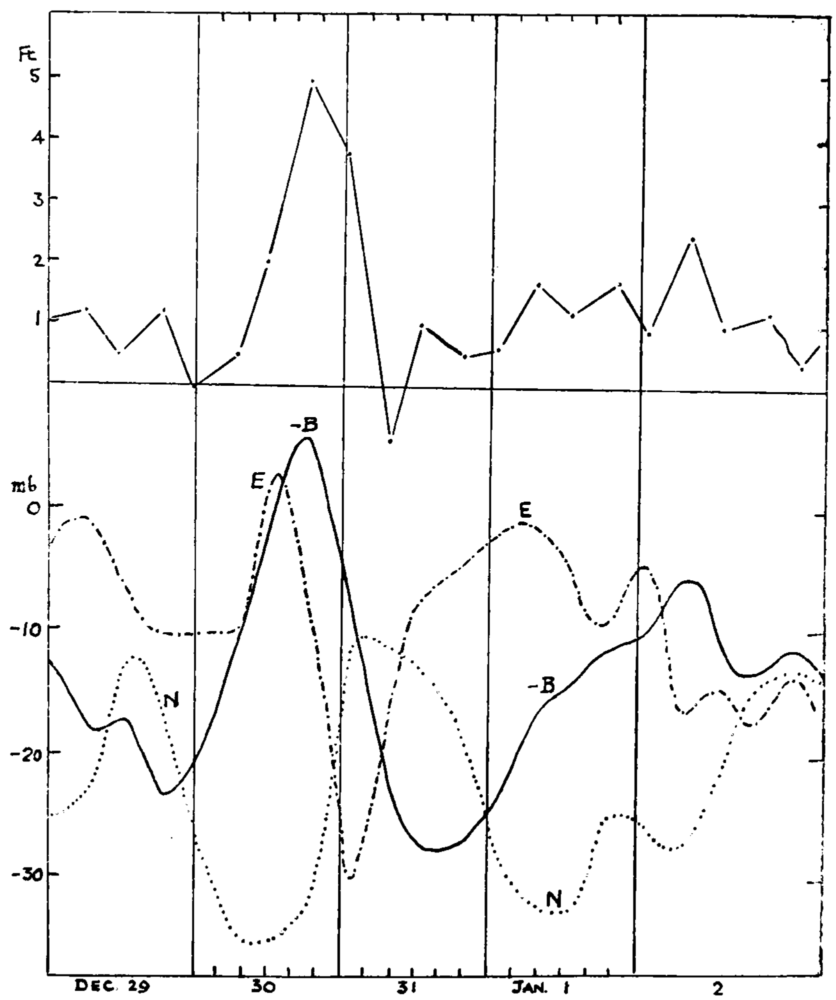


Fig. 1b. Storm Surges of Dec. 30, 1921, to Jan. 2, 1922, at Liverpool, with Barometric Data.

§ 6—The Storm Surge of January 5–8, 1928

It is not easy to trace the progress of a storm surge whose maximum is only 5 feet at Southend, as in distant places the maximum will be much less, but the information available yields similar results to those just discussed. From Fig 2a we see that the first effect of the storm was to lower sea level by over 3 feet, and then a rapid rise set in about 5 p.m. and a maximum of 5 feet was recorded about 11 p.m. on Jan. 6 The curve for Dunbar indicates a surge with a maximum of about 1·6 feet at 3 p.m. We notice that the time interval from Dunbar to Southend is about 8 hours, whereas in the previous case it was about 9 hours, and that the ratio of the maxima at the two places is about 1/3 in each case. There is a rapid rise of level at Dunbar.

The residues at Felixstowe (Fig. 2b) show a depression of about 1·5 feet just after noon, followed by a rapid rise to nearly 4 feet at 11 p.m. As Felixstowe is only a little to the north of Southend we should not expect to detect any appreciable difference in the times of the maxima. At Ostend the rise of level is less abrupt but the time of maximum is about the same.

So far as can be judged from the Dover records the surge is a little later at Dover than at Southend and Ostend. This fact is significant, for such other cases as have been examined tend to show the same result. In general we should expect that any surge propagated up the English Channel would become much reduced after passing the Straits of Dover, owing to the increasing width of the channel; and consequently in this investigation the influence of meteorological conditions in the Channel have been left out of account. It is significant, however, that even at Dover the storm surge of Jan. 6–7 seems to have been propagated southwards along the eastern shores of Britain, until the Flemish Bight was reached.

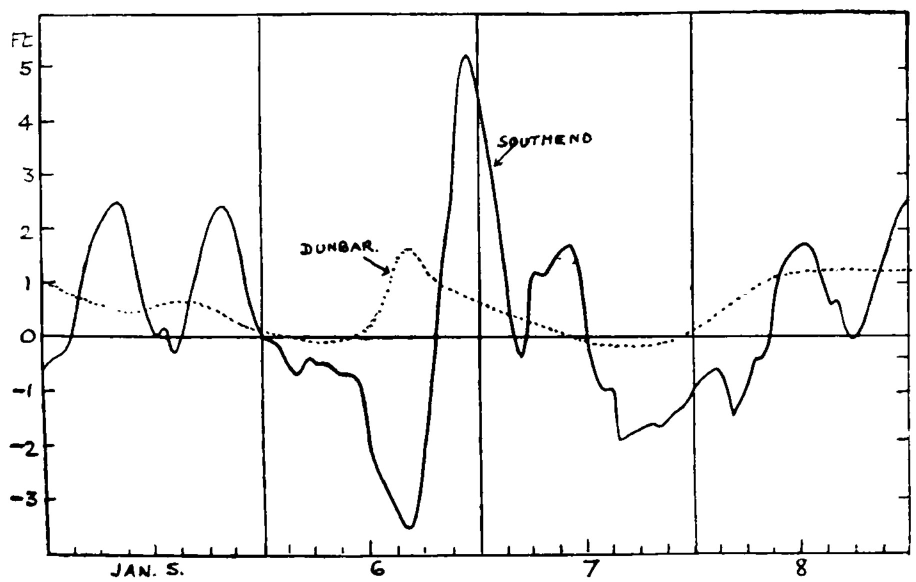


Fig 2a. Storm Surges of Jan. 5-8, 1928, at Dunbar and Southend.

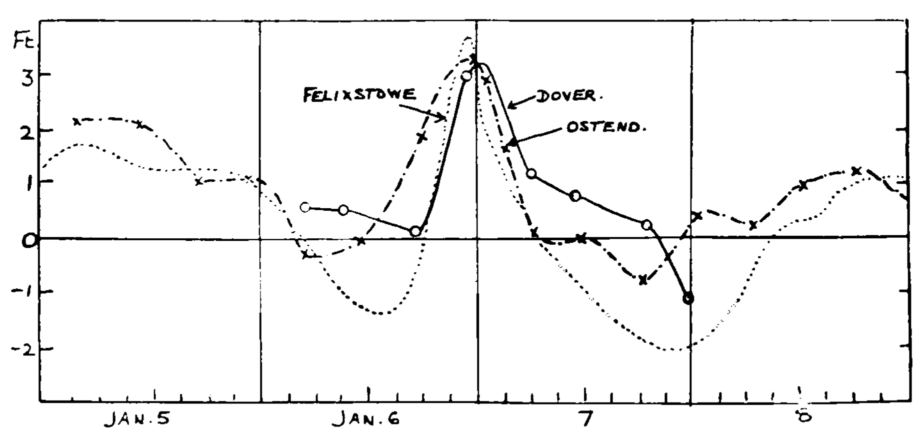


Fig. 2b. Storm Surges of Jan. 5-8, 1928, at Felixstowe, Dover and Ostend.

Fig. 2c shows that the surges experienced at Flushing and Hook of Holland were, if anything, a little earlier than at Southend, though it is difficult to say what was the time of maximum surge. The surge experienced at Ymuiden was definitely later than at Southend and it would appear that at 2 a.m. (G.M.T.) on Jan. 7 the surge was retreating in a northerly direction along the continental shores and this conclusion was verified readily, the surge reaching its maximum about 3 a.m. (G.M.T.) at Norderney, 7 a.m. at Cuxhaven, and 11 a.m. at Esbjerg—a similar result is also in evidence at Hirshals in the Skagerrack. The maxima at these places are not very large but their numerical relationship with that at Southend is about the same as in the case previously considered. Incidentally it may be noted that at all the places there is evidence of a smaller and earlier surge travelling in the same way.

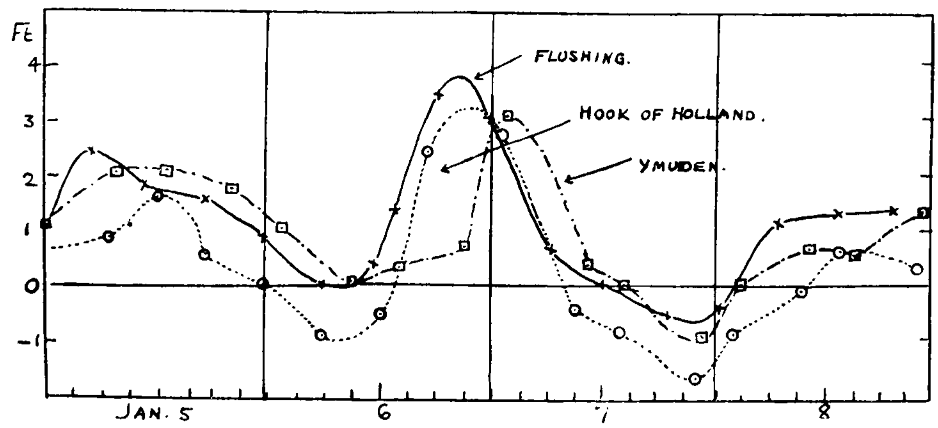


Fig. 2c. Storm Surges of Jan. 5–8, 1928, at Flushing, Hook of Holland and Ymuiden.

§ 7—The Storm Surges of January, 1916

The storms which raged during Jan. 13–16, 1916, were responsible for large surges in the North Sea, and perhaps these have been more intensively studied than any other storm surges. The following memoirs indicate the interest evoked.

P. H. Galle, De Storm van 13–14 Januari 1916. *Amsterdam: Tijdschr. K. Ned. Aardr. Gen.* Tweede Serie, Deel **33**, 1916, pp. 351–63.

A. A. Beekmann, De Stormvloed van 13–14 Januari 1916 Ebenda, p. 364–394.

A. v. Horn, Die Sturmflut vom 13 und 14 Januar in den Niederlanden. *Zentralblatt der Bauverwaltung, Berlin* **36**. Jahrgang 1916. p. 130–131.

Grossmann, Die Sturmfluten an der deutschen Nordseekuste am 13 Januar und 16–17 Februar 1916. *Annalen der Hydrographie, Berlin,* 1916, p. 361–380.

D. la Cour, Abnorme Vandstands Forhold i de Danske Farvande *Danske Meteor. Inst. Meddelelser*, No. 4, 1917, 1–83.

H. Thorade, Die Sturmflut vom 15 und 16 Januar 1916 in den danischen Gewassern. *Annalen der Hydrographie, Berlin,* 1918, p. 234–238.

The first four all deal with a storm surge occurring on Jan. 13–14, while the two latter memoirs deal with a surge occurring two days later. Information for Ostend in the former case is also given by

B. Schulz, Aerologische und Hydrographische Beobachtungen der Deutschen Marine-Stationen während der Kriegszeit 1914—1918.

The Dunbar records (Fig. 3) again yield very interesting information. There are two well marked surges with maxima of about 3 feet (*a*) about 1 p.m. on Jan 13 and (*b*) about 3 p.m. on Jan. 15. There is hardly sufficient evidence to indicate whether these two surges were propagated round the North Sea in the same way as the single surges previously described. The German memoirs indicate remarkable elevations of level about 5–6 p.m. on Jan. 13 at Borkum and about 8 p.m. at List, so that there is at least a progression eastwards along the continental shore, but the time lag on the first surge at Dunbar is not sufficiently great to allow for a progression round the Flemish Bight. The disturbances in the Baltic, about midnight, Jan. 15–16, described by D. la Cour and H. Thorade, are no doubt connected with the second surge (*b*) at Dunbar but no evidence is available concerning the intermediate stages, as none of the German memoirs give information for Jan. 15—probably the surges were not coincident with high water and therefore escaped notice.

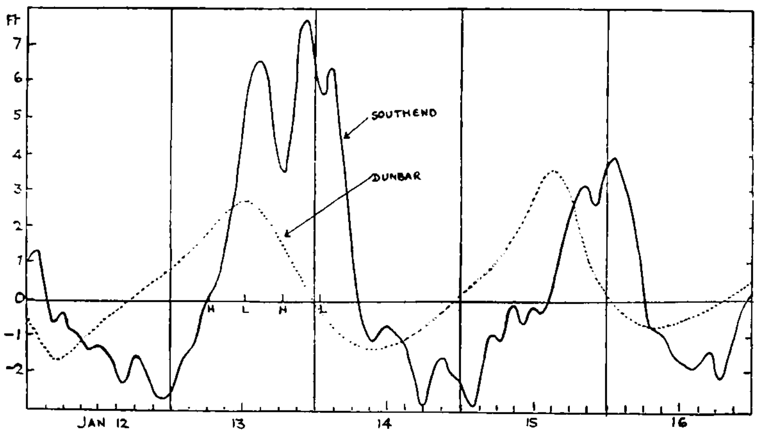


Fig. 3. Storm Surges of Jan. 12–16, 1916, at Dunbar and Southend.

Of course there is no theoretical necessity for the surges to be propagated always in the same manner, but when we consider the Southend results (Fig. 3) we notice that again there is a remarkable correlation with Dunbar ; ignoring small variations there is a double-headed surge with maxima of about 7 feet at 3 p.m. and 10 p.m. on Jan. 13, and a single surge of over 3 feet at midnight, Jan. 15–16. The time lags, compared with Dunbar are respectively 2 hours and 9 hours on the first surge at Dunbar and 9 hours on the second surge.

We notice that the second surge at Dunbar is almost synchronous with that in the Baltic, which seems to indicate a mode of action somewhat different from that of the first two cases (§§5 and 6).

The remarkable point to observe regarding the Southend oscillations is that the times of the maxima are definitely correlated with those of the maxima of the Dunbar surges, with the same time lag of 9 hours as in previous examples, and therefore we may conclude that they have been propagated down the east coast of Britain. The origin of the first surge at Southend at 2 p.m. on Jan. 13 must be looked for elsewhere. It is worthy of note that it is situated with respect to high water in exactly the same way as the surge of 11 feet described in § 5. There is no double surge on Jan. 15, and the maximum occurs a little after high water.

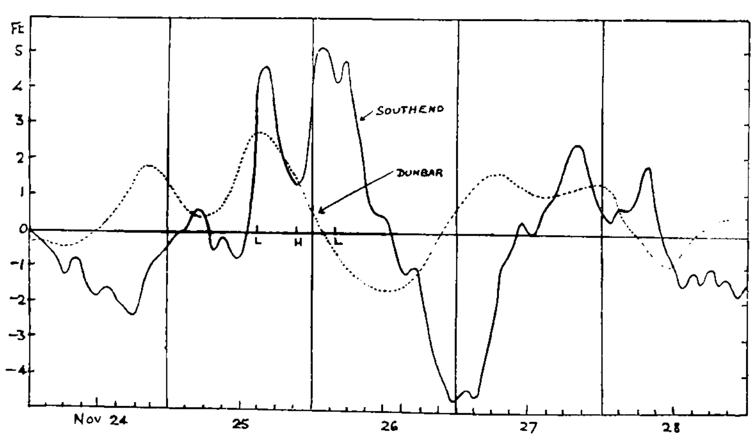


Fig. 4. Storm Surges of Nov. 24–28, 1917, at Dunbar and Southend.

The Ostend results, given by Dr. Schulz, for high waters and low waters, indicate that a similar action took place there.

§ 8—The Storm Surge of November, 1917

A very similar phenomenon occurred on Nov. 25–26, 1917. The Dunbar records (Fig. 4) show that a surge took place there on Nov. 25 about 4 p.m. and the Southend "residues" (Fig. 4) show that the first surge there had its maximum about 4 p.m. and that the second maximum occurred about 2 a.m. on Nov. 26, 10 hours later than at Dunbar. The ensuing motions at Southend are closely connected with those at Dunbar. Again the first surge at Southend is just after low water and the actual "residue" at high water is small.

§ 9—Conclusions

General reasoning indicates that the effects of an increase of depth of somewhat long duration over a wide area will be to decrease the range of tide ; that is, the apparent meteorological effects (as shown by the residues) are a general average increment of level, with minima at high water and maxima at low water. These conditions hold when there has been a long-continued NW wind. Apart from this purely tidal effect, the local wind will probably have most influence at low water and will tend to give maximum results between then and high water. Hence there are two theoretical reasons for believing that there is a marked tendency for sea level to be most raised, by meteorological causes, shortly after low water. If, in addition, the surges propagated southwards happen to arrive about this time we have the most favourable conditions for excessively large perturbations of level, and only a single peak in the residues will result : this, in fact, is exactly what happened on Dec. 31, 1921, when the maximum perturbation of 11 feet was recorded.

The relative water-raising powers of local winds and winds elsewhere appear to be about equal if our explanation of Figs. 3 and 4 is correct, for the two maxima of the double surge in each case are about equal. If in each case the second surge had arrived from the north about 9 hours earlier, so being coincident with the first surge generated locally, then superposition of the two effects would have yielded maxima of about 14 feet and 10 feet respectively. Even such large surges as these, taken at half tide, would not cause flooding. We may also conclude that local winds play a minor part in the generation of surges which raise high water to a dangerous level ; these appear to be propagated southwards, and are thus independent of local high water, both in phase and size. Since we have distinct evidence of such surges reaching a maximum of 7 feet we must conclude that there is a definite possibility of such a surge becoming coincident with local high water, with disastrous effects. The probability of such an occurrence is another matter, which we shall deal with later.

Though conditions have been studied principally at Southend, such tide-gauge records as have been available have definitely shown that any storm surge experienced at Southend will also be experienced in greater or less degree at other places in the Thames Estuary, probably in close ratio to the mean ranges of tide at the places. Thus we should expect storm surges at London Bridge to exceed those at Southend in the ratio of 1.2 : 1.

PART II—STATISTICAL INVESTIGATIONS

§ 10—Definition of Symbols.

The investigations recorded here follow the methods of my paper[4] on "Meteorological perturbations of sea level and tides," dealing with Newlyn and Liverpool, and therefore explanations of the statistical terms and methods will not be repeated here.

[4] London : *Mon. Not. R. Astr. Soc.* Geophysical Supplement, April, 1924.

It will be assumed that the perturbation of sea level can be represented as a linear function of the atmospheric pressure and its gradients in two directions. Such an assumption is only warranted if there is reason to believe that the effects on sea level are changed in sign when the wind is reversed in direction. Certain results given for Ostend by Dr. Schulz (loc. cit.) definitely indicate that this is so at that place, and it is quite likely that the same will hold in the Thames Estuary. Further, the formula assumes implicitly that the sea level varies with the velocity of the wind, whereas it should be as the square of the velocity: hence it is unlikely that a close representation of the variations of sea level will be obtained, but our principal object is to ascertain the relative importance of various areas and winds as affecting sea level and the formula can be used with confidence for this purpose.

Therefore we take

$$\zeta - \bar{\zeta} = \kappa (B - \bar{B}) + \lambda (E - \bar{E}) + \mu (N - \bar{N})$$

where the variables ζ, B, E, N may be taken at specified times, not necessarily simultaneous.

Here

ζ = height of sea, attributed to meteorological causes
B = atmospheric pressure at a place P
E = excess of pressure 500km. east of P over the pressure 500km. west of P
N = excess of pressure 500km. north of P over the pressure 500km. south of P
$\bar{\zeta}, \bar{B}, \bar{E}, \bar{N}$ = arithmetic means of ζ, B, E, N in the interval of time considered
κ, λ, μ = constants such that if B, E, N are measured in millibars ζ is measured in centimetres.

We also write

Z = mean value of ζ from 25, or more, hourly heights symmetrically arranged with respect to the time t.
M = number of observations dealt with in evaluating the constants of the formula.

Angles will be denoted in general by θ, measured from the east round by the north. It is readily verified that an alternative form of (1) is given by

$$\zeta - \bar{\zeta} = \kappa (B - \bar{B}) + G\sqrt{\lambda^2 + \mu^2} \cos (\psi - \epsilon) - \text{constant}$$

where

ψ = direction of maximum gradient,
$\epsilon = \tan^{-1} (\mu/\lambda)$,
G = atmospheric pressure gradient over a distance of 1,000km. taken in the direction ψ,

and the constant represents the mean value of the second term on the right hand side.

Obviously, for a given intensity of gradient at a given place, the sea level is raised most when

$$\psi = \epsilon.$$

If we take the direction from which the wind blows as 70° behind the direction of maximum gradient, then the most effective wind comes from the direction

$$\epsilon - 70^\circ$$

The values of Z, (M = 346), have been computed for $t = -23, -17, -11, \ldots$ 61, 67, from hourly heights of tide at London Bridge during the year 1925. Three sets of values of B, E, N were computed from the synoptic charts at 7 a.m. on each day; these are denoted, whenever necessary, as follows:—

B, E, N about a point (60°N., 0°E.) between Scotland and Norway.
B', E', N', about London Bridge.
B'', E'', N'', about a point (50°N., 10°W.) south of Ireland.

§ 11—Correlations Between mean Sea Level and Meteorological Elements in three Localities

The correlation coefficients connecting the mean sea level Z at various times with the 9 pressure elements B, E, N, B', E', N', B'', E'', N'' are given in Table I with the values of the standard deviations, corrected for grouping. Table II gives the correlation coefficients between the 9 meteorological elements.

Table I—Correlation coefficients between the mean sea level (Z_t) at time t at London Bridge, with the barometric pressure and its gradients in three localities at $t = 7$, with standard deviations of Z_t and the meteorological elements.

t	Norwegian Sea.			Local.			Atlantic Ocean.			S. D. of Z_t in cm.
	B	E	N	B'	E'	N'	B''	E''	N''	
−23	·094	−·119	−·034	·087	−·132	·123	·113	−·074	·187	14·07
−17	·147	−·115	−·039	·099	−·141	·220	·097	−·088	·256	13·89
−11	·156	−·142	−·076	·109	−·200	·223	·114	−·057	·254	15·09
− 5	·169	−·220	−·072	·075	−·255	·288	·104	−·117	·328	14·58
1	·129	−·297	−·040	−·006	−·294	·297	·051	−·175	·360	14·07
7	·125	−·382	·000	−·055	−·345	·313	·035	−·219	·415	13·95
13	·060	−·424	·039	−·107	−·333	·218	·023	−·260	·370	15·14
19	·013	−·494	·045	−·143	−·331	·220	·005	−·313	·410	14·53
25	−·067	−·391	·085	−·202	−·235	·154	−·064	−·303	·311	13·93
31	−·098	−·281	·099	−·213	−·114	·121	−·105	−·267	·245	13·88
37	−·137	−·176	·076	−·190	−·022	·031	−·145	−·183	·129	15·03
43	−·145	−·173	·069	−·166	−·028	·020	−·144	−·138	·135	14·48
49	−·132	−·148	·119	−·185	−·011	·016	−·189	−·094	·140	13·91
55	−·101	−·144	·096	−·141	·015	·026	−·176	−·039	·152	13·83
61	−·142	−·115	·058	−·133	·052	−·063	−·183	·020	·081	14·92
67	−·131	−·159	·065	−·136	·061	−·056	−·144	·004	·094	14·45
S. D. in mb.	4·76	4·92	4·20	4·44	3·67	3·55	4·82	3·80	3·46	

Table II.—Correlation coefficients between pressure and its gradients in three localities.

	Norwegian Sea.			Local.			Atlantic Ocean.		
	B	E	N	B'	E'	N'	B''	E''	N''
B		−·146	−·060	·718	−·209	·799	·587	·096	·704
E			·020	−·121	·716	−·119	−·425	·515	−·527
N				−·687	·116	·066	−·584	−·265	·002
B'					−·239	·268	·878	·349	·335
E'						−·149	−·682	·597	−·415
N'							·187	−·119	·825
B''								−·151	·368
E''									−·226
N''									

It will be noticed that the coefficients vary regularly with t. Thus, the correlation coefficient between Z and E has a maximum numerical value when t is about 19 so that the sea level is apparently most highly correlated with the east gradient of pressure in the Norwegian Sea when the sea-level is taken 12 hours later than the pressure ; any slow variations of pressure gradient will therefore apparently tend to be reproduced in the sea about 12 hours later ; in other words, there is an *apparent* time lag of 12 hours with the east gradient in the Norwegian Sea. We speak of an *apparent* time lag because we have yet to separate the effects of winds in the three localities, and as yet we cannot draw definite conclusions regarding the most effective winds and their time lags in the separate localities. It is, however, of interest to note that the time lags vary in the three localities and that the directions of the winds most effective for raising sea-level also vary. Since an east gradient corresponds approximately to a south wind, and a north gradient to an east wind, then the negative signs attached to the coefficient under E, and the small coefficients under N, show that the effective wind in the Norwegian Sea must be N. The effective wind locally is *apparently* from the NNE., and that in the Atlantic is *apparently* from the SE., approximately. The influence of the pressure, considered as operating statically is *apparently* very small ; the change in sign of the coefficients is of some interest.

§ 12—Separation of Influences exerted in each Locality

In order to separate the influences exerted in each locality we assumed the following formula

$$Z = \kappa' b' + \lambda e + \mu n + \lambda' e' + \mu' n' + \lambda'' e'' + \mu'' n''$$

where $z = Z - \bar{Z}$, $b = B - \bar{B}$, $e = E - \bar{E}$, $n = N - \bar{N}$, etc., and undashed symbols refer to the Norwegian Sea, symbols with single dashes to the local conditions, and symbols with double dashes to the Atlantic Ocean south of Ireland. Thus we have expressed the variations in mean sea level at London Bridge as a linear function of the local barometer and of the components of pressure gradient in each of the three localities.

Results are given in Table III which also gives values of $\lambda^2+\mu^2$ and $\epsilon-70°$, viz. the ' intensity coefficient ' and the direction of wind respectively.

The standard deviation of the values of Z is 0·47 ft., and for hour 13 the standard deviation of the residues

$$z-\kappa'e'-\lambda e-\mu n-\lambda'e'-\mu'n'-\lambda''e''-\mu''n''$$

is 0·866 times this, so that the formula is by no means a good representation of the variations of sea level. At Liverpool the standard deviation was reduced to about half its original value. The absolute value of the correlation coefficient between sea level and meteorological changes according to the formula is 0·501.

TABLE III.

t	κ'	λ	μ	λ'	μ'	λ''	μ''
1	−·457	−·158	−·288	−·357	·376	·227	·225
7	−·570	−·234	−·293	−·398	·360	·294	·307
13	−·585	−·325	−·263	−·302	·177	·227	·397
19	−·615	−·421	−·307	−·135	·131	·147	·463
25	−·550	−·319	−·252	−·021	·053	·028	·412
t		$\sqrt{\lambda^2+\mu^2}$	$\epsilon-70°$	$\sqrt{\lambda'^2+\mu'^2}$	$\epsilon'-70°$	$\sqrt{\lambda''^2+\mu''^2}$	$\epsilon''-70°$
1		·328	171°	·518	64°	·320	335°
7		·375	161	·535	68	·425	336
13		·419	149	·350	80	·459	350
19		·520	146	·188	66	·485	2
25		·407	148	·057	42	·412	16

Always bearing in mind that this method is theoretically only applicable to slow changes of pressure and wind we find that now we have allowed for the separate influences, the winds in each locality (judged by the intensity coefficient) are practically of equal influence, but the times taken to develop the full effects, and the directions of the effective winds, are quite different.

Thus a local wind is most effective when it blows from the direction $\theta = 64°$ to $68°$, that is, when the wind is NNE., and its effects are almost instantaneous (it should be remembered that the barometric data are taken at hour 7); in fact there is a small advance in time but in the complicated circumstances no real significance can be attached to this.

The winds operating in the Norwegian Sea are most effective when they come from the directions $\theta = 146°$ or NW. by W. and the maximum effect on sea level is 12 hours later than the time of maximum wind.

The Atlantic winds south of Ireland are most effective in raising sea level when they blow from direction $\theta = 350°$ to $2°$, or almost due E., and again a time lag of about 12 hours is necessary for the effect to be developed.

(It is somewhat curious that the directions of these winds are precisely those which we should get with an anticyclone over Scotland, but in such circumstances the winds must necessarily be small and consequently the elevation of sea level must be small; the effects of the winds in an anticyclone, however, tend to raise sea level while the pressure (considered as operating statically) tends to lower it, so that perhaps we have an explanation of the small value obtained for κ' in the equation $Z = \kappa' B'$, winds being ignored—at Liverpool the corresponding value is nearly unity, which is the statical value.)

§13—Discussion of Time Lags

If we consider the upper part of Table III more closely we notice that the winds operating over the Norwegian sea have practically the same time lag in their effects whatever be the direction of the wind; for the values of λ and μ are greatest, numerically, when $t = 19$, so that the time lag of the meteorological perturbations of sea level for southerly or northerly and easterly or westerly winds is about 12 hours in each case. Similarly local winds are almost independent of direction as regards the time lag, there being a slight tendency for easterly or westerly winds to be quicker in action than southerly or northerly winds. The Atlantic information is very interesting; the values of λ'' indicate that a southerly or northerly wind there, operates almost instantaneously on sea level in the Thames, while an easterly or westerly wind has a lag of about 15 hours in its effects. These results throw light on the motions taking place. It seems quite reasonable that NW. by W. winds in the Norwegian seas, and NNE. winds in the Flemish Bight, with time lags of 12 hours and zero should be effective in raising sea level, and that the time lags should be independent of direction of wind.

It is popularly and erroneously assumed that the water will be driven in the direction of the wind. As Ekman showed,[5] the rotation of the earth must be considered, and in deep water away from land the *surface current* is inclined at 45° to the right of the wind direction and the velocities of the lower layers are such that taking the whole of the fluid into consideration the resultant transport of water is not in the direction of the wind but at right angles to it. When the water considered is near a long straight coast, Ekman's theory indicates that "the surface current is always deflected to the right of the wind's direction, the angle of deflection is between 0° and 53° . . . and a wind of given strength would have the greatest effect when directed a little more than 13° to the left of the coast-line; and perpendicularly to this direction it would have its smallest effect. If the wind be conceived as having all possible directions relative to the coast, the average velocity of the surface water would be 1·66 times the value it would have in the absence of coasts."

Hence we see that the most effective wind operating in the Norwegian Sea would cause a surface current to be directed almost due south, and in fact the direction of this wind with respect to that of the coast line is in accordance with Ekman's theory.

If we take the Atlantic results as being typical of the actions even further west, in really deep water, we would expect (on Ekman's theory) that a S. wind would

[5] V. Walfrid Ekman: On the Influence of the Earth's Rotation on Ocean-Currents. *Stockholm. Arkiv för Mat., Astron., Fysik*; 1905. Band 2. No. 11.

cause a resultant drift eastwards, whereas an E. wind would give a drift northwards ; any variation in the E. wind would affect the drift and ultimately the elevation in the Thames but because of the time required to travel round Scotland we get a time lag of over 12 hours, whereas the variations in a S. wind in the Atlantic would cause variations of drift which would probably travel up the English Channel arriving in the Thames by a short route, as is indeed indicated by the values of λ''

§14—Connexion with Part I

These results may be connected with those of Part I to a certain extent ; a westerly wind in the Atlantic, according to the statistical investigation would tend to lower sea-level in the Thames, and a wind from NW. by N. in the Norwegian Sea would tend to raise it. When a cyclonic system is found west of Ireland the winds over the Atlantic south of Ireland will be westerly and thus the sea level in the Thames will fall ; later, as the cyclone travels east, the winds over the Norwegian Sea will veer to the north-west and the sea levels will rise—this sequence is actually observed in most of the cases of large storm surges.

Thus the results of the statistical investigation, with all its limitations, are quite consistent with those of Part I and they will serve to give guidance in the further investigation which is required before the meteorological conditions can be specifically formulated in so definite a manner that forecasts can be prepared as a matter of routine.

PART III—THE EFFECTS OF LAND WATER

§15—Gradient due to water passing Teddington Weir

The effects of land water have been studied in connexion with the values of mean sea level (Z) for the year 1925, as used in the statistical investigations of Part II. The Engineer to the Thames Conservancy Board provided me with a table of gaugings of river water passing Teddington Weir, in millions of gallons per day. As we should anticipate the variations in land water and the resulting effects on sea level at London Bridge and Southend to be fairly regular in character, as indeed is the case, a simple test of the effects of land water is to compare the mean values of Z each month at London Bridge and Southend with the monthly mean values of the weir gaugings (F) as follows :—

Month	$\bar{Z}$ London Bridge	$\bar{Z}$ Southend	$\bar{F}$	$\Delta\bar{Z}$
Jan. ..	11·07	9·87	4,842	1·20
Feb. ..	10·77	9·70	3,756	1·00
March ..	10·80	9·63	2,749	1·17
April ..	10·67	9·67	1,594	1·00
May ..	10·67	9·67	1,401	1·00
June ..	10·93	9·97	643	0·96
July ..	10·67	9·90	449	0·77
Aug. ..	10·87	10·10	578	0·77
Sept. ..	10·87	10·20	603	0·67
Oct. ..	10·83	10·17	1,330	0·66
Nov. ..	10·93	10·37	2,046	0·56
Dec. ..	11·00	10·24	1,876	0·76

Here $\Delta\bar{Z}$ is the difference between the monthly mean values of sea level at London Bridge and Southend. The values of Z are given in feet above the datum 21 feet below T.H.W. for both London Bridge and Southend. We notice that on the average mean sea level at Southend is 0·9 foot lower than at London Bridge. It would be natural to assume that this is due to the gradient set up by land water, but this explanation is not at all satisfactory for, since the mean value of F is 1,813 million gallons it would imply that 4,842 million gallons per day of flood water must result in a difference of elevation of 2·4 feet, which is much too large. Taking the maximum and minimum values we find that the January and September values give

fall in F = 4,239 m.g.
fall in Z = 0·53 ft.

so that with F = 10,000 m.g. per day the fall in elevation for London Bridge to Southend would be, on this basis 1·25 ft., but the variations from month to month are not very satisfactory. The correlation method applied to these numbers gives the same result, approximately, while a rough graph of Z against F gives

F = 10,000 m.g. Z = 1·0 ft.

Since there is an annual variation of F and an annual variation in Z at London Bridge, and since some part of the latter may not be of local origin, correlation between Z and F would give a spurious result on this account. Hence in correlating values of Z with F for each day of the year the mean values in each month were subtracted from the daily values in order to avoid the spurious correlation. Values of Z centring on $t = 25$, with F centring on noon, so allowing a lag of 13 hours, yielded

F = 10,000 m.g., increment in Z = 0·826

and if Z is taken at $t = 37$ the increment in Z is less in the ratio 3/4.

Mr. Binns, engineer to the P.L.A., has computed the rise due to 10,000 m.g. per day at Teddington using the formula

$$\text{Rise from A to B} = \frac{1{,}111{,}111 \text{ c. ft.} \times \text{time of travel of wave from A to B in minutes.}}{\text{Area of surface between A and B in sq. ft.}}$$

and obtains

Rise from Southend to Tilbury = 0·03 ft.
Rise from Southend to London Bridge = 0·67 ft.

It may be assumed that at Southend the effects of land water are negligibly small. The result obtained by Mr. Binns is even smaller than the result obtained by the method of correlation, which was smaller than any of the approximate figures previously discussed.

We may therefore conclude that at London Bridge when 10,000 m.g. of water per day are passing over Teddington Weir the general level of the river is raised by 0·8 to 1·0 ft., and that the variations in land water are not of primary importance in connexion with the possibilities of floods in London, though it has to be granted that one foot may make all the difference between safety and disaster if a storm surge is superposed with it on high water.

The mystery of the difference in mean sea level between Southend and London Bridge must remain unexplained.

PART IV—PROBABILITIES

§ 16—Use of Frequency Curves

The probability of an event happening in the future is generally stated on the basis of the frequency of its occurrence in the past. If a sufficient number of cases are available so that the event has happened several times then the statement of probability can be accepted as substantially accurate. Where only one instance has occurred in past experience the measure of probability is subject to grave uncertainties ; the *direct method*, based on actual occasions, is then often abandoned and the actual statistics are replaced by a " frequency curve " obtained mathematically ; the advantage of the mathematical process is that the general trend of the statistics is given proper weight. We shall make frequent use of the system of frequency curves developed by Prof. Karl Pearson. As these are well known, the symbols and methods used will not be specially defined.[6]

[6] Reference may be made to " Tables for Statisticians . . . " edited by Karl Pearson, Cambridge University Press. " Frequency curves and correlation," by W. P. Elderton, published by C. and E. Layton.

§ 17—Data from Southend

It is necessary, of course, that there should be continuity in the statistical data in the sense that no permanent changes of conditions have taken place. At London Bridge there has been a change of tidal conditions owing to dredging, and consequently the statistics of tides need special care. At Southend, however, all the evidence shows that there has not been any marked change in the tides and therefore we commence with an examination of the frequencies with which the observed values of high water lie within specified limits. Table IV gives the frequency distribution for the winter months (January, February, March, October, November, December) in each year. Observations are lacking during the winter of 1923–4. The observations are given in feet above a datum 20 ft. below T.H.W. Thus, in 1927, we see that only one tide exceeded the height of 20 feet (*i.e.*, T.H.W.), 12 tides reached elevations between 19 and 20 feet, and so on. The total numbers of occurrences in the 12 years are given in the last column but one.

Table IV.

Limits	1927	1926	1925	1924	1923	1922	1921	1920	1919	1918	1917	1916	Sums	Successive Sums
ft. 21—22							1						1	1
20—21	1		1	2	1		2			5	2	2	16	17
19—20	12	16	3	11	4	10	6	5	8	7	14	13	109	126
18—19	42	56	54	27	8	41	32	31	31	43	43	55	463	589
17—18	71	78	101	35	18	67	93	91	79	66	62	75	836	1,425
16—17	82	76	92	49	23	75	84	91	77	80	84	78	891	2,316
15—16	77	77	54	27	32	60	67	65	62	71	66	61	719	3,035
14—15	53	39	30	23	24	39	45	30	33	46	47	35	444	3,479
13—14	7	10	11	3	7	14	17	17	16	14	9	16	141	3,620
12—13	3	1	1	1	1		1	6	2	1		4	21	3,641
11—12	1					1	1		1			1	5	3,646
	349	353	347	178	118	307	349	336	309	333	327	340	3,646	

§ 18—Crude Estimation of Probability

Now the exceptional tide of January 6–7 reached 2·5 feet above T.H.W. at Southend and 5·9 feet above T.H.W. at London Bridge, and therefore we can reasonably consider that the probability of floods occurring in London might be very approximately that of the tide reaching 22·5 ft. at Southend. The last column of Table IV shows that during the years 1916–1927 inclusive, only one tide exceeded 21 ft., 17 exceeded 20 ft., 126 exceeded 19 ft., 589 exceeded 18 ft. The ratios 126/589, 17/126, 1/17 are approximately 1/4, 1/8 1/16, and we might conclude that the probabilities of exceeding 21 ft., 22 ft., 23 ft. are respectively in the ratio 1, 1/32, $1/32 \times 1/64$ and therefore that the probability of exceeding 22·5 feet would be $(1/32)^2$ $(1\sqrt{2})$ relatively to that of exceeding 21 ft. Since the probability of exceeding 21 ft. gave an occurrence of one in 12 years, the probability of exceeding 22·5 ft., and therefore of causing floods in London, would, on this basis, give an occurrence of one every $12 \times (32)^2 \times \sqrt{2}$ years, that is of one every 17,000 years! In order to illustrate the difficulties involved in estimating probability by such methods, suppose that the tide of 22·5 ft. of January 6, 1928, had occurred in December 1927. Then the ratios used in estimating the probabilities would be very much modified, and, in fact, the method would fail.

§ 19—FREQUENCY CURVES OF TIDES AT SOUTHEND

The methods of fitting frequency curves were applied and the technical details are given in Appendix III. The criteria indicated that the frequencies (y) could be represented by

$$y = y_0\left(1 - \frac{x^2}{a^2}\right)^m$$

where x is the excess of the elevation over the mean elevation (16·505 ft.), $m = 7{\cdot}649$, $a = 6{\cdot}405$, and y_0 (not evaluated) is the maximum value. The most important fact about this frequency curve is that the range is limited in both directions, the limits being $16{\cdot}505 \pm 6{\cdot}405$. Hence, on this basis, an elevation of 22·91 ft. is indicated as the absolute maximum possible at Southend. Physically, we are only entitled to say, that the probability of exceeding 22·9 ft. would be extremely small.

If the statistics include the tide of Jan. 6 the values of m and a become 9·590 and 7·067 respectively and the limits of tide become $16{\cdot}507 \pm 7{\cdot}067$, so that the upper limit is raised to 23·57 ft.

The actual probabilities can be evaluated from these curves. Calculation is simplified if we take $m = 10$, which corresponds to $a = 7{\cdot}2$, so that the probability of flooding is a little greater than is given by either of the two cases above.

The result is to show that the probability on this basis, is such that a flood corresponding to that of Jan. 6 would only occur once in 1,700 years.

Ultimately if m and a were supposed to increase together we should get the "normal" probability curve.

$$y = y_0 e^{-\frac{x^2}{2\sigma^2}}$$

where σ is the "standard deviation," which in our case is not indicated as being much more than 1·5 ft. The probability of reaching or exceeding 22·5 ft. ($x = 6$ ft.) according to Shepherd's Tables, is ·0000317 ; that is, 1 tide out of 31,500 would reach 22·5 ft., and since there are about 354 tides in the winter months the probability is such that the event would happen once in 89 years.

§ 20—ALTERNATIVE METHOD

A disadvantage of the methods hitherto discussed is that the statistics are dominated by the usual tidal motion ; the middle portion of the frequency distribution would thus be the same if the meteorological disturbances had not taken place, and therefore only the extremes of the distribution are really affected by the meteorological disturbances. An alternative method of attack is therefore to study the separate probabilities of

(*a*) the meteorological disturbance reaching a specified amount ;

(*b*) an undisturbed (*i.e.*, predicted) tide reaching a specified height.

When these have been obtained it is possible on certain assumptions to combine them so as to obtain the probability for a flood to occur.

Using such data as were available, the method has been applied to observations and predictions for London Bridge.

§ 21—FREQUENCY CURVES FOR METEOROLOGICAL DISTURBANCES OF TIDES AT LONDON BRIDGE

Considering firstly the meteorological disturbances of predicted tide, an examination of the differences of observed and predicted tide was made, using data for 1925. This was the year for which an analysis of the tides had been made at the Institute, and harmonic corrections to predictions had also been evaluated ; a test prediction on the sequence of high waters following the upper transit of the moon had been made and the resulting "errors" are thus entirely free from periodic variations. Unfortunately there are only 172 values during the winter months. The distribution is given in Table V.

TABLE V.—FREQUENCY DISTRIBUTION OF ERRORS OF SPECIAL PREDICTIONS AT LONDON BRIDGE, 1925

Range of Error	Frequency
ft.	
−4·0 to −3·6	1
−3·5 ,, −3·1	
−3·0 ,, −2·6	
−2·5 ,, −2·1	3
−2·0 ,, −1·6	5
−1·5 ,, −1·1	7
−1·0 ,, −0·6	32
−0·5 ,, −0·1	41
0·0 ,, 0·4	36
0·5 ,, 0·9	30
1·0 ,, 1·4	9
1·5 ,, 1·9	2
2·0 ,, 2·4	4
2·5 ,, 2·9	2

and it is shown in App. III that the appropriate frequency curve is

$$y = y_0\left(1+\frac{x^2}{a^2}\right)^{-m}$$

where $m=4{\cdot}24$, $a=4{\cdot}32$, and x is measured from the mean 0·24 ft. (The mean error is due to the neglect of known long-period tides in the predictions.)

The Meteorological Office, having extracted errors of tidal predictions for the winter months of 1924–7, inclusive, kindly placed the results at my disposal. The predictions were known to be inaccurate and the errors were read to the nearest 0·5 ft. only, but it was considered desirable to investigate the law of error. The mean results for the four years are given in Table VI.

TABLE VI.—FREQUENCY OF ERRORS OF PREDICTED TIDE AT LONDON BRIDGE

Average Error	FREQUENCY				SUM
	1924	1925	1926	1927	
ft.					
−5·5			1		1
−5·0					
−4·5					
−4·0	1				1
−3·5			3	1	4
−3·0		2		1	3
−2·5	2	2	2	2	8
−2·0	6	9	11	2	28
−1·5	10	12	9	13	44
−1·0	32	46	40	44	162
−0·5	88	73	76	85	322
0·0	77	87	84	78	326
0·5	69	55	61	53	238
1·0	42	39	41	44	166
1·5	21	10	23	18	72
2·0	5	8	3	8	24
2·5	1	8	1		10
3·0		1		1	2
3·5		1		1	2
Mean Error	−0·024	−0·016	−·056	−0·004	

In the above table an average error of 0·5 ft. was allowed for in 1924, and 1·0 ft. in the other years ; this makes the mean errors approximately zero and also makes the frequency curves very nearly the same for small errors between −1·5 and 1·5 ft. It is shown in App. III that the frequency curve is of the same type as that just given, with $m=4{\cdot}08$, $a=4{\cdot}15$.

Hence, the two distributions are very little different from one another, and a mean value was taken. The frequency curve yielded the following probabilities :—

TABLE VII

Error equal to or greater than	PROBABILITY	With 350 winter tides average occurrence is
3·0 ft.	·0031 = 1/320	1 per year
3·5	·0013 = 1/770	1 in 2 years
4·0	·0006 = 1/1700	1 " 5 "
4·5	·00032 = 1/3000	1 " 9 "
5·0	·00017 = 1/6000	1 " 17 "
5·5	·00009 = 1/11000	1 " 30 "
6·0	·00005 = 1/20000	1 " 60 "

These probabilities are in general accordance with the results of the scrutiny of Southend tide gauge described in Part I and Appendix I, and with Table VI and they can be considered as being fairly well established. It may be noted that the probability is halved for every increment of 0·5 ft. in the error.

§ 22—FREQUENCY CURVES OF PREDICTED TIDES AT LONDON BRIDGE

Before any application can be made of these figures it is necessary to consider the distribution of the elevations of predicted tide. The predictions for London Bridge for the years 1919 to 1929 were taken, and for each year a frequency table was constructed for every tenth of a foot giving the number of occasions on which the predicted tide equalled or exceeded a specified level. The predictions for 1928 and 1929 are on a more accurate basis than those for the previous years. As the middle portion of the frequency distribution should be independent of the methods of prediction, the distributions of earlier years were made to correspond with those of 1928 and 1929, as nearly as possible, by subtracting 0·8 ft. for the predictions for 1919 to 1924 and 1·2 ft. for the predictions of 1925 to 1927. The results are summarised in Table VIII.

TABLE VIII—FREQUENCY DISTRIBUTIONS OF PREDICTED TIDES FOR THE WINTER MONTHS OF 1919–1929.

(There are about 354 tides in each half year).

YEAR	Elevations equal to or greater than						
	20·5	21·0	21·5	22·0	22·5	23·0	23·5 ft.
1919	199	149	91	52	29	8	0
1920	166	126	89	50	16	2	0
1921	171	125	93	50	23	7	0
1922	166	120	80	48	31	13	5
1923	164	120	71	46	32	14	3
1924	169	128	93	52	20	3	0
1925	171	133	99	61	20	2	0
1926	159	126	83	46	27	12	1
1927	154	111	63	46	28	16	2
1928	173	128	86	54	33	14	2
1929	161	119	68	23	3	0	0
Averages							
1919–1927	169	126	85	50	25	8·6	1·2
1928–1929	167	124	77	39	18	7·0	1·0
1919–1929	168	126	83	48	24	8·3	1·2

As it happens the predicted tides are exceptionally high in 1928 and exceptionally low in 1929 for all places. It is unfortunate that accurate predictions are only available for two years for the frequency distribution changes considerably from year to year for the higher values of the elevation, as would be expected, but the average values of Table VIII may be accepted for discussion.

§ 23—Deduction of Probability

The application of the results of Tables VII and VIII is by no means a simple matter, as some difficult questions in probability arise. It is quite clear that a storm surge of 6 feet may only occur once in 60 years on the average and that it cannot rise to the level of the flood works (26·5 ft.) unless the tide is greater than 20·5 feet, as it is in 168 cases out of 354 per year ; the resulting probability of a flood occurring *in this specified way* gives a frequency of one in 60 × 354/168 years ; that is, one in 126 years. It is necessary to consider the total probability and to do this I determined firstly from the results of Table VIII the number of cases to be expected per annum in which the predicted tide was a specified height, taking heights at intervals of a tenth of a foot. Against each I wrote the probability of an associated storm surge increasing the elevation to, or more than, 26·5 ft. as obtained by interpolation in Table VII, and the sum of the products gives the total probability of a flood occurring in a year's time. The result was approximately ·055 which would suggest a possibility of a flood every 18 years. Such a method as this is subject to much criticism and I can place little confidence in the result. It assumes, for one thing, that an increase of 6 feet, say, in high water is equally probable with neap tides and spring tides, and though it is clear from Part I that the surges which markedly raise high water are largely propagated inwards and thus are largely independent of local tidal conditions, yet there is a further point to consider, which has been ignored in Part I. At neap tides the effects of friction on reducing the range of tide are small, but a large spring tide is smaller than it would otherwise be if friction were absent. We see a tendency in Table VII for large errors to be greater when the error is negative than when it is positive. A more exact frequency distribution would take account of this, but it hardly seemed desirable with such data as are given in Tables VII and VIII to undertake a more laborious investigation. There are other questions to be considered in connexion with the independent probabilities which have been assumed. Hence, on many grounds, I am of the opinion that the probability of a flood in London once in 18 years is much too high.

On the whole, therefore, I consider that much greater weight must be given to the results of §19 and that the Gaussian (or normal) frequency curve will give the best representation if all extreme cases are included. Even if we increased the standard deviation somewhat the probability is not likely to be much different from about 1 in 60 years.

The effects of raising the flood works can be estimated in two ways. The frequency distribution of predicted heights is constant and we note that in Table VII the probability of a surge is halved when the amplitude is raised by 0·5 ft., so that on this basis raising the defences by 0·5 ft. would diminish the probability to one half its present value, and raising them by 1·0 ft. would make the probability of a flood only one quarter of its present value. The statistics of Table IV apparently give very different results, and we make use of the normal or Gaussian probability curve.

The ranges of tide and amplitudes of surges are smaller at Southend than at London Bridge in the ratio 0·8 : 1 ; if, therefore, the flood works in London are raised by 0·5 ft. it will be necessary to consider an increase of 0·4 ft. in the elevation of the sea at Southend for flooding to be caused in London. At present, in the expression for the probability we have

$$x = 6{\cdot}0 \text{ ft.}, \ \sigma = 1{\cdot}50 \text{ ft.}$$

and taking $x = 6{\cdot}0$ ft., $6{\cdot}4$ ft., and $6{\cdot}8$ ft. we get ·0000317, ·0000102 and ·0000029 as the probabilities of floods in London with the defences as at present, 0·5 ft. and 1·0 ft. higher, respectively. The reductions are smaller than those obtained by the alternative method. We conclude that if the defences are raised by 0·5 ft. or by 1·0 ft. the frequency of occurrence of floods will be reduced approximately in the ratio 1/2 to 1/3, 1/4 to 1/10 respectively.

APPENDIX I

List of Dates on which Storm Surges have been Prominent

T denotes that the elevation exceeded T.H.W.
⊙ denotes cyclone.
H denotes an elevation of sea level.
L denotes a depression of sea level.

Year	Dates	Tidal disturbance		Meteorological conditions	
		Class	Notes	Type	Notes
1928	Jan. 6–7	A T		I	
1927	Dec. 26	A/B T	H a.m.	?	
	Oct. 29	B	L a.m.	IV.	Moves NE., winds remain SW.
	Oct. 3	B	H about noon	I	
	Jan. 28–29	A	Changes rapidly about noon of 29th L–H	?	
1926	Dec. 18–20	B	H on 18th p.m.; L on 19th; H on 20th	I	Two normal types
	Nov. 13	A	L p.m.	IV	Deep ⊙ almost stationary N. Scotland.
	Nov. 5	A/B	L p.m.	IV	Deep ⊙ over W. Ireland.
	Oct. 25	B	L a.m.	II	
	Oct. 9–10	A	H a.m. on 10th	I	
	Mar. 5–11	A	H a.m. on 5th; L on 6th	I	
1925	Dec. 23–24	A/B	H a.m. on 23rd; L a m 24th	I/II	
	Nov. 25–27	A	H p.m. 25th; H a.m., L p.m. 26th	I/III	
	Jan. 29–30	A/B	L p.m. 29th; H a.m. and p.m. 30th	?	
	Jan. 14–15	B	L about noon 14th; H about noon 15th	IV ?	
	Jan. 1–2	A	L a.m. on 2nd	IV	
1924	Dec. 27–28	B T	L on 27th; H on 28th	IV	
1923	Aug. 30	B	L a.m.	II/IV	
	Apr. 25	B	L a.m. and p.m.	IV ?	
1922	Dec. 25	?	Poor record		
	Dec. 6	B	H a.m. and p.m.	I	
	Nov. 10	B	L	?	S. winds.
	Nov. 1	A/B	L p.m.	IV	
	Sept. 16–20	B	L on 16th p.m., L 19th noon; H 20th p.m.	I	
	Jan. 4	A	H	III	
1921	Dec. 31	A T	H about 9 a.m. Double H.W. at London Bridge	I	
	Dec. 25	B	L a.m.		
	Dec. 24	B	H a.m.	I	
	Dec. 20	B	L a.m.		
	Dec. 18	A T	Rather complex	III	
	Nov. 6–7	B	H p.m. 6th, H a.m. 7th	I/III	
	Nov. 1	A T	H 2 p.m.	I	
	Oct. 23–24	A	H p.m. 23rd	I	
	Mar. 2–3	A/B	H on 2nd; L on 3rd	III	Backing NW. to SW.
	Jan. 19	A	H 18th p.m.; H 19th; L on 20th	III	
1920	Dec. 4	A	L 3rd; H 4th	I	
	Feb. 27–28	B	Records not good, L on 28th p.m.	IV	
	Feb. 13–14	A/B	Records not good, L on 13th a.m.; H 14th	I	
	Jan. 11	B	Records not good		
1919	Dec. 19	A	Poor record	I	
	May 2	C T			
	Feb. 18	C T			
1918	Dec. 24–28	A	Very L on 27th; very H on 23rd–24th	I	
	Feb. 26	B	L p.m.		
	Jan 16	B T	L on 15th; H on 16th a.m.	I ?	
	Jan. 15	B			
	Jan. 11	B	H		
1917	Dec. 17	C T		III	
	Dec. 2–3	A	Very complex H on Nov. 25–26, L on Dec. 1, H on Dec. 2, falls rapidly Dec. 3		
	Nov. 25–26	A			
	Oct. 30	B	L		
	Oct. 25–26	B	L 25th; H 26th		
	Aug. 3	B	L p.m.		
1916	Oct. 14–15	B	L on 14th p.m., 15th a.m.; H 16th a.m.		
	Feb. 14–16	A/B	Complex		
	Feb. 5	A T	H on 5th; L on 6th		
	Jan. 13–16	A			
	Jan. 8	B/C T			
	Jan. 2–4	B	H on 2nd p.m.; L p.m. on 4th		
1915	Dec. 27–28	B	L p.m. on 27th; L a.m. on 28th		
	Dec. 9	B T	H a.m.		
	Oct. 25	B	H p.m. 24th; H a.m. 25th		

APPENDIX I—*continued*

Year	Dates	Tidal disturbance		Meteorological conditions	
		Class.	Notes	Type	Notes
1915	Feb. 17	A	L		
1914	Dec. 26–30	A/B	L on 26th ; H on 29th ; L on 30th		
	Dec. 3–7	A/B	L on 3rd, 5th and 7th ; H on 6th		
	Nov. 11–13	A	H p.m. 11th; H on 12th; L on 13th		
	Sept. 28–29	A	L on 28th a.m. ; H p.m. 28th ; H a.m. 29th		
	Jan. 7–8	B	H a.m. 7th; L pm. 7th and a.m. 8th		
1913	Dec. 26	B	L p.m.		
	Dec. 13–14	B	H a.m. 13th, and a.m. 14th		
	Apr. 16–17	B	L a.m. 16th ; H a.m. 17th		
	Mar. 24	B T }	H p.m. 22nd; L a.m. 23rd ; H p.m. 24th		
	Mar. 22	B T }			
	Mar. 18–19	A/B	Complex		
	Feb. 28– Mar. 7	B	Complex		
	Feb. 8	B	L a.m. ; H p.m.		
	Jan. 25	C/T	H p.m.		
1912	Dec. 10–19	A/B	L on 13th–14th		
	Dec. 4	B	L		
	Nov. 27	A	H 26th a.m. ; L p.m. 26th ; L a.m. 27th		
	Nov. 11–12	B	H p.m. 11th ; H a.m. 12th		

APPENDIX II

A Method whereby the Meteorological Perturbations can be separated from the Tidal Oscillations when Tidal Predictions are not available

The method is best explained by an example for Dunbar, Jan. 11–18, 1916, for which observations were available at each hour of the day. The method makes use of six series of observations at intervals of six hours, and the following table gives the series for hours 2, 8, 14, 20 on each day :—

Day	Hour 2	Hour 8	Hour 14	Hour 20
Jan. 11	9·6	17·5	10·3	17·9
12	7·6	16·7	8·7	17·6
13	10·5	18·3	12·9	17·4
14	10·0	13·6	9·7	13·9
15	12·2	14·9	16·2	14·4
16	13·2	10·7	14·5	10·9
17	16·5	11·0	17·5	9·6
18	17·3	9·5	18·5	8·5

If the tides were entirely unperturbed by meteorological influences the elevations at intervals of 12 hour should run quite smoothly ; thus the series of observations at hours 2 and 14 would give a smooth curve on plotting, and the series 8 and 20 would also give a smooth curve ; there is a definite relationship between these curves for semi-diurnal tides, for if the values at hours 8 and 20 are subtracted from twice the value of mean sea-level the results will fit perfectly the curve at hours 2 and 14.

We therefore plotted the hourly heights of tide at Dunbar for hours 2 and 14, showing them by a full line, and on the same diagram we plotted, as shown by a broken line, the values of $(2A_0 - \delta_8)$, $(2A_0 - \delta_{20})$ where δ_8, δ_{20} are elevations at hours 8 and 20, and A_0 is the value of mean sea level, in this case 13·0 ft. (Of course the plotting was carried out with correct time spacing). Now we remark that if both high water and low water are raised the two " curves " will move in opposite directions, and that the curve representing the elevation as unperturbed by meteorological influences is the mean curve shown by the dotted line. The value of this method lies in the fact that the two " actual curves " cross and recross the " unperturbed curve." Using a small paper scale we now read off the differences between each of the " actual curves " and the unperturbed curve, remembering that the " curve " for hours 8 and 20 is below the " unperturbed " curve when sea-level has been raised.

Six such curves give information at each hour of the day. The value of the method has been shown quite clearly when there has existed a diurnal tide as well as a semi-diurnal tide, the resulting curves showing the diurnal tide occurring very regularly. Similarly, quarter-diurnal tides appear very regularly in the final curves, but these can be easily smoothed out if required.

Fig. 3 shows very well indeed the surges occurring on January 13 and 15 at Dunbar.

It may be remarked that any error in the assumed value of A_0 will lead to a shift upwards or downwards of the broken line (Fig. 3) as a whole, relatively to the full line; the resulting irregularities in the curve of residues can be smoothed out.

APPENDIX III.

TECHNICAL DETAILS OF FREQUENCY DISTRIBUTION.

Table IV and §§ 18–19.

The frequency distribution of the last column but one in this table yields

$$a = \nu_1 = \cdot 00521 \qquad \sigma = 1\cdot 4974$$
$$\mu_2 = \nu_2 = 2\cdot 24215 \qquad \beta_1 = \cdot 01588$$
$$\mu_3 = \nu_3 = -\cdot 42314 \qquad \beta_2 = 2\cdot 70440$$
$$\mu_4 = \nu_4 = 13\cdot 59567 \qquad \kappa_2 = -\cdot 01878$$

For Type I with $y = y_0\left(1 - \frac{x}{a^2}\right)^m$, $m = \frac{5\beta_2 - 9}{6 - 2\beta_2} = 7\cdot 6488$, $\frac{a^2}{\sigma^2} = \frac{2\beta_2}{3 - \beta_2} = 18\cdot 2977$ whence $a = 6\cdot 405$.

For Type II with $y = y_0\left(1 + \frac{x}{a_1}\right)^{m_1}\left(1 - \frac{x}{a_2}\right)^m$ we have

$$r = \frac{6(\beta_2 - \beta_1 - 1)}{6 + 3\beta_1 - 2\beta_2} = 15\cdot 8586 \quad , b = \tfrac{1}{2}\sigma\sqrt{\beta_1(r+2)^2 + 16(r+1)} = 12\cdot 3985$$

and m_2, m_1 are given by

$$\tfrac{1}{2}\left\{r - 2 \pm r(r+2)\sqrt{\frac{\beta_1}{\beta_1(r+2)^2 + 16(r+1)}}\right\} = 7\cdot 2700 \text{ or } 6\cdot 5886$$

Since μ_3 is negative the higher value is m_1.

Also $a_2 + a_1 = b_2$ and $a_2 = \frac{b}{1 + \frac{m_1}{m_2}} = 5\cdot 8944$

The mode $=$ mean $- \frac{1}{2}\frac{\mu_3}{\mu_2}\frac{r+2}{r-2} = 16\cdot 5 + \cdot 0052 + 0\cdot 1216 = 16\cdot 627$, whence the upper limit is $22\cdot 521$ ft., which is lower than that given by Type I.

If the statistics are made to include the extra case of one value between 22 and 23 feet, we get

$$a = \nu_1 = \cdot 00685 \qquad \sigma = 1\cdot 5005$$
$$\mu_2 = \nu_2 = 2\cdot 25139 \qquad \beta_1 = \cdot 01232$$
$$\mu_3 = \nu_3 = -\cdot 37503 \qquad \beta_2 = 2\cdot 75186$$
$$\mu_4 = \nu_4 = 13\cdot 94850$$

and for Type I $a^2/\sigma^2 = 22\cdot 1799$, $a = 7\cdot 0668$, $m = 9\cdot 590$

Taking $m = 10$, then $\beta_2 = 2\cdot 76$, $a = 7\cdot 2$

$$y_0 = \frac{21\,!}{7\cdot 2 \times 2^{21} \times 10\,! \times 10\,!} = \cdot 257$$

Taking $y = y_0\left(1 - \frac{x_2}{a_2}\right)^m = y_0\, \xi^m (2 - \xi)^m$, where $\xi = 1 - \frac{x}{a}$

then $\int_x^a y\,dx = y_0 \int_0^\xi \xi_m\, 2n\,(1 - \tfrac{1}{2}\xi)^m\, a d\xi$

In order to determine the probability of an error greater than $5\cdot 75$ feet at Southend, corresponding nearly to $\xi = 0\cdot 2$, we get after expansion by the binominal theorem and integration, the integral yielding

$$\cdot 257 \times 7\cdot 2 \times 2^{10} \times \frac{(0\cdot 2)^{11}}{11}\left\{1 - \cdot 917 + \cdot 381 - \cdot 010\right\}$$
$$= \cdot 0000016$$

Multiplying by 354 and dividing the result into units gives the number of years in which such an event can happen once, on the average.

Table V.

We have high contact indicated and therefore use Shepherd's corrections. The origin is taken with the group $-0{\cdot}5$ to $-0{\cdot}1$.

$$\nu_1' = {\cdot}4826 \;,\; \nu_2 = 3{\cdot}74 \;,\; \nu_3' = 4{\cdot}77 \;,\; \nu_4' = 61{\cdot}5$$
$$\mu_1 = {\cdot}4826 \;,\; \mu_2 = 3{\cdot}43 \;,\; \mu_3 = -{\cdot}43 \;,\; \mu_4 = 55{\cdot}7$$
$$\beta_1 = {\cdot}0045 \;,\; \beta_2 = 4{\cdot}73 \;,\; \kappa_2 = {\cdot}00110$$

The type required is $y = y_0\left(1 + \frac{x^2}{a^2}\right)^{-m}$ where $m = \frac{5\beta_2 - 9}{2\beta_2 - 6}$, $\frac{a^2}{\sigma} = \frac{2\beta_2}{\beta_2 - 3}$, and $m = 4{\cdot}24$, $a = 4{\cdot}32$

Table VI.

The frequency distributions for the several years were separately treated, and the resulting values of μ_2, μ_3, μ_4, were averaged, yielding

$$\mu_2 = 3{\cdot}350 \;,\; \mu_3 = 2{\cdot}094 \;,\; \mu_4 = 55{\cdot}05$$
$$\beta_1 = {\cdot}1166 \;,\; \beta_2 = 4{\cdot}905 \;,\; \kappa_2 = 0{\cdot}027$$

The type is $y = y_0\left(1 + \frac{x^2}{a^2}\right)^{-m}$ with $m = 4{\cdot}08$, $a = 4{\cdot}15$

Table VII.

Table XXV of " Tables for Statisticians " were used to compute

$$\int_x^\infty y_0\left(1 + \frac{x^2}{a^2}\right)^{-m} dx$$

in the cases $m = 4$ and $m = 5$. Direct numerical integration was also used to supplement the tables and interpolation for $\beta_2 = 4{\cdot}82$ was used to give the results of Table VII.

METEOROLOGICAL CONDITIONS ASSOCIATED WITH HIGH TIDES IN THE THAMES

By J. S. DINES, M.A., *Superintendent, Forecast Division, Meteorological Office.*

§ 1—INTRODUCTION

The Committee which was appointed at the Conference of Authorities held at the Ministry of Health on January 16, 1928, to consider the question of Thames floods, expressed the opinion that it was desirable that the whole subject of tides in the Thames should receive further expert investigation and that this investigation should be undertaken by the Liverpool Tidal Institute in co-operation with the Hydrographic Department of the Admiralty and the Meteorological Office. That part of the inquiry which has been carried out by the Meteorological Office has consisted of an investigation into the practicability of giving useful warnings of abnormally high tides in the Thames. It may be pointed out at once that the problem of forecasting a disastrous flood similar to that which occurred on the night of January 6–7, 1928, is not an easy one. Past records show that the waters of the Thames had not reached the height attained in central London in January last, at least since 1881, and that there had been no tide in the period of 47 years from 1881 to 1927 of a height sufficient to overflow the top of the Thames defences at their present level. Thus the phenomenon which it is desired to forecast has occurred once in about 50 years. Some evidence was brought before the Thames Flood Committee which indicated that the height of high water at Hammersmith has shown a gradual increase during the past 40 years. The Meteorological Office has not been concerned with an examination of this side of the problem and it is not desired to make any forecast as to how frequently disastrous floods may be expected to occur in the future but if for the present purpose we say that they will be twice as frequent in the next 50 years as in the past 50 years we shall assume that the phenomenon to be forecast may be expected to occur once only in every 25 years.

If the laws governing atmospheric movements and the effect of these upon Thames tides were as clearly understood and as amenable to mathematical treatment as those governing the movements of the heavenly bodies, it might be possible to issue the necessary forecasts with sufficient precision to forecast successfully a phenomenon which occurs only once in 25 years, without at the same time giving many false alarms. But bearing in mind the complications of the subject and the fact that the physical processes involved are at present only imperfectly understood it is quite clear that if a dangerous flood is to be forecast with reasonable certainty, warnings will have to be issued on many occasions besides that on which the flood occurs. The purpose of the present inquiry has been, by a careful examination of the available data to draw up a set of rules by means of which the probability of a marked rise in the waters of the Thames above the level predicted for the astronomical tide can be forecast. If such rules can be so drawn up that they cover all or nearly all of the cases in the past where a marked rise of the water above the predicted level has taken place, it will then be necessary to examine how often the same rules will lead to the issue of forecasts which are not followed by any marked disturbance of the water level. In addition it will be necessary to consider what are the chances that the disturbance if it develops will occur within an hour or two of high tide, the only time at which any damage is likely to result.

§ 2—Data available for Examination

The data available for the investigation fall into three classes :—

CLASS I.—A list of occasions on which the water in the Thames above London Bridge has risen at high tide to such a level as to cause comment. This list covers the period from 1874 onwards and has been obtained in part from papers by J. B. Redman, which will be found in the *Proceedings of the Institution of Civil Engineers*, Volume 49, 1876/7, Part III, pages 67–159 and Volume 72, 1882/3, Part II, pages 254–61; in part from the records of the London County Council, and in part from references to the subject which appeared in *The Times* after the flood of January last.

CLASS II.—A table of the actual and predicted height of high and low water at London Bridge for the period 1924–7 which has been obtained from the Port of London Authority.

CLASS III.—A set of curves from the Tidal Institute, Liverpool, showing in great detail the departure of the actual tide at Southend from the predicted level, hour by hour, for all occasions of abnormally raised tides which were revealed by inspection of the tide-gauge records over the period from 1916 to 1928. These departures must be assigned to a terrestrial as opposed to an astronomical cause.

Examination of the data showed that the great majority of tides which proved high enough to be considered worthy of comment and therefore of inclusion in Class I, and also all those which showed a large positive departure from the predicted level in Class III, have occurred during the six winter months October to March. It therefore seemed desirable to confine the inquiry for the most part to the six winter months of each year though all recorded cases in Class I, at whatever time of year they occurred, have been individually examined.

§ 3—Preliminary Investigation

The list of dates in Class I was the first to become available and as the responsibility for forecasting the probability of a recurrence of a disastrous flood was placed upon the Meteorological Office almost immediately after the January disaster, these occasions were examined and rough rules for forecasting drawn up, although it was realised that the data were far from perfect because a tide which is high enough to arouse comment may either be due to an unusually high spring tide with a small excess due to meteorological factors or it may be a normal spring tide with a large meteorological excess. In the former case it will clearly be waste of time to expect to find meteorological conditions to account for the height of the tide, while in the latter case such conditions may be sought with a reasonable prospect of success. In many of the earlier records no figures are available for the predicted height of the tide and therefore it is not known how far meteorological conditions were the cause. In the later cases predictions are available and show that in a good many instances the meteorological perturbation amounted to only 1 ft. or 18 in. a figure which is entirely insignificant. It may here be useful to remark that the Thames defences are maintained at a level of 26 ft. 6 in. above Admiralty datum whereas the astronomically predicted tide seldom exceeds 23 ft., thus leaving a margin of some 3 ft. 6 in. through which the water may be raised without causing danger. In 1928, for which year accurate predictions of the height of the astronomical tide at London Bridge are available, the height exceeds 23 ft. on 10 days only. The highest figure is 23·6 ft. on March 25.

Examination of the list of tides in Class I above showed that the 37 cases might be divided into three groups :—

(*a*) 22 cases in which the high tide was associated with north-westerly or northerly winds over the North Sea.

(*b*) 9 cases in which the association was with easterly or north-easterly winds over the southern North Sea, and

(*c*) 6 cases which did not permit of classification by meteorological factors.

Taking account of the point discussed above regarding the nature of the data, it was clearly not profitable to examine the cases in the last group but the two earlier groups in which the raising of the water seemed to be due to definite wind systems over the North Sea seemed to call for further consideration.

§ 4—Further Preliminary Work

The data regarding high and low tides at London Bridge, obtained from the Port of London Authority, which comprise Class II above were next examined. When the heights of the actual and predicted tides over the series of years were plotted (for the winter half year only) on squared paper, it was at once clear that during the latter part of the period the predicted heights were on the average seriously in excess of the true heights, the mean difference amounting to one foot in many months. The fact that the predictions lacked precision had been realised by the Port of London Authority and arrangements had already been made to obtain more accurate predictions from the Tidal Institute. Liverpool, from January 1, 1928. Before making any use of these faulty predictions, it was first necessary to apply a correction to the figures by taking out the mean height both of high and low tide for each month separately, and using the difference between the mean actual height and the mean predicted height as a correction to apply to all values of the latter during that month. This assumes that over a period of a month the meteorological perturbations positive and negative will balance, which may not be strictly true. By this means it was possible to obtain figures for the departure of actual tide height from predicted height for every day throughout the winter months during the period 1924–7 both for high and low tide at London Bridge. It must, however, be borne in mind that, owing to the faulty nature of the predictions, too much weight should not be attached to the figures. Examination of these figures served to confirm the broad rules already laid down that—

(*a*) North-westerly or northerly winds over the major part of the North Sea, and

(*b*) Easterly or north-easterly winds over the southern North Sea

tended to raise the water in the Thames. It also became clear that southerly or south-westerly gales over the North Sea tended to lower the water. The figures further suggested that a departure of 3 ft. or over in the height of high or low water from the predicted level might be ascribed with some confidence to definable meteorological conditions but that departures of 2 ft. or less cannot usefully be classified by meteorological factors. In view of the much greater precision and suitability for the purpose in hand of the data provided by Dr. Doodson, of the Tidal Institute, Liverpool (Class III above), it did not seem profitable to try to draw up precise rules for forecasting until these data had been carefully examined. It was somewhat surprising to find in the course of this examination that all cases of large positive departures above predicted level found by Dr. Doodson were associated with northerly to westerly winds over the North Sea and that out of the 17 cases in Class III not one was associated with easterly winds. There seemed some reason for dismissing the previously determined "easterly" class as unimportant and for saying that it was introduced only by the faultiness of the data employed and this course might have been adopted were it not for the tide of January 18, 1881, which until January of the present year (1928), held pride of place as being the highest Thames tide on record. This tide was associated with easterly gales which reached force 9 or over in the southern North Sea. The tide is recorded as having reached a level of 17 ft. 6 in. above ordnance datum, that is 26 ft. above Admiralty datum and it is therefore clear that there must have been a large meteorological perturbation added to the astronomical tide. Insufficient cases are available to allow of drawing up precise rules for the forecasting of high tides due to this cause. All that can be said is that some danger of an abnormal tide may be expected when winds reach force 8–9 from the eastward and perhaps also from the north-eastward over the extreme southern North Sea at a time of spring tide. Fortunately winds of this nature are rare and examination of the weather charts during the past ten winters has only revealed one case when conditions approximated to those of January 18, 1881. This occurred on March 7, 1917, a date on which Dr. Doodson does not note any abnormality in the tide at Southend. The cases in which the raising of the water is due to a north-westerly or northerly wind over the North Sea, can be examined in so much greater detail with the aid of Dr. Doodson's curves than by any other means that we will proceed now to an examination of these records.

§ 5—Precise Tidal Curves

As has already been explained the curves which form the data of Class III show the departure of actual from predicted tide at Southend hourly for disturbed periods between the years 1916 and 1928. It is well to point out that these curves show a disturbance of the water level at whatever time it occurs, as opposed to the data in Class I which showed effects at high tide only and in Class II which dealt with departures from predicted level at high and low tide but not at intermediate tides. It is proposed in dealing with the curves of Class III first to endeavour to ascertain the cause of a raised water level at Southend whenever it occurs and to draw up rules for the forecasting of such an effect. The chances of the occurrence happening at the time of high water and spring tide and so proving dangerous will be considered later. The data are plotted for about 120 days in all, each individual curve covering in general a period of some 4 to 6 days. One or two examples of these curves are illustrated and discussed in detail later. For the purpose of the present inquiry attention has been mainly concentrated on the positive departures which exceeded 4 ft., that is on the occasions when the tide at Southend rose 4 ft. or more above prediction. Four feet was chosen as the limit for two reasons: firstly because it had already been ascertained that departures in the case of high and low tide of less than 3 ft. were not easy to classify meteorologically and a departure of 3 ft. at high tide is generally associated with a much greater disturbance in the tide curve at some neighbouring time. It was therefore not felt that any peak on the hourly tide curve of less than 4 ft. would be profitable for investigation; when taking departures of 4 ft. or over, it is, however, fairly certain that some definable meteorological factor must be the predominating cause of disturbance. Secondly, if a disturbance of 4 ft. or over could be forecast, this would satisfactorily meet practical requirements The danger point is reached when the waters at London Bridge rise 26 ft. 6 in. above Admiralty datum. It is only on the average on one day in 14 that the predicted tide at London Bridge rises above 22 ft. 6 in. so that the chances of a disturbance of less than 4 ft. leading to flooding are small.

§6—Examination of large Disturbances

Dr. Doodson's curves included 17 cases in which a positive departure of 4 ft. or over was shown. These have been examined in detail with the working charts of the Meteorological Office, the principal features of the 17 cases being set out in Table I. The data given in the several columns of the table are as follows:—

(*a*) Number of the case.
(*b*) Date.
(*c*) Extreme positive departure of actual level above predicted.

TABLE I.—TIDES AT SOUTHEND FROM DR. DOODSON'S CURVES.

No.	Date.	Extreme departure. (Raised above predicted level)	Departure at H.	Geostrophic wind over North Sea.	Approx. No. of hours between onset of wind and maximum disturbance	Remarks.
(a)	(b)	(c)	(d)	(e)	(f)	(g)
1	Jan. 13, 1916	6½ feet at 3 p.m. .. 7½ feet at 11 p.m. ..	3½ feet	7 a.m. N.W. 100 m.p.h.	8 16	Westerly gales off north-west Ireland veering N.W. 9 p.m. 12th. N.W'ly North Sea about 6 hours later. Water low before rise. Probably pulsation.
2	Jan. 16, 1916	4 feet at 1 a.m. 16th	3 feet	Previous 1 p.m. N.W. 75 m.p.h.	12	Westerly gales off north-west Ireland. Dropped light 6 p.m. 15th. Wind veered N.W'ly North Sea by 1 p.m. Similar case to (1) above but less intense. Rise of water follows NW. wind very rapidly.
3	Nov. 25, 1917	4½ feet at 4 p.m. .. 5 feet at 1 a.m. 26th	1½ feet	1 p.m. N. 70 m.p.h.	3 12	Westerly gales all West Coast for sometime veering NW.-N. during previous night allowing water to rise to normal. N'ly wind North Sea freshened during 25th and produced rise without pulsation. Rise follows increase of wind quickly. Wind had been NW.-N. for nearly 24 hours.
4	Dec. 2, 1917	Sharp peak to 7 feet at 11 p.m.	3 feet	7 a.m. N.N.W. 100 m.p.h. 6 p.m. N.N.W. 70 m.p.h.	16	Water had been high for 24 hours. Probably no Atlantic effect. Wind N.W'ly North Sea 6 p.m. 1st and water rose to 2½ feet above prediction. Freshened during night. Not clear why effect delayed 16 hours (7 a.m.-11 p.m.).
5	Feb. 12, 1920	5 feet at 1 a.m. ..	? 1½ feet	Previous 7 a.m. W. 60 m.p.h. Previous 6 p.m. N.W. 80 m.p.h.	7	Westerly gales north-west of Ireland 7 a.m. 11th veered NW. 1 p.m. and North Sea wind became NW. 80 m.p.h. by 6 p.m. (Dr. Doodson's curve does not show changes before the maximum). Seems quick acting and probably pulsation effect.
6	Dec. 4, 1920	5 feet at 3 p.m. ..	1½ feet	1 a.m. N.N.W. gales N.E. Coasts 7 a.m. N.-NE. 80 m.p.h.	14	Southerly gales North Sea 3rd seem to have lowered water, then pulsation effect when N.-NE. gales established 7 a.m. 4th. Water rose gradually.
7 & 8	Jan. 18-19, 1921	Several peaks above 4 feet all missing H. Maximum 4½ feet	3 feet	17th 6 p.m. W. 50 m.p.h. .. 18th 1 p.m. W.N.W. 70 m.p.h.		Strong westerly winds off north-west of Ireland. Lowered water 17th. Difficult to explain sharp rise to 4 feet during night of 17th. A westerly gradient continued over the North Sea. Wind veered NW. northern North Sea 1 p.m. 18th, followed by rise of water to 4 p.m. Water continued high while strong north-westerlies prevailed over the North Sea.
9	Nov. 1, 1921	4½ feet at 4 p.m. ..	1 foot	7 a.m. N.W. 60 m.p.h. ..	9	Strong westerly winds off west of Scotland 31st October seem to have lowered water on average though with regular pulsations. Veered NW. 1 a.m. and NW. gradient (60 m.p.h.) covered North Sea 7 a.m. Probably pulsation.
10	Dec. 17, 1921	6 feet at 10 p.m. ..	1½ feet	1 p.m. N.W. 80 m.p.h. ..	9	Westerly gales off west Scotland lowered water 1 p.m. 17th, but this wind continued. North Sea wind veering NW. 80 m.p.h. at 1 p.m. seems to have led to sharp rise of tide in late evening.
11	Dec. 31, 1921	11½ feet at 9 a.m. ..	2 feet	7 a.m. N.N.W. 100 m.p.h. ..	8	Westerly gales north-west of Ireland up to 1 p.m. 30th lowered water. This wind veered by 6 p.m. and allowed water to rise. By 1 a.m. 31st North wind set in over Western North Sea. Probably 1 a.m. wind on east coast British Isles was effective. Probably pulsation.
12	Jan. 4, 1922	5 feet at Noon .. 6 feet midt. 4-5th	1½ feet	1 p.m. N. 80 m.p.h.		Long continued NW.-N. wind North Sea led to raised water with marked pulsations. Gradient stiffening to N. 80 m.p.h. 1 p.m. 4th seems to have given the high value.
13	Jan. 30, 1925	4 feet at 2 p.m. .. (raised since 3 a.m.)	3 feet	7 a.m. W. 60 m.p.h.		Westerly gales off west coasts 29th lowered water. Not clear why raised early on 30th. See January 18th, 1921.
14	Nov. 25, 1925	8 feet at 4 p.m. ..	3 feet	7 a.m. N. 70 m.p.h.	9	Strong northerly gradient North Sea 7 a.m. seems to have led to rapid rise of water about noon.
15	Mar. 5, 1926	4½ feet at 11 a.m. ..	1½ feet	7 a.m. N.N.W. 40 m.p.h. ..	10	Westerly gales West of Ireland previous day veered during evening and decreased during night. Probably surge went round Scotland aided by Northerly wind North Sea 1 a.m. and 7 a.m.
16	Oct. 10, 1926	8 feet at 11 a.m. ..	1½ feet	7 a.m. N.N.W. 60-80 m.p.h. ..	10	Southerly wind 50-60 m.p.h. North Sea 7 a.m. 9th seems to have lowered water. Northerly 1 a.m. and NNW. 60-80 m.p.h. 7 a.m. raised it rapidly. See December 4th, 1920.
17	Jan. 6, 1928	5 feet at 11 p.m. single sharp rise	5 feet	6 p.m. N. 80 m.p.h.	10	Westerly gales north-west coasts 7 a.m. 6th lowered water. Wind veered N. 1 p.m. and dropped 6 p.m. Northerly gale set in North Sea same time (1 p.m.). Probably pulsation effect.

(*d*) Departure at " H " that is at time of predicted high tide.
(*e*) Geostrophic wind over the North Sea.
(*f*) Interval in hours between the onset of the effective wind over the North Sea and the time of the maximum disturbance.
(*g*) Remarks.

Maximum departures are seen to range up to 7 or 8 ft. with one example to 11½ ft. It is clear that if a departure even of 7 or 8 ft. occurred at the time of a high spring tide very serious flooding would occur and it is a very fortunate fact that these maximum departures tend to avoid the time of high tide. Column (*d*) containing the departure at the time of the neighbouring high tide shows in every case but the last in the table, a disturbance markedly smaller than the extreme in column (*c*). This point is one of fundamental importance which will be discussed further later.

Attention has already been directed to the fact that strong NW. winds over the North Sea are closely associated with abnormally high tides and an inspection of the weather charts for the 17 cases derived from Dr. Doodson's curves strikingly confirmed the importance of this factor. In 14 out of the 17 cases the geostrophic wind over a considerable part of the North Sea was from between NW and N. and of 60 m.p.h. or over. In the remaining cases the wind was once from the NW. but of 40 m.p.h. only and twice from the W. For the purpose of bringing out this feature clearly column (*e*) which gives the wind over the North Sea has been included in the table. The figures in column (*f*) which indicate the period between the onset of the wind over the North Sea and the maximum disturbance of the water level are included as it is considered that they give useful information, although they can only be regarded as very approximate. It is clear that no precise time can be assigned to the setting in of a wind of given strength over a considerable area like that of the North Sea and further the Meteorological Office charts are only drawn at 6-hour intervals and one of these charts, that at 1 a.m. is on many of the occasions under discussion incomplete by reason of the lack of observations from the further side of the North Sea. Thus the time of onset of the effective wind can frequently only be assigned to within about 6 hours. Inspection of the individual curves suggests that as soon as a wind of appropriate direction and force is established over the northern and western parts of the North Sea, the effect is felt on the water at Southend almost immediately, a rise setting in on the curves of departure from predicted level. The fact that the lag in column (*f*) ranges (omitting one exceptional figure of 3 hours) from 7 to 16 hours is to be ascribed to the fact that the rise is not sudden but needs to continue for a good many hours before the maximum effect can be reached. Further it is seldom that the curve shows one continuous rise to the maximum; more frequently the rise is interrupted by pulsations which decrease the average rate of increment. It is a fact worthy of mention that it only appears to be the onset of a strong north-westerly wind which is dangerous. One case is included in Dr. Doodson's curves where a strong gradient for north-westerly winds persisted over the North Sea for several days. This led to a marked rise in the water at Southend with periodic fluctuations and the disturbance at high tide was in each case a minimum. It is understood from Dr. Doodson that this is not to be regarded as a fortuitous occurrence and it seems probable that the effect of spells of strong NW. wind on high tide need not be feared. Attention may, however, here be directed to case No. 4 in the table where the onset of the NW. wind led to a rapid rise of the water to 2 ft. 6 in. above prediction, the wind then freshened to 100 m.p.h. but this did not take effect for 16 hours when a very sharp rise to 7 ft. occurred. In this case the maximum effect was not felt until the NW. wind had been established for a longer time than is usual.

The remarks in column (*g*) are concerned to a considerable extent with conditions antecedent to the setting in of the N. wind over the North Sea. In examining the curves it was clear that the rise was in many cases preceded by a depression of the water level and inspection of the synoptic charts suggested that this depression might be brought about in one of two ways, either :

(1) By strong westerly winds over the Atlantic to the west of Ireland and Scotland (the south-west of Ireland did not seem equally effective), or

(2) By strong southerly winds over the North Sea.

The precise action by which a westerly wind over the Atlantic lowers the waters of the southern North Sea is not clear. The operation of southerly winds over the North Sea is more readily understood. It seems probable that if the cause of such a depression of the water were removed at about the same time as the raising effect of a NW. wind over the North Sea set in, there would be a pulsation effect leading to a higher tide than would have been experienced had the previous depression not existed.

§ 7—Causes of Disturbance

With these facts in mind the 17 cases have been divided into four groups :—

(1) 7 cases in which strong westerly winds over the Atlantic to westward of Ireland or Scotland, decreased or veered prior to the setting in of a strong north-westerly or northerly wind over the North Sea.
Numbers 1, 2, 5, 9, 11, 15, 17.
Mean maximum departure from predicted level 6 ft.

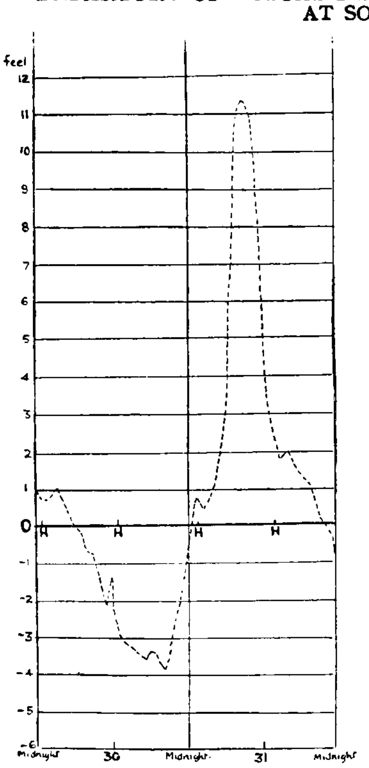
(2) 2 cases in which strong southerly winds over the North Sea preceded north-westerly or northerly.
Numbers 6, 16.
Mean departure $6\frac{1}{2}$ ft.

(3) 6 cases in which strong north-westerly or northerly winds set in over the North Sea without prior wind action.
Numbers 3, 4, 8, 10, 12, 14.
Mean departure 6 ft.

(4) 2 cases in which strong westerly winds prevailed over the Atlantic and North Sea.
Numbers 7, 13.
Both departures 4 ft.

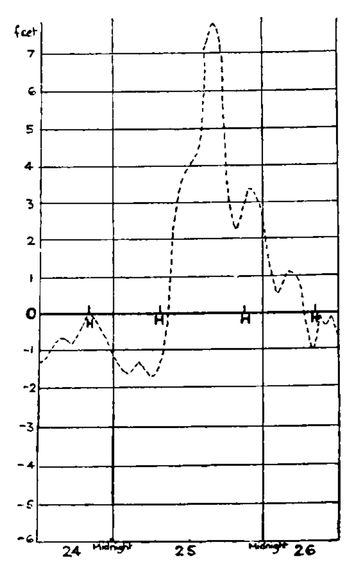
The features of Group 1 are most clearly illustrated by taking the disturbance of December 31, 1921, as an example. The " departure " curve, Fig. 1, shows a

DEPARTURE OF ACTUAL FROM PREDICTED WATER LEVEL AT SOUTHEND.



DECEMBER 1921

Fig. 1.

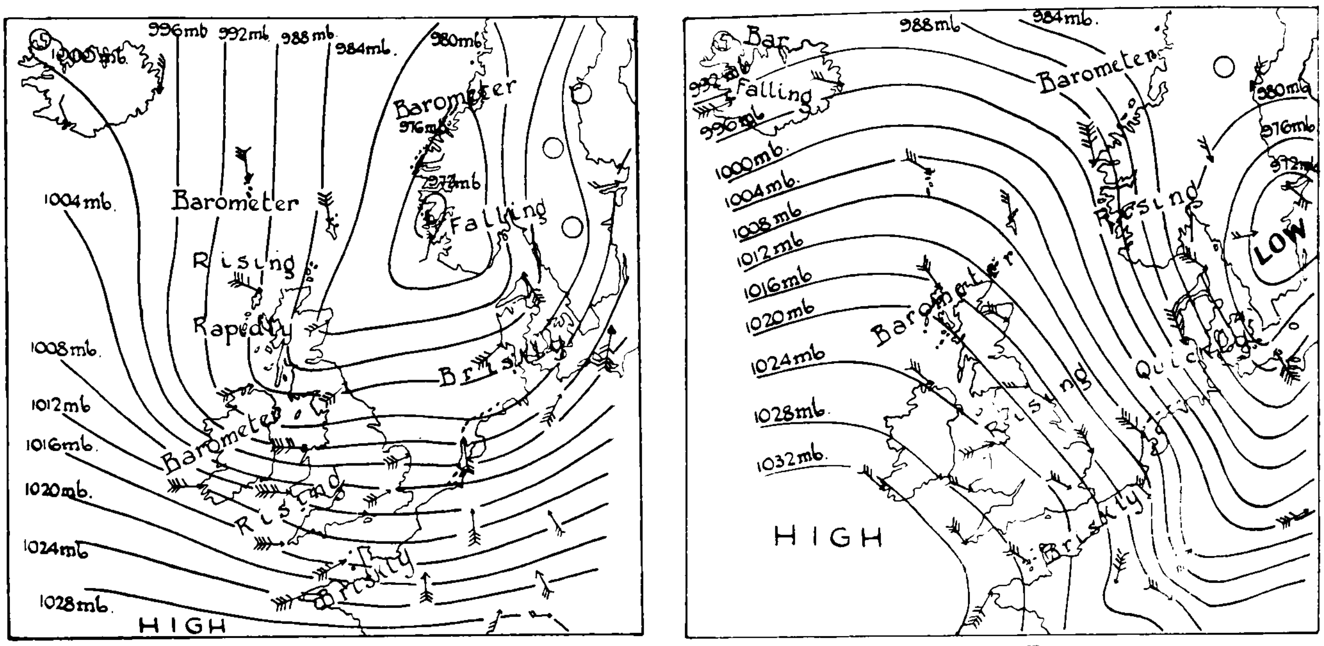


NOVEMBER 1925.

Fig. 3.

H indicates time of predicted high tide.

negative departure during the afternoon and evening of December 30 followed by an outstanding rise to 11½ ft. at 9 a.m. on December 31. This is the most outstanding case of the whole series. Westerly gales were experienced over the Atlantic west of the British Isles during December 30, leading to the depression of the water at Southend. By 6 p.m. on the 30th the wind had veered northerly off the west of Scotland (*See* weather chart Fig. 2) a change which appears to remove this cause of a lowered water level and during the night the wind over the North Sea which had been of moderate force in the north and strong westerly in the south, became strong to a gale from the NW over the whole area leading to a notable rise in the water level.



DECEMBER 30th 1921 6 pm. DECEMBER 31st 1921 7 am

Fig. 2.

It is unnecessary to illustrate Group 2 which appears rare, being only represented by two cases. Group 3 where influences outside the North Sea do not seem to be effective may be illustrated by the case of November 25, 1925. Here the water was slightly depressed during the night of November 24, but the depression only amounted to 1½ ft. and does not appear to have had much significance (*see* Fig. 3). On the afternoon of the 24th moderate north-westerly winds covered both the region off the west of Scotland and most of the North Sea but their strength was not such that any noticeable disturbance of the tide would be anticipated. (*See* Fig. 4.) By 1 a.m. on the 25th the winds over the North Sea had become northerly and were rapidly increasing in force so that by 7 a.m. the average geostrophic velocity reached 70 m.p.h. A rapid rise in the Southend curve occurred about this time and led to a maximum of 8 ft. nine hours later. With regard to Group 4 strong westerly winds over the regions surrounding the British Isles are not infrequent. An inspection of the charts does not reveal any peculiarity to which the rise of water in the two cases of Group 4 can be assigned. The departure in each case only amounted to 4 ft. and was therefore the minimum for inclusion in the list. It does not appear that when considering the possibility of forecasting high tides it is necessary to take much account of these two cases.

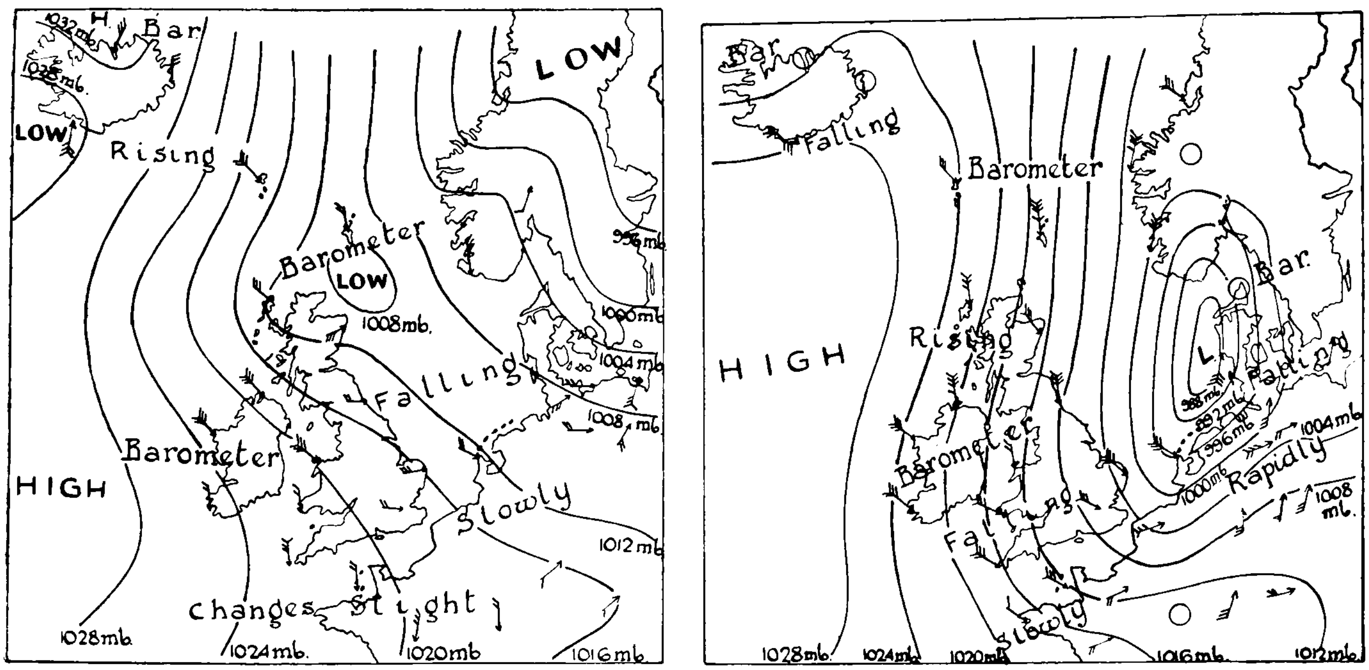
§ 8—Wind Strength and Tidal Disturbance

It is of interest to examine whether there is any degree of proportionality between the strength of the wind over the North Sea and the effect produced on the water at

Southend. The 15 cases associated with north-westerly or northerly winds in the North Sea have therefore been separated according as the geostrophic wind lay between 40 and 59 m.p.h., 60 and 79 m.p.h. or 80 m.p.h. and over. The maximum departures from predicted height were as follows :—

Wind 40–59 m.p.h.—**4½** *ft.*
60–79 m.p.h.—**4** 5 4½ **4½** 8 **8**.
80 m.p.h. and above—**7½** 7 **5 5 6 11½** 6 **5**.

These show some tendency for large departures to be associated with high winds and suggest that as a working rule winds of less than 60 m.p.h. need not be considered dangerous. The cases in Groups 1 and 2 where the NW. wind was preceded by a depressing influence on the water level, are shown in the above table by figures in heavy type. If the depressing influence is of importance in leading to a subsequently increased rise through a pulsation effect, the figures in heavy type in each class would be expected to be larger than the figures in ordinary type in the same class. The fact that the greatest departure of all, 11½ ft., and the only case where a wind of less than 60 m.p.h. was operative both followed a depressing influence cannot be overlooked, but it does not appear on the whole that such an influence is of any great importance and it is certainly not a feature which can be regarded as essential when forecasting a large disturbance of the water level.



NOVEMBER 24TH 1925. 6 p.m. NOVEMBER 25TH 1925. 7 a.m.

Fig. 4.

§ 9—Rule for Forecasting Raised Water Level

This detailed consideration of the individual cases leads to the following rule for the forecasting of a raised water level at Southend :—

Conditions for a raising of the water by 4 ft. or more above the predicted level at Southend.

The onset of a geostrophic wind over a considerable part of the North Sea of 60 m.p.h. or over from between NW and N.

Such onset is likely to be followed within a period of 7–16 hours by a large positive departure of the water from predicted level. The fact that the wind over the extreme southern North Sea may be westerly with no north component is no bar to the occurrence of a raised water level, so long as the requisite NW.—N. wind exists over other parts of the area. A favourable prior occurrence appears to be the existence of either

(1) Westerly gales or strong winds off the west of Ireland or Scotland which veer or die away shortly before the onset of the wind over the North Sea, or
(2) Southerly gales or strong winds over the North Sea, preceding the northerly wind.

The rule should be regarded as applicable only during the winter six months, October to March, since large positive disturbances of the water level are not found to occur during the summer half-year (see § 2 and Table I).

§ 10—Test of Applicability of Rule

Having drawn up the above rule it remained to test it by observing how satisfactorily it would serve to give warning of all cases of a marked rise in the waters of the Thames and further how many needless warnings would be given. It may be noted that as a good many hours generally elapse between the onset of the strong wind and the raising of the water to maximum level, it would not be necessary to forecast the wind long in advance in order to use the rule. It would almost suffice to wait until the requisite pressure gradient were shown upon the charts. The question of forecasting the meteorological elements therefore hardly enters into the problem. In order to test the operation of the rule a professional assistant in the Forecast Division, Mr. L. Dods, was asked to examine the charts for the winter six months during the past 12 years, the period covered by Dr. Doodson's curves, and to note all dates on which the geostrophic wind had been 60 m.p.h. or over from between NW. and N. over a considerable part of the North Sea. Mr. Dods had not previously had to do with the forecasting of Thames floods and had therefore nothing to guide him except the wording of the rule. The most satisfactory charts to use for this purpose would have been the working charts of the Forecast Division but these when bound in monthly volumes are heavy and awkward to handle so that it was not practicable to employ them for a survey of this kind which would involve the handling of 72 volumes and the charts in the *Daily Weather Report* were used. These charts are satisfactory for the 7 a.m. and 6 p.m. maps but are quite inadequate for 1 a.m. and 1 p.m. when no readings are shown across the North Sea. It was anticipated that the list of dates found by Mr. Dods would be a long one and that subsequent examination of the working charts would be necessary to weed out those cases which proved, on a more detailed examination, not to be dangerous. This, however, was not the case, only 36 days during the course of the 12 winters being found in which the necessary conditions were fulfilled. The first point was to examine how many of the occasions when Dr. Doodson's curves had shown a positive disturbance of 4 ft. or over were included in Mr. Dods' list. It was satisfactory to find 13 of the 17 dates noted. The 4 cases omitted were the following :

Nos. 7 and 13 of Table I when the disturbance was associated with a westerly wind and No. 15 when the geostrophic velocity reached 40 m.p.h. only. It was of course already known that these cases were not covered by the rule. The fourth omission was No. 10 when the strong wind occurred at 1 p.m. There is little doubt that this case would have been included had it been practicable to use the working charts for the preliminary examination instead of the *Daily Weather Reports*. It appears, therefore, that application of the rule even by one having no previous acquaintance with the subject would lead to the forecasting of 14 cases of marked disturbance of the water level out of 17.

It was next necessary to see how many needless warnings would have been given during the 12 years by an application of the rule. (The word "warning" is used here to indicate warning of a raised water level, not necessarily of a Thames flood.) The 23 cases which had been noted by Mr. Dods but where nevertheless no marked disturbance of the water level was found amongst Dr. Doodson's curves, were examined individually and it was found that in a good many of these cases the geostrophic wind velocity over the North Sea only just reached 60 m.p.h. This suggests the desirability of not issuing a warning unless the velocity reaches some value a little higher than 60 m.p.h. if it is desired to avoid too many false alarms. Five cases were, however, found in which conditions definitely appeared dangerous. We may assume that warnings would have been issued on these five occasions leaving a further 18 cases in which considerable doubt would have been felt as to whether a warning should be issued or not. Even though a good deal of discretion were used it is hardly likely that it would have been considered wise to avoid issuing a warning on all of these 18 cases and we must therefore allow for some 10–15 false alarms having been sounded altogether. In addition the case of easterly gales which have previously been referred to as a possible cause of danger must be taken into account. Not many warnings would have been issued under this heading owing to the rarity of easterly gales of sufficient intensity, but we might perhaps allow for another two or three warnings in the 12 winters so that the facts would be as follows :—

On 17 days in the 12 winters the water level at Southend was raised more than 4 ft. above prediction. On 14 of these occasions a warning could have been issued by following the rule given above, while about 15 false alarms would have been sounded.

It is here assumed that the discretion in issuing a warning referred to in the last paragraph would not have led to any of the 14 successful warnings being missed. This assumption is probably justified.

§ 11—Cause of Rarity of Floods

The situation revealed by these figures is much more satisfactory than was anticipated would be the case when the work was commenced and if every positive disturbance of 4 ft. or over resulted in a Thames flood, it would clearly be practicable to issue warnings which were successful in a sufficient percentage of cases to be of considerable value. The fact, however, remains that only one serious flood has occurred during the past 50 years, which is very different from the 17 cases of raised water at Southend in 12 years.

The discrepancy is due to two causes. (1) Floods do not occur at times of neap tide. At these times the water at London Bridge only rises to some 17 or 18 feet above Admiralty datum and a disturbance of 9 ft. would need to be superimposed on the predicted tide to cause danger of a flood. (2) Every positive disturbance of 4 ft. or over even at the time of spring tide does not result in a flood. Cause (1) could easily be taken into account in issuing forecasts, cause (2) could not. We will take account of (1) and calculate how many warnings would be issued in a period of years.

In practice it would probably be considered desirable to issue a warning if conditions over the North Sea were very threatening, on any occasion when the predicted tide rose to 20 ft. or over, and if conditions were moderately threatening, when the predicted tide rose to 22 ft. or over. In order to form an idea how many warnings of a flood would actually be issued in a series of years, we may assume that the rule given above would be followed on all occasions when the predicted tide exceeded 21 ft. and that no warning would be issued on other occasions. The predicted tide rises above 21 ft. on 128 days in the year 1928, and assuming that there is complete independence between the distribution of these days and those of strong winds over the North Sea, which assumption seems justifiable, warnings of a flood would only be issued on one third of the occasions when the North Sea conditions were such as to lead to a positive disturbance of 4 ft. or over in the water level. We have seen that 14 successful warnings of a raised water level would have been issued and 15 unsuccessful warnings during the past 12 winters, or 29 warnings in all. Dividing this number by 3, we find that 10 warnings of a Thames flood would have been issued in 12 years. At the beginning of this paper it was suggested that a Thames flood might perhaps be anticipated once in 25 years and 20 unsuccessful warnings would therefore be issued for every one which was successful. It is necessary to examine the cause for this more closely. The reason appears to be one to which attention has already been directed, that is the extremely important fact that the maximum raising of the water level has a strong tendency to avoid the time of high tide. This is clearly shown by the figures in the following table and is a fact which cannot escape notice when the individual curves of departure of water level from prediction are examined. In the preparation of this table all positive departures of 3 ft. or over have been taken from Dr. Doodson's curves and the interval between the time of maximum departure and the nearest time of predicted high tide taken out. The limit has been set at 3 ft. here in order that a larger number of cases might be included than if the limit of 4 ft. previously used had been adhered to. The cases were classified according as they occurred 5-6, 4-5 .... 0-1 hours before high water, or 0-1, 1-2........ 5-6 hours after high water. The distribution is as follows (a similar distribution is shown when disturbances above 4 ft. only are taken):

	Hours before high water.						*Hours after high water.*					
	5–6	4–5	3–4	2–3	1–2	0–1	0–1	1–2	2–3	3–4	4–5	5–6
Frequency	0	6	14	6	2	0	1	2	2	1	3	0

There is a very marked tendency for the maximum disturbance to occur 3–4 hours before the time of predicted high tide, that is at about half tide. Of the 37 cases examined only 5 occurred within two hours of high water and only one within one hour of high water. A chance distribution would have given 12 and 6 respectively. Of the five within two hours of high water only one was a "major" disturbance exceeding 4 ft., and that was the disastrous occurrence of the night of January 6 last. It was this fact which led to the extensive damage. The maximum departure of 5 ft. at Southend was by no means abnormal and if it had occurred at the common time of 3–4 hours before high tide, it would have occasioned no comment. If the reason for the pronounced tendency to avoidance of the time of high tide by these disturbances could be found and it were such that it could be clearly foreseen on the Meteorological Office charts, this would make all the difference between the practicability of forecasting a dangerous disturbance and the contrary. Examination of the charts has so far failed to suggest any such reason.

§ 12—Disturbing Factors other than Wind

The title of this paper refers to meteorological conditions associated with high Thames tides but it will be noticed that the only meteorological element which has been considered thus far has been wind (or pressure gradient, which is closely correlated with wind). It is necessary to consider briefly whether any other factors are of sufficient importance to be taken into account in the issue of warnings. Barometric pressure suggests itself as such a factor. Under static conditions water level in any spot would rise about one foot for every one inch (that is 33 mb.) decrease of barometric pressure. The barometric pressure over the Thames Estuary in each of Dr. Doodson's 17 cases has been noted. Pressure was seldom much below normal. The reason for this becomes clear on consideration of the matter. These raised water levels have been shown to be intimately associated with a strong gradient for NW winds over the North Sea and with such a gradient pressure will be some 25 mb. lower in Denmark than in London. Unless therefore the barometer is abnormally low in Denmark it cannot be much below the average in London. The conclusion reached is that the barometric pressure over the Thames Estuary is so intimately connected with the wind factor which has already been shown to be of paramount importance that nothing will be gained by taking separate account of it. A second factor which, while not in itself meteorological, is yet closely associated with meteorological conditions, is the flow of water over Teddington Weir from the Upper Thames. It has frequently been suggested that this may be a factor of importance. It is in a way unfortunate that the most satisfactory data for investigation regarding water level are the readings from the tide gauge at Southend where the effect of the water from the Upper Thames must be negligible, owing to the openness of the river estuary at this point. It appears that the only way to obtain clear evidence regarding the effect of the flow from the upper river would be by examination of a large number of figures for the flow at Teddington Weir in comparison with the height recorded on the tide gauge at London Bridge. The effect is almost certainly small and would be masked by meteorological conditions existing in the North Sea so that a large number of figures would be needed to obtain a satisfactory result. Some indirect evidence may be obtained by noting the flow at Teddington on the occasions included in Class I. § 2 when the Thames reached a noteworthy level in London. It is quite clear from these cases that high tides can occur when the flow at Teddington Weir is below normal and no close association between the flow at Teddington and the height of the tide is suggested. It may also be worth referring to the case of January 18, 1881, which has already been mentioned as an outstanding example of an easterly gale leading to an abnormally high tide, an unusual occurrence. No proof is afforded by a single example but it is noteworthy that this high tide followed a period of abnormal dryness in the Thames Valley, the rainfall both at London and at Oxford having been nil in the preceding six days, and ·12 in. and ·15 in. at London and Oxford respectively during the preceding 18 days. The Thames flow must clearly on this occasion have been abnormally small. The evidence available therefore does not suggest that the flow of the Thames at Teddington Weir is a factor of which much account need be taken.

§ 13—Summary

A close association has been found between geostrophic winds of 60 m.p.h. and over from the NW. or N. over the North Sea and a raised water level at Southend and it is considered that it would be practicable to issue forecasts of a disturbance in the water level amounting to 4 ft. or more above the predicted height. It is, however, found that such disturbances tend to occur at half tide and to avoid high tide, thus nearly always passing without danger of flooding. The reason for this has not been ascertained and without further knowledge it does not appear possible to issue useful warnings of Thames Floods at the present time.

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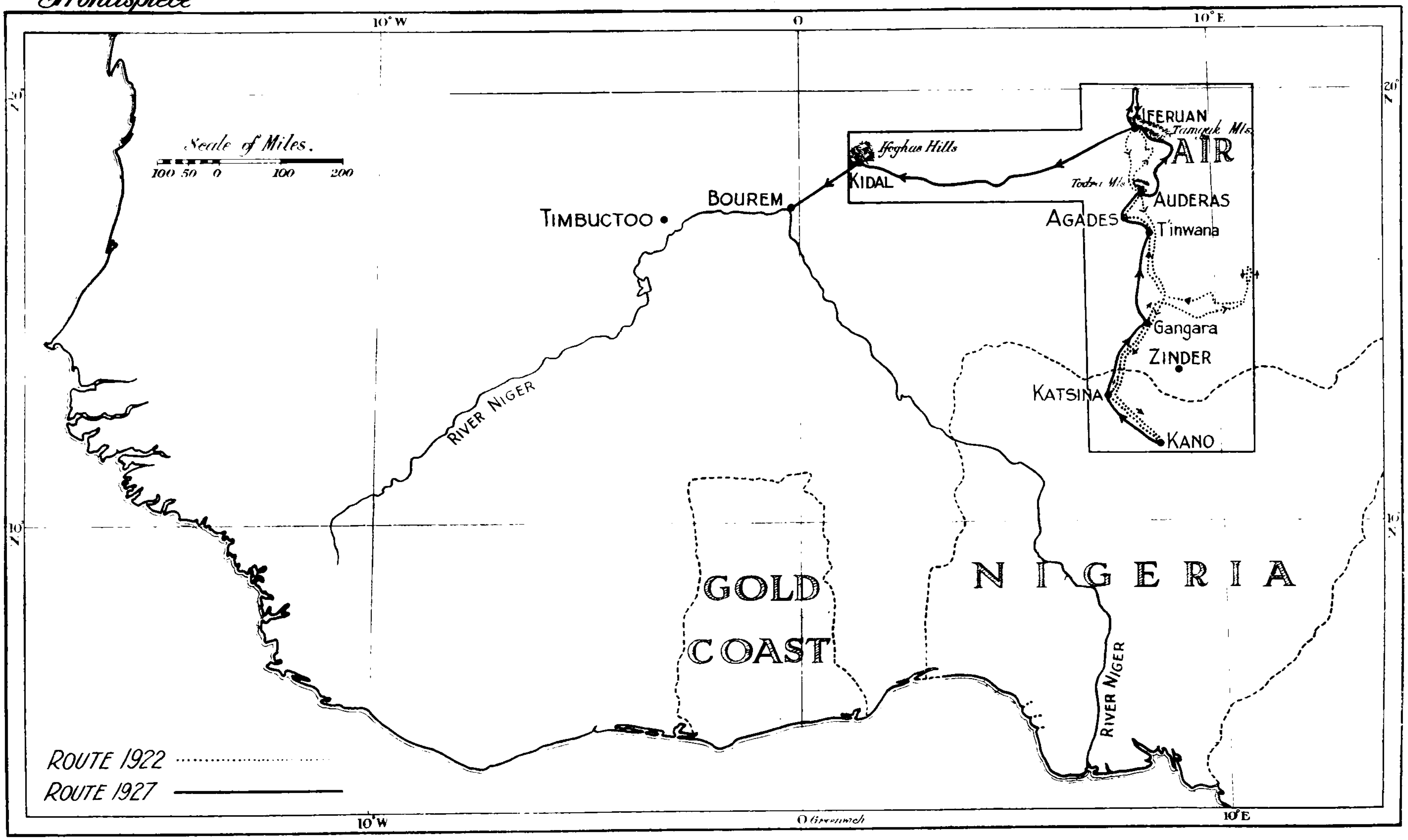

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METEOROLOGICAL OFFICE

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(*Eighth Number of Volume V*)

The Meteorological Results of Journeys in the Southern Sahara, 1922 and 1927

Made by
Francis Rennell Rodd, F.R.G.S.

Discussed by
C. E. P. Brooks, D.Sc., and S. T. A. Mirrlees, M.A.

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THE METEOROLOGICAL RESULTS OF JOURNEYS IN THE SOUTHERN SAHARA, 1922 and 1927 made by Francis Rennell Rodd

GEOGRAPHICAL INTRODUCTION

This *Memoir* is a study of the meteorological data collected in the south central Sahara in 1922 and 1927. Full geographical accounts of these two expeditions have appeared in the *Journal of the Royal Geographical Society*, Volume LXXIII, Nos. 1 and 2 (January and February, 1929), and in previous numbers, notably August, 1923. Detailed maps of the areas in which I travelled were published in the last two numbers. Other more general maps are referred to on the sheets published by the Royal Geographical Society ; in addition to these the French 1/1,000,000 Croquis du Sahara (on the projection and arrangement of the International Million map) may be consulted. The latter and the R.G.S. sheets use the Greenwich meridian which is also referred to throughout this *Memoir* where longitudes are given : most of the other French maps use the meridian of Paris which is 2° 20′ 14″ east of Greenwich. Times in this *Memoir* are in Greenwich mean time, and temperatures in °F.

No determinations of height by levelling in the areas I visited have been made except at Kano, the head of the railway from the coast at Lagos. I have made some calculations of heights above mean sea level using boiling-point data and sea-level isobars and isotherms[1] : the results accord reasonably well with the conclusions of French surveyors in the area in various years before the war. The following table gives some of the results for certain places mentioned in this *Memoir* :—

	Heights above mean sea level	
	Rodd.	French results.
	ft.	m.
Katsina Rest House	1,660	—
Gangara Rest House	2,057	—
Tinwana	2,218	—
Auderas Camp	2,641 (=805 m.)	798 (Foureau).
Tegidda Mellen	2,150 (=655 m.)	700 (Foureau).
Tanekert	1,205 (=367 m.)	386 (Meunier map).

The French have recently established, or perhaps re-established since the war, a meteorological station at Agades in Aïr, equipped with thermometers and rain-gauge, but without a barometer. A meteorological station has also been working for some years at Kidal in the Ifoghas Mountains where some recording instruments are kept. Daily instrumental readings at these stations are now sent by W/T. to Dakar, French West Africa, and will perhaps in future be available for research.

Both the 1922 and 1927 expeditions started from Kano in northern Nigeria and used camel transport. The first journey also ended at Kano : the second journey finished on the Niger near Timbuctoo. On my way north in 1922 I visited a small detached massif in the desert south-east of Aïr in lat. 16° 4′ N., long. 11° E. : the rest of the journey was made to, from, and in, Aïr which lies in the rectangle between lat. 16° 30′ and 19° 30′ N., long. 7° 30′ and 9° 30′ E. In 1927 Aïr was again visited as far north as lat. 20° but instead of returning to Nigeria the expedition marched west, roughly between lat. 17° 30′ and 18° 30′ as far as Kidal in long. 1° 21′ E. From there the expedition descended to the Niger and returned to England via Timbuctoo, Bamako and Dakar. This *Memoir* deals with climatic conditions in Aïr and the neighbouring districts.

A full account of the physical features of the country is contained in my book " People of the Veil " (MacMillan 1926). The following description is a brief note on the regions visited and their configuration.

[1] From London, *Q.J.R. Meteor. Soc.* **43** p. 182 and **44** p. 191.

The belt of cultivated land and park bush in north Nigeria 1,500–1,700 ft. above the sea gives place on the Anglo-French boundary to a belt of dense bush of characteristically equatorial type; in certain cleared areas millet and guinea corn are grown. This belt of bush continues progressively to lose its equatorial, and acquire a Saharan, character as the desert is approached. The ground is sandy and undulating without any marked relief. There are low hills in Gure and some rock outcrop in Elakkos where considerable quantities of millet are produced (lat. 14° N., long. 9° 30′ E.) but these physical features have no climatic importance. A deep belt of uninhabited thorn bush separates Elakkos from the desert which begins in lat. 15° 15′. Further west, however, that is to say due south of Aïr, the belt of bush gives place to an area of open grass-covered steppe with a gently undulating surface (1,600–1,700 ft.) scarcely broken by a few scattered low hills (2,500 ft.). This country, called Damergu, was formerly the granary of Aïr and the district to the south. Grain cultivation has decreased during the last 10 years, owing to depopulation principally connected with political events, but is still considerable.

Damergu is surrounded on all sides by thorn bush. The belt on the northern side is more stunted and thorny than to the south, and nearly 60 miles deep. The open desert is reached south of Aïr only in lat. 16°. The desert, steppe-desert in reality as it carries a tenuous covering of hardy plants and an occasional small tree, lies about 1,600 ft. above the sea. The wide shallow valleys flow west but show no beds or traces of flowing water for more than short discontinuous stretches. The depressions seem to be the product of longitudinal dune formations with a general north-east to south-west orientation but are not very regular and contain many small closed basins. Local precipitation is all absorbed: pools form after the rains and survive a few weeks. For the rest of the year water is obtained from deep wells in the valley bottoms.

The first rock out-crop of importance is the low sandstone massif (summits about 3,000 ft.) of T'inwana-Eghalgawen with a line of cliff (1,500–1,600 ft.) east and west of it. These hills and cliff form the southern bank of the River of Agades, a wide alluvial plain receiving many affluents from the Aïr Mountains to the north and draining all the precipitation of south Aïr westwards, eventually into a series of wide connected basins which belong to the Niger hydrographic system.

From the bottom of the River of Agades some 1,400 ft. above the sea emerge the foothills of the Aïr plateau. The ground rises by a series of steps to 2,700 ft. in central Aïr. Through this Archean plateau at various points have been thrust a number of volcanic massifs whose peaks attain heights of 6,000 ft. and more above the sea. The principal large mountain groups here are Taruaji in south-east Aïr and the Bagezan Plateau, Todra, Dogam and Bila in central Aïr.

Auderas lies under the slopes of the Todra and Dogam groups in a valley on the plateau 2,450 ft. above the sea and west of the central massifs. On the opposite side of the latter the plateau, 2,800–3,000 ft. high, slopes gradually away to the eastern desert which stretches without any break of importance as far as the Tibesti Mountains. Mount Todra above Auderas is about 6,000 ft. above the sea. The valleys of the Bagezan plateau are some 4,000 ft. high with surrounding peaks probably a little over 6,000 ft.

North of the mountains in central Aïr is a rocky area broken by smaller isolated groups of mountains. Levels decline several hundred feet from the high step of the central plateau to the great westward-flowing valleys which drain north-east and north Aïr. Beyond them lies a fringe of high mountains enclosing north-east Aïr and separating the country from the desert into which they disappear rather suddenly. The mountains attain some considerable depth in the Tamgak massif rising to a height of over 6000 ft. above the sea from the plain at their western and south-western bases 2,000 ft. high. (Iferuan on the Ighazar plain is about 2,100 ft. above the sea.)

Precipitation is heaviest in Aïr, in every case west and south of the massifs. The larger valleys are all westward flowing; Aïr as a whole seems to lie definitely and wholly in the Niger basin; it does not form the watershed between the Niger and the Lake Chad or the Kawar basins.

North of Tamgak in the area called Fade the mountains are lower, exist in isolated masses and occupy a narrowing belt of country hemmed in between the eastern and western deserts. The level of the valley beds rises again to some 2,600 feet at Tarazit where a relatively small but high group of mountains called Grebun appears responsible for the fairly ample local rainfall. Between Grebun and Tamgak the hills are too low to have much effect on precipitation at this northern edge of the summer rain belt. Pastures and water therefore are exceedingly seasonal and unreliable in the area.

On the western side the Aïr plateau throughout its length slopes gently away until the last rocks disappear below the sea of sand which is the western desert. This area over 300 miles broad as far as the Ifoghas Mountains is flat and exceedingly bare. Such rock outcrop as occurs is very inconspicuous. The northern part is absolutely barren gravel desert, the southern part merges gradually and imperceptibly into equatorial bush land. The desert is at its lowest in about lat. 17° 20′ N. where a long east and west depression collects the drainage from Aïr and the Ahaggar system by a series of scarcely perceptible broad valleys without beds of flow but having some underground water, as is proved by the wells at points along their course.

This depression or "belly of the desert," called Assakarai, trends gently west and south towards the Niger bend taking the name of Azawad or Azawaq.

On the northern boundary of this immense and barren waste are the arid foothills of Ahaggar; the western side is marked by the low boulder-strewn ridges which are called the Ifoghas Mountains, themselves scarcely worth dignifying by such a name. They are, in fact, a long south-westerly spur of the Ahaggar plateau. The drainage of the Ifoghas Mountains is generally south-west and west: the precipitation appears to be smaller than in Aïr, nor are the valleys subjected to such great or violent floods.

The western desert north of the bush belt carries some scattered desert vegetation wherever showers fall but their distribution is irregular and pasture consequently unreliable. The northern part is as a whole virtually pastureless.

In Aïr the vegetation is confined to the valleys where along the banks there are often substantial trees and dûm palm (Hyphene) forests. In a few favoured districts, where water survives in the sand, there are date-palm plantations and small gardens wholly dependent on shallow well irrigation. The trees are mostly of the Acacia variety. Some of these, and especially some *Balanites Aegyptiaca*, grow to large size with trunks up to 3 ft. and 3 ft. 6 in. in diameter. Local desiccation appears to be going on in eastern Aïr where there are few young trees and many of the older ones are dying. In western Aïr, on the other hand, rainfall appears now to be greater than before, which is one of several reasons why nomad tribes formerly dwelling in eastern Aïr during the last twenty years have moved to the other side.

According to local tradition Aïr appears to be at the end of a phase of decreased rainfall which has now lasted about 14 years.

This is not the place to discuss Saharan desiccation but it may be worth recording my view which agrees with that of certain French authorities. That some desiccation is occurring is undeniable: certain local areas on the contrary are apparently better favoured now than last century. There is no evidence that climatic conditions have changed materially for some ages past if apparent changes involving lesser local rainfall are examined in the light of wider evidence, including native tradition. There are, however, good grounds for believing that desiccation attributable to mechanical causes is in progress by such agencies as sand deposit and dune formation, desertion of cultivated areas, silting up and oblivion of old wells, progressive modification of the physical features by erosion, and silting of valleys, human modification of areas by the destruction of vegetation, etc., etc. It is also probable that a secular loss of local humidity is consequently in progress which is gradually affecting local climatic conditions though not in the manner or to the degree which are generally supposed by casual travellers.

FRANCIS RENNELL RODD.

DISCUSSION OF THE METEOROLOGICAL RESULTS

§1—THE GENERAL CLIMATE OF THE SOUTHERN SAHARA

The two expeditions of 1922 and 1927 covered nearly the same ground, between about 12° to 20° N. latitude and 0° to 11° E. longitude, including the extreme northern part of the northern Provinces of Nigeria and the southern part of the French Sahara in those administrative districts known as the *Colonie au Niger* and the *Soudan Français*. This region has a very interesting climate of the monsoon type, and fortunately the expeditions included parts of both monsoons. The year is divided into a long dry season in the winter half year, with north-easterly winds (the "Harmattan" of the Guinea coast), very clear skies and a practically complete absence of rain, and a summer season with south-westerly winds, more cloudy skies and more or less rain. At Kano in latitude 12° N. the rainy season begins in May, at Zinder, 14° N., in June, and in Aïr, about 18° N., in July.

The mean annual rainfall at Kano in latitude 12° N. is 34 inches, and from here northward the amount decreases. At Zinder (13° 47′ N.) the average is 20 inches, three quarters of which falls in the months of July and August. Still further north the rainfall becomes very irregular and beyond about latitude 15° the average fall is less than 10 inches a year. The amounts are however greatly influenced by the topography, and actually much more rain falls in the mountainous Aïr region between 17° and 19° N. latitude than over the lower ground to the southward[2], between 15° and 17°. Similarly there is an area of relatively heavy rainfall further west, in the mountains of Ifoghas, in latitude 16° to 18° N., but between these two areas of high ground the rainfall is negligible, probably less than five inches a year. Monthly normals[3] for Kano and Zinder are as follows :—

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Kano .. (1905-27)	0·01	0·05	0·09	0·48	2·40	4·55	7·99	11·95	5·59	0·42	0·00	0·02	33·55
Zinder .. (1905-9; '11; '14)	0·00	0·00	0·01	0·09	0·32	1·27	5·40	9·64	2·92	0·04	0·00	0·00	19·69

The north-easterly winds are associated with a low relative humidity and a large daily range of temperature, so that while the days may be very hot, the nights are cool. During the period of south-westerly winds the humidity is much greater; the day temperatures are not so high but the nights are warm and oppressive. The following average data for Kano illustrate the annual variation in these respects.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Mean daily max. temperature °F.	85·3	90·7	98·7	103·2	100·6	94·7	88·8	86·0	89·7	94·7	93·4	87·0	92·7
Mean daily min. temperature °F.	53·7	57·7	64·6	73·2	74·9	72·7	70·4	69·7	70·6	66·5	59·3	54·3	65·6
Relative humidity % at 9h. ..	35	31	32	41	50	63	73	79	71	54	35	34	50

[2] I should say that Auderas probably received some 8 in. rain (in 1927): and that village was very badly favoured (unusually badly even compared with 1922). I am convinced by the vegetation I saw that the country 10 miles east and 10 miles north received much more rain, probably not less than 12 in., which is probably normal for central Aïr though the last few years have been notorious for very *irregular* distribution. A very slight modification from one year to another in the prevalent winds would have a large local effect in central Aïr owing to the shape of the mountainous reliefs. F.R.

[3] Prepared in the Meteorological Office.

The south-westerly current of the summer monsoon is shallow, probably only about 1,000 metres in thickness, and is overlain by easterly winds. At times during the occurrence of rainstorms these easterly winds break through and reach the surface. An interesting feature of the inter-action between these north-easterly and south-westerly winds is the occurrence of tornadoes, of which a few instances are noted in the records.

§2—The Instrumental Equipment and the Methods of Observation

For both expeditions meteorological instruments were lent by the Royal Geographical Society, some of the instruments which were used in 1922 being used again in 1927.

The following is a list of the instruments :—

1922	1927
Dry and wet bulb set.	Whirling hygrometer.
2 maximum and minimum sets.	3 maximum and minimum sets.
Thermometer for water temperatures.	Thermometer for water temperatures.
4 sling thermometers.	3 sling thermometers.
2 boiling-point thermometers.	3 boiling-point thermometers.
4 aneroid barometers.	4 aneroid barometers.
	Barograph.
	Thermograph.
	Rain-gauge.
	Air meter.

Certain of the instruments were adopted as standards and others regarded as spares, but a considerable number of simultaneous readings were made so as to provide a good overlap in case of accident to a standard instrument. Instrumental corrections were not applied at the time of reading.

The method of exposure usually adopted was to hang the instruments in a hut or tent or in a shelter, so that free access of air was permitted, but any access of direct solar radiation prevented. On occasion the barograph and thermograph were placed in a doorway or on a rock ledge.

In 1922 after it was suspected that the readings might have been affected by direct radiation, a ventilated box was constructed, in which the dry and wet bulbs were exposed. This box was placed 3 ft. 6 in. to 4 ft. 6 in. from the ground, had no back or post and was hung from the eaves of a hut in a draught near the doorway or in the shade of some shelter made for the purpose, where no sun could reach it. After this box was brought into use the readings appeared more consistent, such differences as occurred being due to radiation from the walls of the hut and not to insufficient ventilation. Owing to this exposure, the special method of working up the humidity values described on page 19 was adopted.

In 1927 the maximum and minimum thermometers as well as a dry and wet bulb set were mounted on a specially constructed instrument board. The published readings of the dry-bulb and humidity were obtained from the whirling hygrometer, and as it was considered that the ventilation in this case was sufficient, no special procedure was adopted and the humidity values were worked out by the Hygrometrical Tables[4] of the Meteorological Office.

At Auderas, where the expedition camped from July 25 to the end of August, 1927, the instruments were hung up in a tree under a shelter composed of two canvas sunproof roof covers, with loosely hanging sides, the back and front being open, and a floor constructed of sticks and ropes. In 1922 when the expedition was also at Auderas from August 10 to September 5 a similar arrangement was adopted.

[4] M.O. Publication 265, 1924.

The main observation hours adopted were 6h. and 18h. G.M.T. At these hours, or as near as circumstances permitted, the barometers and thermometers were read, while wind direction and force, weather, state of sky and occasionally visibility were noted.

During 1927, when camp was pitched for a single night the minimum thermometer was set up in the evening and read next morning ; and if the halt extended over the day the maximum thermometer also was set up and read in the evening. Thus in most months the number of minimum exceeded the number of maximum readings.

In 1922 the same procedure was observed when possible, but march was at times resumed early in the morning before the normal time of occurrence of the minimum termperature ; it was then usually possible to set the maximum thermometer, camp being pitched about mid-day and the time of maximum temperature being usually later than this.

Besides the regular morning and evening observations a number of observations were made at intermediate hours. Amongst these were a few sets of hourly observations, required in connexion with height determinations. In 1927 the rain-gauge was set up occasionally ; a few measurements of wind velocity were made with the air meter, and several sets of autographic records were obtained including a complete month's record in August.

TABLE I.—DIURNAL INEQUALITY OF

Station	Lat. N.	Long. E.	Dates	Hours								
				0	1	2	3	4	5	6	7	8
	° ′	° ′										
Katsina ..	13 0	7 38	May 23–28	+ 5	+ 2	0	0	+ 2	+ 6	+10	+15	+19
Gangara	14 36	8 30	June 13–16	+ 4	+ 3	0	− 1	0	+ 4	+12	+21	+24
T'mwana ..	16 42	8 27	July 5–9	+ 7	+ 6	+ 5	+ 4	+ 7	+11	+15	+21	+25
Auderas ..	17 38	8 25	July 26–31	+ 8	+ 8	+ 9	+ 9	+10	+12	+16	+21	+24
Auderas ..	17 38	8 25	Aug. 1–31	+ 8	+ 7	+ 4	+ 4	+ 5	+ 6	+ 9	+11	+12
Iferuan ..	19 5	8 25	Sept. 22–28	+14	+13	+11	+ 9	+10	+14	+17	+18	+17
Various stations	18 20	5 40	Nov. 8–9, 15–16, 27–28	+ 6	+ 4	+ 3	+ 4	+ 4	+ 3	+ 5	+ 7	+ 8
Mean			May to Sept. ..	+ 8	+ 7	+ 5	+ 4	+ 6	+ 8	+11	+15	+16

The scales of the barograph and thermograph charts were as follows :—

Barogram pressure scale 1 mercury inch	=	1 inch on sheet.
,, time scale 24 hours	=	10·8 in.
Thermogram temperature scale 100°	=	3·2 in.
,, time scale 24 hours	=	10·6 in.

Both clock drums revolved once in about 24 hours, but showed variations of rate with temperature change, losing slightly during the day and gaining slightly during the night. This effect was more marked in the barograph clock.

In tabulating the autographic records it was assumed that the clock rates had been uniform between the time marks, which were generally made at 6h. and 18h. G.M.T., at least, and on several days at intermediate times as well ; by means of a scale on transparent paper the hours between the time marks were marked off on each chart, taking account of all the time marks.

The temperature curves were controlled by the readings of the sling thermometer only, the differences being more consistent than the differences between the extreme readings on the curves and the maximum and minimum thermometer readings.

§ 3—Barometric Pressure

The distribution of barometric pressure over West Africa undergoes a considerable seasonal change. According to the maps compiled by Col. Sir Henry Lyons[5] the distribution in winter shows an area of high pressure over the north-western Sahara, and a trough of low pressure over equatorial Africa, the whole region between being occupied by a belt of steady north-easterly winds. In summer the high pressure area moves north-westward over the Atlantic, and the low pressure trough moves northward to a position between about latitudes 15° and 20° N. South of latitude 15° the prevailing winds at this season are south-westerly, while within the trough the winds are variable.

It has been considered that no useful purpose would be served by the full discussion of the daily observations of pressure, as such, obtained during Mr. Rodd's two expeditions. The sites of observation were constantly changing, and the

Pressure in 1927 (unit 0·1 mb.).

(G.M.T.)															Stations
9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
+21	+17	+10	+ 2	− 5	−12	−16	−19	−22	−21	−15	− 9	− 1	+ 4	+ 7	Katsina.
+23	+19	+13	+ 5	− 2	− 9	−15	−21	−24	−23	−21	−14	− 4	+ 1	+ 4	Gangara.
+22	+18	+11	+ 1	−10	−19	−22	−23	−27	−27	−20	−12	− 5	+ 2	+ 7	T'inwana.
+23	+19	+11	+ 2	− 7	−16	−25	−32	−34	−30	−21	−13	− 3	+ 4	+ 6	Auderas.
+12	+ 9	+ 5	− 2	− 9	−14	−17	−19	−18	−14	− 9	− 5	+ 1	+ 5	+ 7	Auderas.
+13	+ 7	− 2	−13	−24	−31	−31	−28	−24	−18	−10	− 1	+ 8	+13	+15	Iferuan.
+12	+15	+10	0	−12	−19	−21	−20	−15	− 8	− 4	+ 1	+ 5	+ 8	+ 7	Various stations.
+16	+12	+ 6	− 2	−10	−16	−20	−22	−22	−19	−13	− 7	0	+ 5	+ 8	Mean.

observations of pressure were in fact fully utilised for the determinations of height above mean sea level. It is only when camp was fixed at one site for some weeks or where a series of observations were made at brief intervals, that the pressure readings are of meteorological interest, and these readings are set out in Tables III and IV.

Variations of pressure.—In 1927 Mr. Rodd carried an aneroid barograph with his other instruments, and when camp was fixed at one spot for some time, he obtained valuable series of barograms. These are summarised in Table I, and in Fig. 1. All the curves in the latter show a principal maximum in the morning hours, about 8h. or 9h. G.M.T., and a principal minimum in the afternoon, at 16h. or 17h. There is also a small secondary maximum about midnight and a secondary minimum about 3h., but these do little to modify the 24-hour pressure wave. The average daily range of pressure is about 4 mb.

[5] *London, Q.J.R. Meteor. Soc.*, **43**, 1917, pp. 113-150.

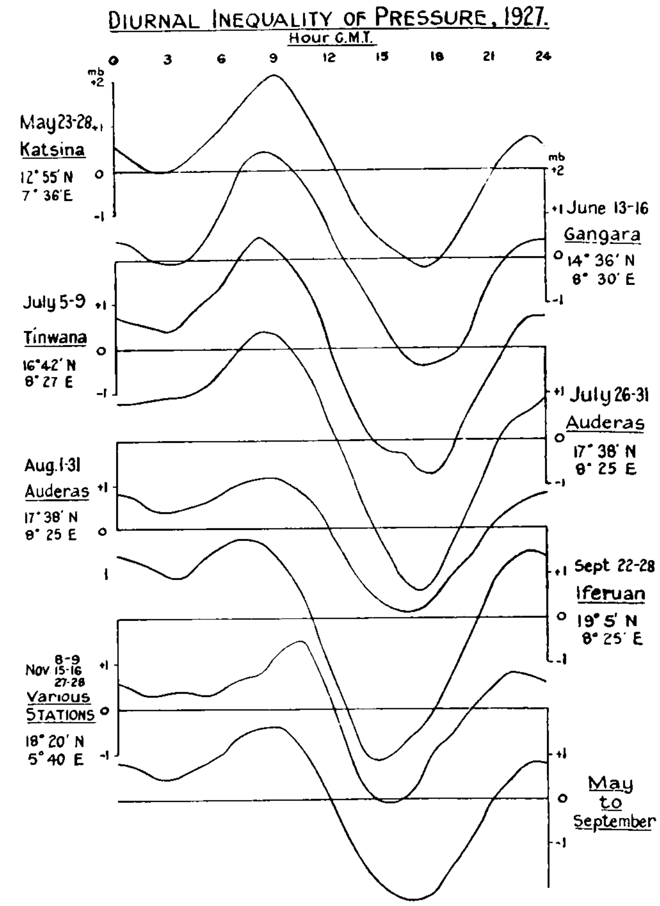


FIG. 1.

The figures were analysed by means of the harmonic series :—

$$\Delta P = a_1 \sin (t + \theta_1) + a_2 \sin (2t + \theta_2) + a_3 \sin (3t + \theta_3)$$

the amplitudes being expressed in millibars, and the phase angles reduced to local mean time[6]. The values are shown in Table II.

TABLE II—CONSTANTS OF DIURNAL VARIATION OF PRESSURE

	a_1	θ_1	a_2	θ_2	a_3	θ_3
	mb.	°	mb.	°	mb.	°
May–June ..	1·5	356	1·0	157	0·3	120
July	2·2	6	1·1	150	0·1	132
August	1·2	20	1·0	156	0·1	79
September ..	2·2	37	1·1	174	0·1	86
November ..	1·1	28	1·0	166	0·3	337
May – September	1·5	15	1·0	156	0·1	100

The diurnal wave is large but this is a natural result of the large diurnal variation of temperature and the continental position. The phase agrees closely with the phases found at other continental stations[7], and it seems that the instrumental temperature effect, if any, must be very small.

---

[6] Aïr being in about longitude 8° 30′ E., local time is about 34 minutes ahead of G.M.T.

[7] Hann, J. v. Die ganztägige (24-stundige) Luftdruckschwankung in ihrer Abhängigkeit von der Unterlage (Ozean, Bodengestalt) *Wien, Sitz Ber. Ak. Wiss.*, IIa, 128, 1919, p. 413.

The twelve-hourly oscillation shows a remarkable constancy of amplitude, even extending to November, for which only three days' curves are available. Although the morning minimum is almost eliminated by the 24-hour oscillation, to an extent unusual in the tropics, both amplitude and phase accord well with the results obtained by G. C. Simpson[8]. Even the eight-hourly oscillation, in spite of its small amplitude and apparent variability of phase, agrees excellently with Hann's results[9].

In 1922 no autographic instruments were carried. Eye readings were made at frequent intervals on a few days, but these were insufficient for the determination of harmonic constants. The readings of pressure are shown in Table III, and are illustrated, with the corresponding readings of temperature and humidity, in Fig. 4.

TABLE III—DIURNAL VARIATION OF PRESSURE SHOWN BY SERIES OF READINGS ON DAYS IN 1922

Hour G.M.T.		06.30	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
SEPT. 9. Auderas—17° 38′ N. 8° 25′ E.																		
in.	27·00+	·26	—	·29	·30	·28	·28	—	·22	·21	·20	·20	·20	·21				
mb.	920+	3·1	—	4·1	4·5	3·8	3·8	—	1·8	1·4	1·1	1·1	1·1	1·4				
SEPT. 24. Auderas—																		
in.	27·00+	·32	—	·36	·36	·36	·35	·33	—	·28	·27	·27	·26	·25	·27	·30	·30	·32
mb.	920+	5·2	—	6·5	6·5	6·5	6·2	5·5	—	3·8	3·5	3·5	3·1	2·8	3·5	4·5	4·5	5·2

Irregular variations of pressure, of the order of a few hours or days in length, are generally small compared with the diurnal variation. Day-to-day changes could only be studied when camp was fixed at the same place for a period of ten days or more. The daily readings on these occasions are shown in Table IV. The average change of pressure from 6h. or 18h. on one day to the same hour on the next, irrespective of sign, was calculated for certain of these occasions. The results gave :—

1922 : April 11–28, Fanisau, 6h. 0·8 mb.; 18h. 1·1 mb.
August 10–20, 24–31, Auderas, 6h. 1·4 mb.; 18h. 1·6 mb.
September 1–5, 8–30, Auderas, 6h. 0·6 mb.; 18h. 1·0 mb.

1927 : August 1–31, Auderas, 6h. 1·5 mb.; 18h. 1·6 mb.
October 1–21, Tegidda Mellen, 6h. 0·9 mb.; 18h. 0·9 mb.

The general average, 1·2 mb., is little more than a quarter of the average range of pressure on any one day. For comparison it may be remarked that near Iceland the average change of pressure from one day to the next is 8–10 mb. From observations at stations in French West Africa it appears that this small variation of pressure from one day to another is true of most Saharan stations.

§ 4—TEMPERATURE

Satisfactory observations of temperature on an expedition are naturally more difficult than at a fixed station where a screen can be installed in a suitable site. In 1922 Mr. Rodd carried ordinary dry and wet bulb and self-registering maximum and minimum thermometers, and also sling thermometers. Early in this expedition he realised that the exposures of his ordinary thermometers—in doorways, verandahs, etc.—were not always satisfactory, since they frequently read considerably higher than the sling thermometers owing to insufficient protection from radiation. On May 12 he accordingly constructed a ventilated box, described on p. 7, and from that date onwards the readings were more consistent. In 1927 he carried a whirling hygrometer.

[8] The twelve-hourly barometer oscillation. *London, Q.J.R. Meteor. Soc.*, **44**, 1918, p. 16.

[9] *Meteor. Zs.*, **34**, 1917, p. 185.

TABLE IV—PRESSURE READINGS BY

FANISAU. 12° 5′ N. 8° 33′ E.		
Date	Morning	Evening
1922.	in.	in.
April 11 ..	29·38	29·30
12 ..	29·39	29·27
13 ..	29·35	29·25
14 ..	29·35	29·25
15 ..	29·38	29·26
16 ..	29·38	29·27
17 ..	29·38	29·23
18 ..	29·38	29·27
19 ..	29·37	29·35
20 ..	29·35	29·22
21 ..	29·30	29·24
22 ..	29·34	29·26
23 ..	29·34	29·21
24 ..	—	29·22
25 ..	29·32	29·22
26 ..	29·31	29·20
27 ..	—	29·23

DANKABA. 13° 13′ N. 7° 45′ E.		
Date	Morning	Evening
1922.	in.	in.
May 8 ..	—	29·35
9 ..	29·46	29·38
10 ..	29·45	29·37
11 ..	29·45	29·43
12 ..	29·50	29·45
13 ..	29·51	29·43
14 ..	29·50	29·42
15 ..	29·46	29·34
16 ..	29·43	29·36
17 ..	29·44	29·34
18 ..	29·42	—

AUDERAS. 17° 38′ N. 8° 25′ E.		
Date	Morning	Evening
1922.	in.	in.
August 10 ..	—	27·14
11 ..	27·22	27·17
12 ..	27·23	27·16
13 ..	27·18	27·13
14 ..	27·22	27·18
15 ..	27·28	27·22
16 ..	27·25	27·18
17 ..	27·20	27·14
18 ..	27·23	27·20
19 ..	27·27	27·27
20 ..	27·31	27·21
21 ..	27·24	—
23 ..	—	27·11
24 ..	27·20	27·09
25 ..	27·16	27·12
26 ..	27·24	27·23
27 ..	27·28	27·26
28 ..	27·24	27·19
29 ..	27·19	27·12
30 ..	27·22	27·18
31 ..	27·26	27·18
Sept. 1 ..	27·22	27·18
2 ..	27·24	27·18
3 ..	27·24	27·24
4 ..	27·25	27·23
5 ..	27·26	—

AUDERAS.		
Date	Morning	Evening
1922.	in.	in.
Sept. 7 ..	—	27·12
8 ..	27·25	27·20
9 ..	27·26	27·21
10 ..	27·25	—
11 ..	—	27·25
12 ..	27·33	27·30
13 ..	27·24	27·20
14 ..	27·27	27·24
15 ..	27·29	27·22
16 ..	27·27	27·20
17 ..	27·26	27·22
18 ..	27·25	27·18
19 ..	27·28	27·23
20 ..	27·28	27·24
21 ..	27·28	27·26
22 ..	27·30	27·26
23 ..	27·30	27·29
24 ..	27·32	27·25
25 ..	27·35	27·26
26 ..	27·28	27·23
27 ..	27·28	27·23
28 ..	27·28	27·23
29 ..	27·30	27·20
30 ..	27·30	27·22
October 1 ..	27·26	27·16
2 ..	27·25	27·18
3 ..	27·23	27·24
4 ..	27·16	—

ANEROID AT VARIOUS STATIONS

AUDERAS. 17° 38′ N. 8° 25′ E.			AUDERAS.			AUDERAS.			TEGIDDA MELLEN. 19° 12′ N. 8° 21′ E.		
Date	Morning	Evening	Date	Morning	Evening	Date	Morning	Evening	Date	Morning	Evening
1927.	in.	in.	1927.	in.	in.	1927.	in.	in.	1927.	in.	in.
July 24 ..	—	27·05	August 8 ..	27·13	27·07	August 23 ..	27·14	27·10	Sept. 30 ..	—	27·44
25 ..	27·11	26·95	9 ..	27·19	27·10	24 ..	27·18	27·07	Oct. 1 ..	27·52	27·49
26 ..	27·10	26·95	10 ..	27·12	27·06	25 ..	27·10	27·08	2 ..	27·54	27·45
27 ..	27·11	26·91	11 ..	27·08	27·02	26 ..	27·09	27·04	3 ..	27·50	27·44
28 ..	27·04	26·91	12 ..	27·10	26·99	27 ..	27·05	27·04	4 ..	27·53	27·46
29 ..	27·02	26·97	13 ..	27·10	27·06	28 ..	27·05	27·09	5 ..	27·50	27·43
30 ..	27·13	27·01	14 ..	27·08	27·05	29 ..	27·11	27·06	6 ..	27·53	27·42
31 ..	27·15	27·03	15 ..	27·09	26·98	30 ..	27·16	27·06	7 ..	27·49	27·43
August 1 ..	27·07	27·02	16 ..	27·08	26·99	31 ..	27·11	26·98	8 ..	27·55	27·47
2 ..	27·02	26·95	17 ..	27·09	27·05	Sept. 1 ..	27·02	26·98	9 ..	27·52	27·42
3 ..	27·10	27·07	18 ..	27·16	27·11	2 ..	27·06	27·06	10 ..	27·47	27·38
4 ..	27·15	27·07	19 ..	27·18	27·11	3 ..	27·13	27·15	11 ..	27·46	27·39
5 ..	27·10	26·95	20 ..	27·09	26·94	4 ..	27·10	27·08	12 ..	27·50	27·44
6 ..	27·00	26·97	21 ..	27·04	26·97	5 ..	27·03	—	13 ..	27·51	27·51
7 ..	27·08	27·04	22 ..	27·10	27·07				14 ..	27·51	27·48
									15 ..	27·53	27·46
									16 ..	27·54	27·47
									17 ..	27·56	27·46
									18 ..	27·53	27·46
									19 ..	27·56	27·51
									20 ..	27·61	27·54
									21 ..	27·61	—

Observations were taken as near to 6h. and 18h. G.M.T. each day as circumstances permitted. The readings of the dry bulb and of the extreme thermometers have been checked as far as possible against those of the sling thermometers, and corrected where necessary.

The readings are summarised in Table V. The " mean " temperature is derived from the morning and evening observations corrected to the 24-hour mean by the figures of diurnal variation derived from the records of the thermograph in 1927 (see p. 16). On the days with autographic records the correction C required was found to be approximately a linear function of the daily range R in the form

$$C\ (°\text{F.}) = -2{\cdot}3 + 0{\cdot}22\,R$$

and the observations for both 1922 and 1927 were corrected on the basis of this formula.

The mean temperature shows a well-marked double maximum in June and September. Combining the two series and reducing to a mean height of 2,000 feet by means of an assumed upward decrease of 3°F. per 1,000 feet, we obtain :—

April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
86·3	88·6	89·1	87·1	83·0	88·4	86·8	77·0	68·6

TABLE V—MEAN AND EXTREME VALUES OF TEMPERATURE

Month	Mean		Approx. height	Mean temperature			Mean daily		Highest max.	Lowest min.
	lat. N.	long. E.		6h.	18h.	mean	max.	min.		
1922	° ′	° ′	feet	°F.	°F.	°F.	°F.	°F.	°F.	°F.
April ..	12 10	8 30	1830	73·9	93·3	86·8	98·7	74·0	103	64
May ..	13 37	8 0	1530	76·5	95·5	90·1	103·1	74·5	109	69
June ..	14 59	9 27	1630	81·0	97·4	93·1	105·7	77·4	114	65
July ..	15 58	9 2	1660	77·3	88·8	86·7	101·1	74·3	109	64
Aug. ..	17 29	8 15	2730	76·6	82·0	81·0	90·8	72·8	99	66
Sept. ..	17 37	8 20	2870	76·1	85·5	82·9	93·2	73·1	100	67
Oct. ..	17 45	8 36	3000	68·8	85·4	81·3	94·0	64·5	100	51
Nov. ..	18 38	8 28	2400	60·8	83·1	77·5	93·7	57·9	(96)	41
Dec. ..	15 32	8 32	1730	47·3	73·2	66·2	—	45·8	—	31
1927										
June ..	14 24	8 11	1490	78·5	89·9	87·7	101·1	75·0	109	68
July ..	16 52	8 26	2120	80·4	91·0	89·2	102·3	76·1	111	69
Aug. ..	17 38	8 25	2641	74·3	81·5	80·9	95·4	71·5	102	66
Sept. ..	18 36	8 32	2920	75·8	90·1	88·5	103·0	67·5	114	55
Oct. ..	19 9	8 23	2290	76·9	91·6	88·6	102·9	73·0	(111)	(68)
Nov. ..	18 17	5 51	1410	60·9	78·9	77·2	97·4	53·9	(105)	45
Dec. ..	17 50	1 17	1310	61·7	75·2	74·0	88·9	53·4	—	(41)

The minimum in August is associated with the clouds and rain of the SW monsoon. This decrease is however almost confined to the day temperatures. The mean daily maxima in August are 5-8° F. lower than those of July and September ; the night minima in August are a few degrees lower than in July, but are actually higher than those of September, owing to the rapid decrease of night temperature in the second half of the latter month, after the rains are really over. Hence the mean daily range shows a very pronounced minimum in August :—

April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
24·7	28·6	27·2	24·9	20·9	27·8	29·4	38·5	35·5

Towards the close of the year the daily range becomes very large, exceeding 40°F. on many days.[10]

[10] A very high range of temperature was recorded on December 14/15, 1922. On the march on the 14th at 14h. 30m. the sling thermometer gave a reading of 92°F. A few miles away at Tiworshekaken the minimum on the following night was 31°F., giving a range of 61°F.

No outstandingly high temperatures were recorded, only 9 days reaching or exceeding 110°F., distributed as follows :—June 3, July 1, September 4, October 1. The two maxima of 114° were recorded on June 24, 1922, and September 22, 1927. At the other extreme the minimum fell below freezing point on one occasion only, in December, 1922. Mr. Rodd remarks that he has perhaps encountered in his travels less than his fair share of frost at night but in 1927 rather more than his due of low day temperatures.

On several occasions during 1927 series of records were secured from the thermograph. These have been standardized by means of the eye observations and are summarised in Table VI and in Fig. 2. The latter shows several interesting features. First, there is a remarkably regular fall of temperature during the night, the decrease

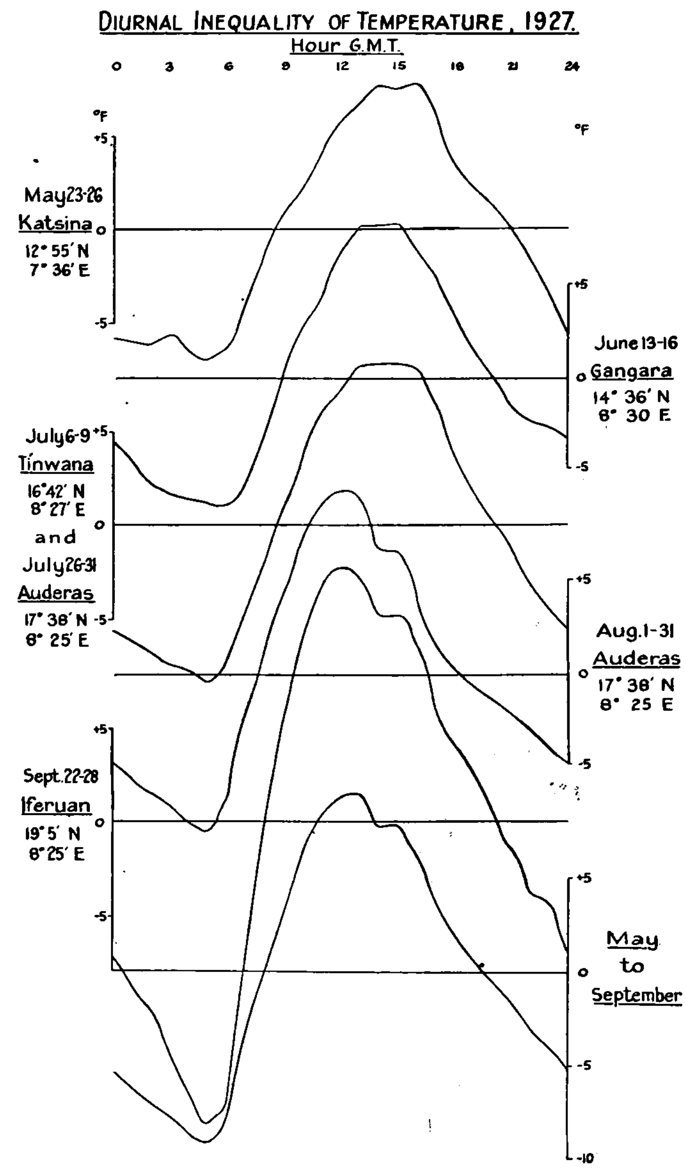


FIG. 2.

from 18h. to 5h. (the times are G.M.T. throughout) averaging almost exactly 1°F. per hour. Shortly after sunrise the steady fall is suddenly replaced by a very rapid rise, amounting to 14·3°F. in the four hours from 6h. to 10h. The night minimum is thus very pronounced, in strong contrast to the flattened minimum in moister regions. In the clear weather of the last week of September these conditions are even more pronounced, the rate of fall from 18h. to 5h. being 1·8°F. per hour, and the rate of rise from 6h. to 10h. no less than 6·3°F. per hour. The maximum for the day occurs between 12h. and 13h., but from 14h. to 15h. there is a remarkable interruption in the fall of temperature, which almost amounts to a secondary maximum at 15h. This feature is shown more or less in all the groups of days in Table VI and is the result of a curious feature in the weather of the southern Sahara. On many days the air is very dry and the sky remains nearly clear, and temperature rises from

TABLE VI—DIURNAL INEQUALITY OF

Station	Lat. N.		Long. E.		Dates	Hours							
						0	1	2	3	4	5	6	7
	°	′	°	′									
Katsina ..	13	00	7	38	May 23–26 ..	−58	−60	−61	−56	−65	−70	−64	−41
Gangara ..	14	36	8	30	June 13–16 ..	−35	−45	−58	−64	−66	−68	−70	−59
T'inwana .. Auderas ..	16 17	42 38	8 8	27 25	July 6–9 .. July 26–31 }	−56	−62	−69	−75	−77	−85	−73	−47
Auderas ..	17	38	8	25	Aug. 1–31 ..	−49	−58	−65	−71	−81	−86	−68	−25
Iferuan ..	19	5	8	25	Sept. 22–28 ..	−71	−87	−100	−122	−144	−161	−151	−79
Mean ..					May to Sept. ..	−52	−61	−69	−76	−86	−92	−79	−39

a deep minimum about sunrise to a flat maximum about 15h., falling again very steadily in the late afternoon. These are the conditions during the "quiet" days of Table VII and Fig. 3. On some days during the SW. monsoon, however, when more moisture is present, the diurnal variation of temperature follows a markedly

TABLE VII—DIURNAL VARIATION OF TEMPERATURE ON

	No. of Days	Hours									
		0	1	2	3	4	5	6	7	8	9
"Quiet" days	16	79·1	78·0	77·7	76·7	75·4	74·2	75·0	79·8	84·0	86·5
"Disturbed" days	15	75·9	75·2	74·2	73·2	72·2	72·3	74·3	77·7	81·9	85·9

different course. The morning is clear, and temperature rises rapidly until 11h. or 12h., the curve being almost identical with that for "quiet" days from 5h. to 11h. Then heavy cumulo-nimbus clouds gather, the upper NE. wind (see § 7) breaks through the south-westerly surface wind, there may be a shower of rain, and temperature falls many degrees in a few minutes. Examples of a number of such sudden drops, with the associated weather, are illustrated in Fig. 6. Temperature not infrequently falls by 20°F. or more in less than an hour. We have termed these days "disturbed." The broken curve in Fig. 3 evidently represents the combination of a number of similar curves.

The average figures of diurnal inequality for all days in Table IV were analysed by means of the harmonic series :—

$$\triangle T = a_1 \sin (t + \theta_1) + a_2 \sin (2t + \theta_2) + a_3 \sin (3t + \theta_3)$$

The constants, with the phase angles corrected to local time, are given in Table VIII.

From May to July the variation is almost a pure sine curve with its maximum at 15h. In August and September the semi-diurnal wave becomes important, reaching its maxima about 0h. and 12h. and its minima about 6h. and 18h. This component thus causes the maximum to occur earlier than 15h. and accentuates the fall of temperature during the afternoon, and evidently represents the effect of the "disturbed" days described above. This is confirmed by the components of

TEMPERATURE IN 1927 (UNIT 0·1°F.).

G.M.T. 8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Station
− 16	+ 8	+ 22	+ 41	+ 59	+ 66	+ 76	+ 75	+ **77**	+ 61	+ 35	+ 23	+ 12	− 2	− 17	− 37	Katsina
− 31	− 1	+ 28	+ 44	+ 69	+ 81	+ 81	+ **82**	+ 67	+ 54	+ 34	+ 17	+ 1	− 16	− 24	− 27	Gangara
− 22	+ 8	+ 38	+ 61	+ 72	+ 86	+ 87	+ **89**	+ 85	+ 67	+ 39	+ 19	+ 5	− 14	− 33	− 45	{ T'inwana Auderas
+ 11	+ 43	+ 73	+ 92	+ **98**	+ 95	+ 67	+ 65	+ 42	+ 18	+ 4	− 6	− 14	− 23	− 32	− 41	Auderas
− 4	+ 54	+102	+126	+**137**	+131	+112	+112	+ 96	+ 60	+ 40	+ 28	+ 7	− 15	− 38	− 43	Iferuan
− 2	+ 32	+ 64	+ 84	+ 94	+ **95**	+ 78	+ 78	+ 61	+ 38	+ 19	+ 6	− 5	− 18	− 31	− 41	Mean

the diurnal variation during the "disturbed" days of July, August and September, in the lowest line of Table VIII. Here the maximum of the diurnal wave comes at $13\frac{1}{2}$h., the maxima of the semi-diurnal wave at $11\frac{1}{2}$h. and $23\frac{1}{2}$h. and its minima at $5\frac{1}{2}$h. and $17\frac{1}{2}$h.

"QUIET" AND "DISTURBED" DAYS, JULY TO SEPTEMBER.

G.M.T. 10	11	12	13	14	15	16	17	18	19	20	21	22	23	
89·7	92·0	93·9	95·3	95·8	**96·4**	95·3	92·2	88·8	87·2	85·7	83·7	81·6	80·7	"Quiet" days
89·3	**91·8**	91·7	90·4	84·3	83·5	81·5	80·8	80·0	79·0	78·9	78·3	77·4	76·6	"Disturbed" days

TABLE VIII—CONSTANTS OF DIURNAL VARIATION OF TEMPERATURE

	a_1	θ_1	a_2	θ_2	a_3	θ_3	a_2/a_1
	°F	°	°F	°	°F	°	
May 23–26	7·20	220	0·66	45	0·16	338	·09
June 13–16	7·22	219	1·82	46	0·21	344	·25
July 6–9, 26–31.. ..	8·38	224	1·28	49	0·57	352	·14
August 1–31	7·91	240	2·82	94	0·59	337	·36
Sept. 22–28	12·76	227	4·39	94	1·70	347	·35
"Disturbed" days ..	7·30	247	3·74	105	1·20	306	·51

The variation of temperature from day to day is comparatively small, but shows one interesting peculiarity, which is also connected with the alternation of "quiet" and "disturbed" days. The figures are shown in Table IX.

Table IX—Interdiurnal Variations of Temperature

Dates	Place	6h.	18h.	Max.	Min.
1922		°F.	°F.	°F.	°F.
April 11–28	Fanisau	2·2	3·7	0·9	2·5
August 10–20, 24–31	Auderas	2·6	5·2	2·5	2·4
Sept. 1–5, 8–30	Auderas	4·5	3·7	2·1	3·3
1927					
August 1–31	Auderas	2·7	5·9	3·3	2·8
October 1–21	Tegidda Mellen	3·2	2·1	3·7	3·2

It will be noticed that apart from the low variability of the maximum temperature in April, 1922, the figures are generally fairly uniform, with the exception of those for 18h. in August, 1922 and 1927, both of which are abnormally high. Fig. 3 shows

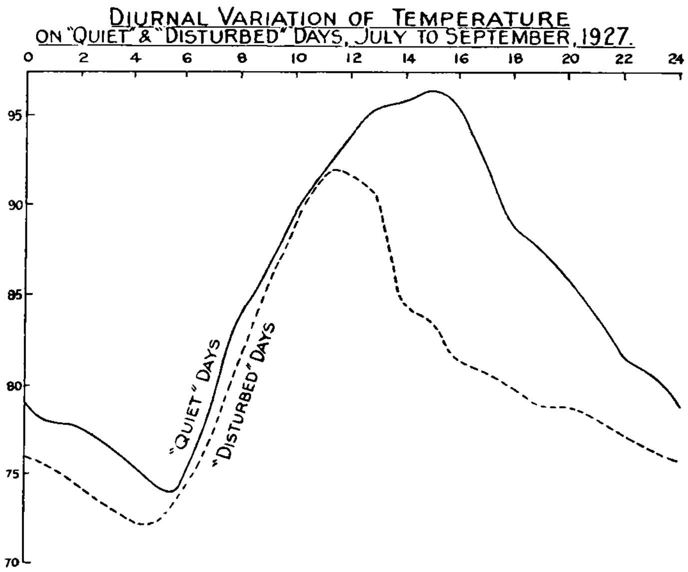


FIG. 3.

that the difference of temperature between "quiet" and "disturbed" days is greatest about 16h. and it is during August that such days alternate most frequently.

Well-water temperatures.—Table X gives details of a number of observations of the temperature of water in wells. The column headed "Depth" gives in each case the distance measured from the surface of the ground down to the water surface. The depth of water in the well was not recorded but is understood to have varied between 2 ft. and 3 ft. 6 in.

Table X—Well-Water Temperatures

Date	Place	Position		Depth	Water temp.	Air temp. at surface	Mean air temp. for month
		Lat. N.	Long. E.				
		° ′	° ′	feet	°F.	°F.	°F.
1922 May 6 ..	Katsina ..	13 00	7 38	66	84	96	90·1
1927 June 11 ..	Kurdidifi ..	14 31	8 28	102	81	94	87·7
,, ,, 24 ..	Tinawgarakan	15 18	8 16	82½	85·5	97	87·7
,, Sept. 16 ..	Tintaralle ..	18 27	8 56	19½	79·5	91	88·5
,, Nov. 28 ..	Tanekert ..	17 49	3 11	31½	84	60	77·2

The water temperature in the deeper wells appears to be approximately the same as the mean annual temperature for the districts, but in the less deep wells it is about the same as the mean monthly temperature 6 or 8 months previous to the observation.

According to experiments in this country, the amplitude of the yearly temperature variation becomes inappreciable at about 50 feet below the ground[11]. Although the daily range of temperature of a desert surface may reach very large figures, this variation does not penetrate far. Experiments made at the Desert Laboratory at Tucson, Arizona[12] showed on one occasion that a daily range of temperature of 56·5° C. at a depth of 0·4 cm. was reduced to 0·1° at 45 cm. The number of observations is too small to give definite conclusions, but it is probable that in the deeper wells the annual variation is very small.

§ 5—Humidity

Owing to the generally large values of the depression of wet bulb recorded, the estimates of relative humidity and vapour pressure are affected not only by the uncertainties in measuring the temperature referred to above but also by the uncertainties in regard to the reduction formulæ.

For reasons already described the ventilation of the dry and wet bulb thermometers during the 1922 expedition was presumed to be deficient, and the vapour pressure figures were therefore calculated by the use of Pernter's "calm air" formula[13]. When sling thermometer readings were available the vapour pressure was first calculated from the "screen" readings, and the relative humidity was then computed from this vapour pressure and the reading of the sling thermometer. In a few cases where only one or two sling-thermometer readings were missing in a series of days, values were interpolated by comparison of the "sling" and "screen" readings on adjacent days. In the later months simultaneous "sling" readings were not available and the relative humidity figures were computed from the "screen" readings alone. The procedure followed is indicated against the various mean readings in Table XI.

Table XI—Averages of Relative Humidity (per cent) and Vapour Pressure (mb.)

Month	Mean lat. N.		Mean long. E.		Approx. Height	6h. R.H.	6h. V.P.	18h. R.H.	18h. V.P.	Notes.
	°	′	°	′	feet	per cent	mb.	per cent	mb.	
1922										
April	12	10	8	30	1830	77	23·5	39	20·6	"Sling" dry bulb.
May	13	37	8	0	1530	62	19·3	33	17·4	,, ,,
June	14	59	9	27	1630	35	12·4	13	7·5	Few sling readings.
Aug.	17	29	8	15	2730	72	22·5	57	20·2	Screen observations.
Sept.	17	37	8	20	2870	57	17·0	39	15·5	,, ,,
Oct.	17	45	8	36	3000	26	6·2	11	4·7	,, ,,
Nov.	18	38	8	28	2400	36	7·5	23	9·5	,, ,,
1927										
May (23–31) ..	13	00	7	40	1570	74	23·5	49	20·9	Whirling hygrometer.
June	14	24	8	11	1490	66	21·7	38	17·3	,, ,,
July	16	52	8	26	2120	53	18·9	30	14·1	,, ,,
Aug.	17	38	8	25	2641	70	20·2	51	17·4	,, ,,
Sept.	18	36	8	32	2920	40	11·3	21	9·3	,, ,,
Oct.	19	9	8	23	2290	26	7·9	15	6·8	,, ,,
Nov.	18	17	5	51	1410	29	5·2	17	5·5	,, ,,
Dec.	17	50	1	17	1310	52	9·5	39	11·0	,, ,,

[11] See, e.g., Rambaut: Underground temperature at Oxford . . *London Phil. Trans. R. Soc.* A, **195**, 1900, p. 235.
[12] Sinclair, J. G. Temperatures of the Soil and Air in a Desert. *Washington Mon. Weather Rev.*, **50**, 1922, p. 142.
[13] Meteorological Office Hygrometric Tables, M.O. 265, Introduction p. 6.

For the 1927 figures, the ventilation was assumed sufficient and the vapour pressure and relative humidity were worked out from the Meteorological Office Tables referred to above.

While it is hoped that the procedure adopted may have removed some uncertainties in the 1922 readings, the latter must be regarded as definitely inferior in accuracy to those obtained in 1927.

At times the formulæ became invalid, thus at 18h. on 17th June, 1922, the readings of the dry and wet bulb were 101·6° and 67·0° F. The usual procedure in this case leads to a negative vapour pressure, and the reading was neglected for computation of the mean value of the vapour pressure, while a nominal value of 2 per cent was entered, in this and similar cases, for computing the mean relative humidity.

Another difficulty occurred in April, 1922, when on one occasion the difference between dry bulb and "sling" reading was such that the computed vapour pressure was higher than the saturation vapour pressure corresponding with the "sling" reading. In this case the relative humidity was taken as 100 per cent. After the exposure of the dry and wet bulb was improved (see § 2) the differences between dry bulb and "sling" readings were much smaller.

Table IX shows the average readings of the relative humidity and vapour pressure at the morning and evening observation hours in 1922 and 1927. The figures indicate that June was much drier in 1922 than in 1927 and this point seems to be supported by an observation in 1927 that "the wind experienced crossing the Azawagh steppe desert between Damergu and Aïr was prevalently SW. to W., though in 1922 it was NE."

While both sets of figures show a double maximum and minimum, experienced as the expedition moved northward, it seems more probable that the course of events at a fixed station near the northern limit of the expedition would include only a single maximum, and from remarks in the weather diaries it appears that Mr. Rodd's expedition in 1922 was probably keeping slightly in advance of the northward trend of the belt of "the rains," which "follows the sun" northward through Nigeria, but in 1927 the rains were ahead of the expedition. In 1927 it was considered that the rainy season had opened while the expedition was in Nigeria.

In 1922 hourly readings of the wet and dry bulb thermometers were taken on three days. The values of relative humidity and vapour pressure computed from these are shown in Table XII, and serve to some extent to indicate the nature of the diurnal variation of these elements. The relative humidity on two of these days is shown in Fig. 4, from which the variations are seen to depend almost entirely on those of the temperature. The curves suggest that the relative humidity reaches a

TABLE XII—HOURLY READINGS, 1922 EXPEDITION

	Hour	6½h.	8h.	9h.	10h.	11h.	12h.	13h.	14h.	15h.	16h.	17h.	18h.	19h.	20h.	21h.	22h.
KATSINA. May 7—	Dry °F. ..	81·0	81·0	85·4	89·0	91·8	93·0	94·0	96·6	96·0	95·4	94·0	93·5	—	—	—	—
	Wet °F. ..	61·6	—	62·4	62·5	69·0	71·0	71·8	73·4	73·6	71·1	73·2	73·8	—	—	—	—
	R.H. % ..	15	—	8	2	16	20	20	20	20	16	25	27	—	—	—	—
	V.P. mb. ..	5·3	—	3·5	1·0	8·3	10·6	11·1	11·9	11·6	9·0	13·4	14·7	—	—	—	—
AUDERAS. Sept. 9—	Dry °F. ..	75·8	81·0	83·8	85·4	88·0	—	88·5	89·0	88·8	78·5	74·0	71·2	—	—	—	—
	Wet °F. ..	70·6	72·0	74·0	74·2	74·8	—	74·9	75·0	74·5	72·0	68·0	68·0	—	—	—	—
	R.H. % ..	72	57	55	51	45	—	44	43	41	67	67	81	—	—	—	—
	V.P. mb. ..	22·0	20·5	21·8	21·1	20·2		20·1	19·9	19·2	22·3	19·2	21·2	—	—	—	—
AUDERAS. Sept. 24—	Dry °F. ..	78·0	83·5	88·1	92·3	94·0	95·5	—	94·4	95·0	91·9	92·0	90·0	87·9	86·0	86·8	86·6
	Wet °F ..	65·2	69·0	70·0	71·2	71·5	72·0	—	73·0	73·5	70·0	71·2	72·0	71·0	67·9	67·4	67·8
	R.H. % ..	38	36	28	22	19	18	—	23	23	19	23	29	31	23	22	23
	V.P. mb. ..	12·3	14·1	12·5	11·4	10·6	10·4	—	12·8	13·2	9·8	11·6	14·2	14·1	10·1	9·4	10·1

low value as early as about 10h. and remains low until about 15h. The variations of vapour pressure are small, but there are indications that this element reaches its minimum about 10h.

The difference between September 9 and 24 is conspicuous. In this connexion remarks from the weather diary give the probable explanation. As regards September 9, it is noted that after noon, temperature fell rapidly with the approaching rain, while the day's rain was more than usually heavy. This was probably a "disturbed" day of the type mentioned in § 4. On September 13 it was noted that the rains appeared to be over.

The driest period encountered in 1927 was during October, in which month out of 24 readings of relative humidity at 18h. none exceeded 25 per cent, 20 were below 20 per cent and 5 below 10 per cent, the minimum reading being 7 per cent on October 1 and the mean for the month 15 per cent.

A figure of 7 per cent was also reached on September 12 and 21 at 18h., these exceptionally low readings being all associated with wet-bulb depressions of 30° or more. Taking the maximum temperatures for these days, and assuming the vapour pressures to have remained constant, approximate values can be derived for the minimum relative humidity for the days, in each case of 5 per cent. Such a figure while very low is not unprecedented, values of 2 per cent having been obtained at several stations. The vapour pressure is generally high in the months of the SW. monsoon, but falls to very low values in the autumn. As showing the variability of this climate, it may be mentioned that the conditions encountered in the mornings of the first few days in June, when temperature was between 75° and 80° and relative humidity about 80 per cent, corresponded closely with average conditions for the same time at Lagos, a coastal station some 500 miles nearer the equator.

SERIES OF READINGS ON TWO DAYS IN SEPT. 1922.

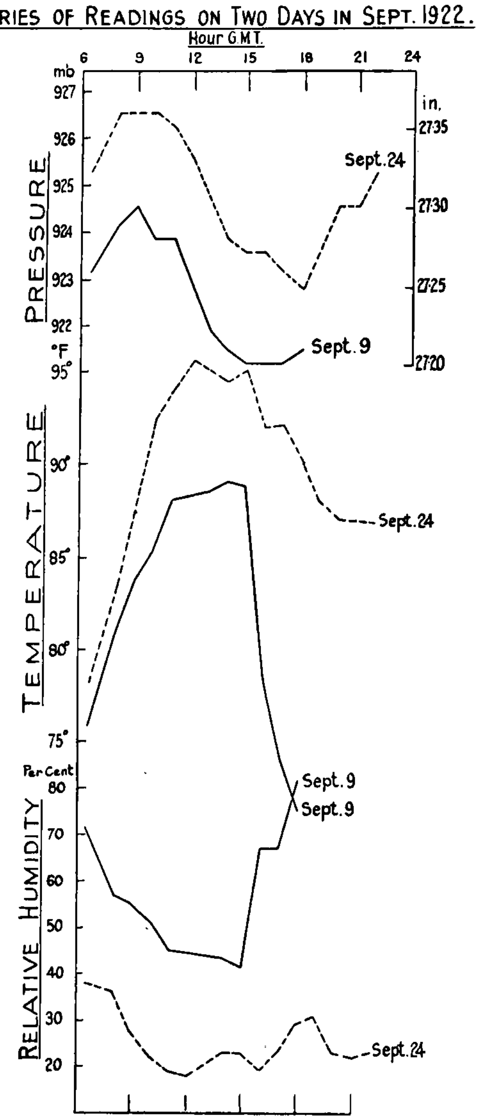


FIG. 4.

The interdiurnal variability of relative humidity for periods when camp was fixed for several days is shown in Table XIII.

TABLE XIII—INTERDIURNAL VARIABILITY OF RELATIVE HUMIDITY

Place and date	6h.	18h.
AUDERAS.		
1922.	%	%
August 10–20 .. .. } 24–31 .. .. }	10	18
September 1–5 .. .. } 8–30 .. .. }	17	17
1927.		
August 1–31	9	19
TEGIDDA MELLEN.		
1927.		
October 1–21	6	5

The high figure for 6h. in September 1922 may be associated with disturbed conditions at the close of the rainy season. On several occasions a strong E. wind blew all night, while on other mornings the wind was calm or westerly.

As further evidence of the transport of appreciable quantities of water vapour into the Sahara by " monsoon " winds, the numbers of occasions on which dew was observed in the various months of 1927 are given in Table XIV together with the corresponding mean dry-bulb and dew-point figures.

TABLE XIV—TEMPERATURES OF AIR AND DEW POINT ON MORNINGS ON WHICH DEW WAS RECORDED.

Month	No. of occasions of dew	Morning observations on these days					
		Mean dry-bulb temperature	Mean dew-point temperature	Difference			
				Average	Slight dew	Dew	Heavy dew
		°F.	°F.				
June ..	12	77*	67*	10	11	11	4
July ..	6	78	62	16	19	23	12
Aug. ..	22	74	64	10	12	12	7
Sept. ..	5	73	44	29	37	21	9
Oct. ..	2	74	35	39	39	—	—
Nov. ..	2	58	29	29	35	24	—

* 11 occasions only.

The observations for September, October and November point to the extraordinary difference of temperature between the ground and the air which must occur on the rare occasions when dew is formed. In the months of the SW. monsoon the humidity of the air is much greater and a moderate degree of cooling is sufficient, so that dew is frequent, especially in August.

§ 6—WINDS

Mr. Rodd's observations of wind direction at fixed hours, mainly 6h. and 18h., were supplemented by very full notes of the changes during the day, and often during the night as well. Hence the best way of summarising them appeared to be to estimate the total duration of winds from different directions each day, and to convert

TABLE XV—PERCENTAGE FREQUENCY OF WINDS FROM DIFFERENT DIRECTIONS.

	Average Position Lat.	Long.	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Calm
	° ′	° ′									
1922.											
April	12 10	8 30	0	5	7	21	1	41	3	3	19
May	13 37	8 0	4	3	17	9	5	23	6	14	19
June	14 59	9 27	0	3	30	25	0	33	1	0	8
July	15 58	9 2	2	5	3	1	0	21	66	0	2
August	17 29	8 15	1	7	8	11	2	32	7	12	20
September ..	17 37	8 20	0	4	49	4	0	3	18	4	18
October	17 45	8 36	0	1	39	51	1	0	0	0	8
November	18 38	8 28	0	0	25	19	1	17	11	4	23
December	15 32	8 32	0	55	14	10	0	0	9	1	11
1927.											
May 22–31.. ..	13 00	7 40	3	8	5	6	9	16	9	1	43
June	14 24	8 11	0	3	1	2	6	34	17	8	29
July	16 52	8 26	2	2	3	0	1	21	35	10	26
August	17 38	8 25	9	9	18	8	0	7	12	13	24
September ..	18 36	8 32	4	25	26	10	0	2	[illegible]	0	31
October	19 9	8 23	13	51	11	2	2	2	0	1	18
November	18 17	5 51	7	29	13	0	0	2	0	1	48
December 1–15 ..	17 50	1 17	10	30	20	0	0	7	4	5	24

the monthly totals into percentages of the total number of hours observed. The results for 1922 and 1927 are given in Table XV. It will be seen that from April to August, 1922, and from May to July, 1927, the prevailing winds were southerly or south-westerly, while from September to December easterly winds prevailed. In August, 1927, westerly and easterly winds were of approximately equal frequency. The resultant directions were as follows :—

	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1922 ..	SSW.	SSW.	SE.	W.	SW.	E.	ESE.	SSE.	ENE.
1927 ..	—	SSW.	WSW.	W.	NNE.	ENE.	NE.	NE.	NE.

In the northern part of the northern province of Nigeria the observations show that the north-easterly winds continue to prevail until some time in March, and are steadiest in December and January, while the SW. winds are steadiest in June.

Between Taberghit and Tagedufat (about 16° N., 8-9° E.) to the south of Aïr, the small mobile crescentic sand dunes, the horns of which point down wind, indicate a prevailing direction from E. or NE.

During the SW. monsoon there was a tendency for the winds in the early morning to be more westerly and those in the late afternoon to be more south-westerly, while the occasional bursts of north-easterly wind (see below) were limited to the middle of the day. During the NE. monsoon there was a slight tendency for the winds to be more northerly in the morning and more easterly in the afternoon. Both tendencies represent a veer of the wind and probably result from the increasing turbulence during the day, but the changes were not very definite. The wind force showed a distinct maximum at mid-day ; where definite estimates were made the distribution was as follows :—

TABLE XVI—PERCENTAGE FREQUENCIES OF WINDS OF DIFFERENT FORCE

Force	Calm	1–3	4–7	8 or more
Morning ..	47	51	2	0
Mid-day ..	7	80	10	3
Evening ..	35	60	5	0

Upper Winds.—For 1927 a number of observations of the direction of cloud motion are available. These are shown in Table XVII, divided into two periods May 24 to August 13 and August 14 to December 16, which roughly correspond with the prevalence of surface winds from SW. and NE. respectively. The clouds were divided into two classes, lower cloud, chiefly cumulus and nimbus, and middle or

TABLE XVII—SUMMARY OF OBSERVATIONS OF CLOUD MOTION

	Direction from (per cent.)									
	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Calm	No. of obs.
MAY 24–AUG. 13—										
Lower cloud	3	49	26	13	3	2	2	2	0	39
Corresponding surface wind	2	10	8	8	13	24	15	5	15	39
Upper cloud	0	40	33	17	3	0	2	2	3	30
Corresponding surface wind	0	3	0	0	3	33	13	10	38	30
AUG. 14–DEC. 16—										
Lower cloud	2	21	52	10	0	7	3	5	0	41
Corresponding surface wind	11	33	18	6	2	5	1	4	20	41
Upper cloud	0	10	74	0	3	7	3	3	0	30
Corresponding surface wind	8	17	15	0	0	0	0	3	57	30

upper cloud, chiefly cirro-stratus, cirro-cumulus and cirrus. During the first period the prevailing direction of motion of lower clouds was from NE., in direct opposition to the surface winds. The upper clouds moved from a slightly more easterly direction than the lower clouds. Comparison with the surface-wind directions at the time of observation brings out two interesting points; first that during the occurrence of low cloud north-easterly winds at the surface are fairly frequent even during the SW monsoon. This is especially true of nimbus clouds, which seem to be carried on a powerful burst of the north-easterly upper current, often powerful enough to sweep away the surface layer of air moving in the opposite direction and to extend down to ground level. On these occasions the wind frequently attains gale force. The second point is the greater frequency of surface calms with high cloud than with low; this results partly from the converse phenomenon that when low cloud is absent the wind is generally light, and partly from the large number of observations of upper cloud which were taken at 6h.

During the second period, from August 14 to December 16, the upper winds are more in accord with the surface-wind directions, though with a progressive deflection towards the E. The resultant direction of the surface winds during this period, measured from N. towards E., is 52°, that of the lower cloud 82° and of the upper cloud 89°.

On October 19th, 1927, two levels of " high " cloud were observed, cirro-cumulus moving from E. and, above that, cirrus moving from W.

§7—Amount and Type of Cloud

The cloud observations made in 1927 have been analysed with the results shown in Tables XVIII-XXI. The observations have been grouped in periods of two

TABLE XVIII—FREQUENCY OF DISTRIBUTION OF DIFFERENT TYPES OF CLOUD, AS PERCENTAGES OF NUMBER OF CLOUD OBSERVATIONS

Type	Morning	Mid-day	Afternoon	Evening	Morning	Mid-day	Afternoon	Evening
	May and June				July and August			
Ci. ..	30	12	3	7	34	14	9	6
Ci.-St.	—	11	6	14	—	—	—	—
Ci.-Cu.	27	12	12	17	34	7	9	23
A.-St.	—	—	—	—	2	—	—	2
A.-Cu.	—	—	—	—	—	—	3	2
St.-Cu.	—	4	—	—	2	—	—	2
Nb.	5	4	30	31	2	39	44	41
Cu.	3	42	40	14	12	36	26	19
Cu.-Nb.	5	—	6	—	—	—	3	2
St. ..	30	15	3	17	14	4	6	23
No. of observations	37	26	33	29	44	28	34	52
	September and October				November and December			
Ci. ..	19	10	18	3	28	15	27	13
Ci.-St.	11	3	5	3	19	23	21	13
Ci.-Cu.	30	3	3	15	22	8	5	9
A.-St.	—	—	—	—	—	—	—	—
A.-Cu.	2	3	—	3	—	—	—	—
St.-Cu.	9	—	3	12	—	—	—	—
Nb.	2	16	21	26	—	8	5	5
Cu.	6	42	42	12	—	—	5	5
Cu.-Nb.	2	3	—	—	—	—	—	5
St. ..	19	20	8	26	31	46	37	50
No. of observations	47	31	38	34	32	13	19	22

months owing to the comparatively small number of observations, and the method of dividing up the day was chosen so as best to utilize the numerous observations made between the usual morning and evening hours. Consideration of the original figures shows that no important feature of the cloud conditions is obscured by this method of grouping except perhaps the variations from month to month in frequency of Nb., Cu., and St. clouds ; the figures for these separately are therefore given in Table XIX.

TABLE XIX—FREQUENCY OF OCCURRENCE OF NB., CU. AND ST. CLOUDS IN PERCENTAGES OF NUMBERS OF CLOUD OBSERVATIONS

	Morning	Mid-day	Afternoon	Evening	Morning	Mid-day	Afternoon	Evening
		May				June		
Nb. ..	22	—	22	57	—	5	33	18
Cu. ..	—	17	33	14	4	50	42	14
St.	33	50	11	29	29	5	—	14
		July				August		
Nb. ..	—	27	38	19	4	47	54	44
Cu. ..	6	18	24	12	15	47	31	19
St.	13	9	10	19	15	—	—	19
		September				October		
Nb. ..	—	21	32	38	4	8	6	8
Cu. ..	9	58	45	14	4	17	37	8
St.	22	5	—	10	17	42	19	54
		November				December		
Nb. ..	—	—	—	—	—	17	14	10
Cu. ..	—	—	8	—	—	—	—	10
St.	22	29	25	50	43	67	57	50

It will be seen that in all months there is a considerable diurnal variation of cloud, specially marked in the monsoon season as is to be expected from what has already been said about the sequence of weather on a " disturbed " day. Convection cloud is prominent from May to October, but in November and December there is an increase in St. cloud. The reason for the increase in frequency of St. is not clear—it may be an expression of change in longitude as well as of change of type, or of season, the first three weeks or so of November showing little cloud whereas the last week of November and the part of December in which the observations continued showed a considerable increase of cloud. On November 28 it was noted that " since the 22nd the sky has been covered nearly every day up to 10/10 with this Ci. and Ci. St. which however was transparent with blue sky everywhere more or less visible," while regarding the first part of December : "Throughout the last fortnight the weather has been cloudy nearly every day with skies of 10/10 covered all day . . . Drops of rain fell several times, but although the sky was often very threatening no prolonged rain fell . . The clouds seemed for the most part to be coming from N. or W of N."

These observations might indicate the change toward the January type of pressure distribution when the surface " high " is centred about lat. 30° N. and the pressure gradient at 3,000 metres is for westerly winds. On the other hand, the weather of November and December, 1927, was described as unusual by the natives both of Aïr and Ifoghas. But the weather was unusual not in type but in persistency. In November, 1922, a short period of cloudy weather was observed, the cloud coming from the N., over southwesterly surface winds. The rain-cloud of November-December, 1927, also came from N. or W. of N. This is the direction whence the

Aïr winter rains (see p. 29, second paragraph of note under October 14, 1927) used to come according to the natives, who recognize the difference in type between these and the usual summer rains.

TABLE XX—PERCENTAGE FREQUENCIES OF OCCURRENCE OF VARIOUS CLOUD AMOUNTS (scale 0—10)

Observed cloud amount	Morning	Mid-day	Afternoon	Evening	Mean of day*	Morning	Mid-day	Afternoon	Evening	Mean of day*
	May and June					July and August				
0	34	26	24	30	5	42	25	8	20	12
1	15	11	9	14	8	17	15	—	18	7
2	8	7	—	3	26	12	5	8	4	7
3	2	4	9	3	10	5	—	15	2	15
4	2	15	5	—	10	2	—	15	9	15
5	2	11	14	6	8	2	5	—	2	17
6	2	—	—	2	10	2	10	8	4	3
7	5	—	5	3	13	3	—	—	2	22
8	—	4	5	14	2	9	5	15	7	—
9	10	11	5	3	5	3	10	8	18	—
10	20	11	24	22	3	3	25	23	14	2
No. of observations	41	27	21	36	39	59	20	13	45	41
	September and October					November and December				
0	44	40	24	48	27	37	41	25	47	31
1	10	12	20	5	17	7	—	6	12	11
2	10	—	—	4	6	10	—	—	3	8
3	2	4	4	7	2	2	6	6	5	—
4	10	—	—	—	6	—	—	—	—	5
5	2	4	4	11	17	—	—	—	3	8
6	4	—	—	2	9	—	6	—	—	3
7	2	—	—	5	8	2	6	13	3	8
8	4	4	12	5	4	7	—	—	—	—
9	4	8	4	2	4	14	12	19	7	13
10	8	28	32	11	—	21	29	31	20	13
No. of observations	50	25	25	44	48	43	17	16	40	38

* Estimated from consideration of all available information in the weather diaries. In some cases, as when only a morning observation was made, it was not possible to estimate the mean for the day.

The values of mean cloudiness are given in Table XXI. The figures for the mean of the month are in satisfactory agreement with those deduced from the maps of mean cloudiness given by Sir Napier Shaw (Manual of Meteorology, Vol. II).

TABLE XXI—VARIATION OF MEAN CLOUDINESS (Tenths of sky covered)

	Morning	Mid-day	Afternoon	Evening	Mean
May–June ..	3·9	3·9	4·8	4·5	4·1
July–August ..	2·4	4·9	5·9	4·7	4·0
Sept.–Oct. ..	2·7	4·3	5·0	3·1	3·2
Nov.–Dec. ..	4·4	4·9	5·9	3·3	4·1

§ 8—RAIN AND OTHER PHENOMENA

The area traversed by Mr. Rodd lies wholly within the summer rainfall belt, the northern limit of which corresponds fairly accurately with the northern geographical boundary of Aïr at the pools of Tarazit (about 20° N.). In Aïr the rains appear according to the natives to be divided into three parts :

(1) those which fall in July, rarely before the 14th, and last a few days ; three or four good falls may be expected. Then follows a brief rainless period before

(2) the August rains ; these are the useful rains. Then there should be a further brief interval of a few days fine weather, of which the period at the end of August and beginning of September, 1927, was described as being quite characteristic. This is followed by

(3) the fitful September rains, which may include heavy rains but are more usually irregular showers of varying intensity, tailing off into the October weather of which 1922 was more characteristic than 1927. Typical of these rains were the showers on September 9, 10 and 15, 1927. On the 9th showers fell from 17h. 30m. to 18h. 45m. but on the 10th and 15th the rain, although relatively copious above the hot surface stratum of air, scarcely reached the ground.

The extreme dates for the first rains of sufficient volume to fill stream beds of a certain size with flood water, are June 3, recorded by von Bary east of Bagezan in 1877, and September 1, recorded by Barth in northern Aïr in 1850, but both these dates seem to be exceptional.

Most of the rainfall is of the "tornado" type, falling in short heavy showers nearly always between noon and sunset. It is very local, heavy showers often being visible at a distance while no rain, or at most a few drops, fell near the camp. Mr. Rodd records, however ("People of the Veil," p. 123) that :

> "During my stay at Auderas there were a few days when the sky was overcast for the whole of the twenty-four hours, with little rainfall ; the damp heavy feeling in the air reminded one of England, as the atmosphere was cold and misty. On one particular day it rained lightly and fitfully for fourteen hours on end with occasional heavy showers. Such phenomena, however, are rare. Precipitation follows a north-easterly wind and usually lasts three or four hours ; as soon as the westerly wind, prevalent at this season, has sprung up, the nimbus disperses rapidly, leaving only enough clouds in the evening to produce the most magnificent sunsets that I have ever seen."

The incidence of the rains varies from place to place, being generally earlier in the south than the north, though there are many irregularities. Hence Table XXII, which gives the number of days with rain (including days on which rain was seen falling in the vicinity) recorded by Mr. Rodd, shows a more extended rainy period than would have been recorded in Aïr alone.

TABLE XXII—FREQUENCIES OF RAIN

Month 1922	No. of days with rain	No. of days of observations	Month 1927	No. of days with rain	No. of days of observations
April ..	4	30			
May ..	7	31	May ..	6	10
June ..	6	30	June ..	12	30
July ..	14	31	July ..	13	31
August ..	18	31	August ..	24	31
September ..	12	30	September ..	12	30
October ..	2	31	October ..	6	31
November ..	0	30	November ..	2	30
December ..	0	30	December ..	5	15

On the occasions in 1927 on which the rain-gauge was in use, a few falls at the rate of 2 inches or more per hour were measured, for example on June 18 1·04 inches fell in 30 minutes. Several falls during August were at rates of between one and two inches per hour. The full list is shown in Table XXIII. These intense falls produce violent floods in valleys where normally the water-courses are dried up.[14]

[14] All the valleys in the area visited by the expedition are normally dry even during the rains. The only exceptions are two or three ravines high up in the Bagezan and Tamgak Mountains where there are said to be perennial rivulets or springs with a few hundred yards of flowing water. When rain does fall, the valleys, even the largest, flow very strongly and violently, starting and ceasing very suddenly. In one or two areas on the outskirts of Aïr these flood waters make "sumps" where the ground remains soft and is often impossible by camel for weeks at a time. F.R.

The " tornadoes " are generally accompanied by considerable perturbations of the diurnal temperature change (see pp. 18 and 21) but the corresponding disturbance of the pressure changes is less marked.

TABLE XXIII—RAINFALL RATES 1927.

May 27 ;	·53 in.	nearly all in	10 min. ;	equivalent to	3·0 in./hr.	(approx.).
June 18 ;	1·04	,, fell in	30	,,	2·1	,,
August 3 ;	·15	,, ,,	20	,,	0·5	,,
,, 13 ;	·44	,, ,,	25	,,	1·1	,,
,, 14 ;	·22	,, ,,	20	,,	0·7	,,
,, 22 ;	·19	,, ,,	60	,,	0·2	,,
,, 23 ;	·48	,, ,,	20	,,	1·4	,,
,, 28 ;	·2	,, ,,	6	,,	2·0	,,
	·35	,, ,,	12	,,	1·7	,,
September 2 ;	·45	,, ,,	50	,,	0·5	,,

There is a tendency for the tornado to be accompanied by a slight rise of pressure which prevents the usual afternoon minimum of pressure being attained. Fig. 5 shows the diurnal inequalities of pressure on "quiet" and "disturbed" days in August and Fig. 6 gives tracings of selected thermograms, with the corresponding barograms, and notes on the weather.

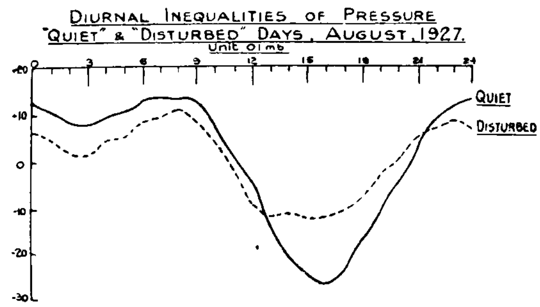


FIG. 5.

On August 10 the disturbance of the temperature was accompanied by comparatively little barometric change, while on September 24 the reverse occurred, the barograph trace showing a fairly well marked disturbance, while the thermograph was hardly affected.

On August 23 it was noted that " The temperature drop did not precede the afternoon storm as it usually does by about ¼ to ½ hour."

The tornado seems to be due in some way to interaction between the upper north-easterly current and the lower, damp, monsoon winds,[15] but the mechanism of the process is not clearly understood. Under the average conditions about the times to which the tracings of the autographic curves refer, a statical change of about 2 mb. (·06 in.) in pressure would be produced if the lowest half kilometre of air were replaced by air 25° colder.

The parts of the curves reproduced are from 12h. to 19h. except (*f*), which runs from 11h. to 18h. The tracings are intended to show the relative values of the temperature and pressure changes, instrumental corrections for absolute values not being indicated. The corrections necessary to the thermograms are, however, small. The base line for the barogram varies from about 28 inches in July to 27 in August and 27·5 in September, the lines across the traced parts being at intervals of 0·1 inch (3·4 mb.).

The following are extracts from the weather notes for the days in question :

July 7—" 1.30 p.m. Cu. and Nb. gathering to E. and NE. A part passed N., but centre of storm apparently broke on camp ; wind E. with squalls force 9-10, wind generally force 8 and 7. Storm began about 1.55 p.m. ; by 2.30 rain finished, 0·63 inches had fallen. Drizzle continued till 4.15 p.m., further ·05 inch fell. Wind between 2.30 and 4 backed through N. to W., whence sudden hot squalls force 5 and 6. Sky clearing south, east and north-east. Squalls ceased just before 5. The later ones were less hot and violent. Wind dropped to calm at 5.15 p.m. Colourless sunset. Cloud 5, Ci. and Ci-Cu. (NE.)."

August 10—" 12.50 p.m. slight shower from NE. 2.15 p.m. sharp shower preceded by gusts NE. force 3."

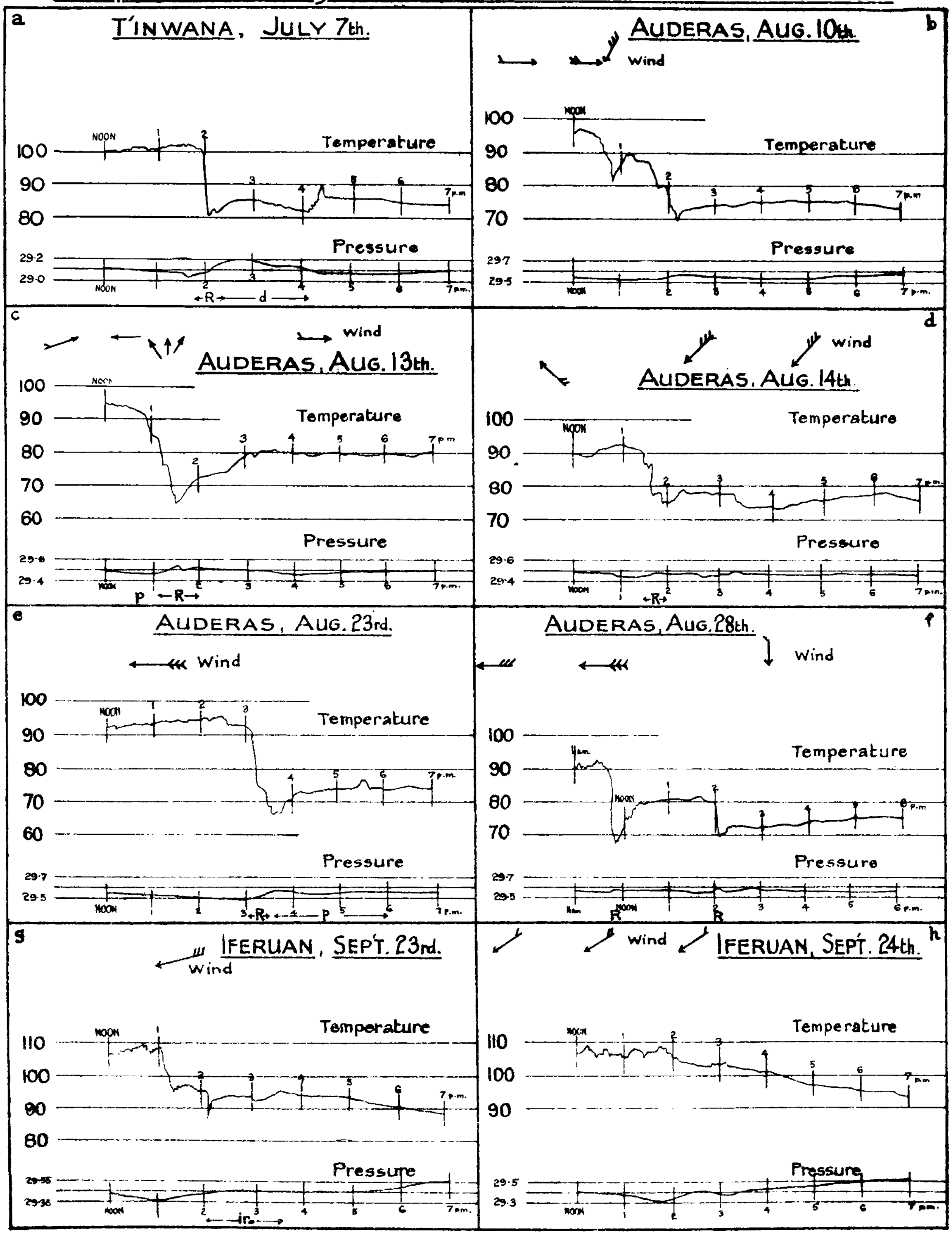
August 13—" 1.20–1.45 p.m. very heavy rain. Storm came from east. Wind E., SE., S. and then SW. Storm passed W., whence N., travelling E."

August 14—" 1 p.m. first drops. 1.30 storm from E., ·22 inch rain in 20 minutes. Passed W. then curled round to N. and returned, a few drops falling.

Hubert, H. Nouvelles études sur la météorologie de l'Afrique Occidentale Française. Paris. 1926.

To face p. 28.

WIND, TEMPERATURE & PRESSURE ON SELECTED DAYS IN 1927.



2830 Malby & Sons, Lith.

FIG. 6.

August 23—" Storm gathering 1.15 p.m. NE. to SE. horizon. Rain preceded by strong puffs and squalls up to force 6 from E. Heavy rain 3.10 to 3.30 then light showers till 6 p.m."

August 28—" 11.45 a.m. wind E. 3, cloud Nb. 6 from ENE. 0·2 inch fell in 6 minutes. 2 p.m. wind E. 6, cloud Nb. 10 from ENE., rain driven by gale. ·35 inch in 12 minutes."

September 23—" 1 p.m. Very heavy packs of Cu. appeared to E., by 2 p.m. whole sky was covered with moderately high Cu and lower Nb. A good deal of rain fell in mountains, but over camp only three small showers of short duration between 2 p.m. and 3.30 p.m."

September 24—" 3 p.m. Some Nb. and Cu. visible to E. and SE.
4 p.m. considerable Nb. came over from E., sky at most times 9/10 covered, till sundown, when Nb. low on W. and S. horizon."

These examples give a description of typical rainy-season weather in this part of the Sahara. Rain during the night is not unknown, though rare. On one occasion in 1922 rain fell practically without interruption for 14 hours.

Some remarks regarding the rainy season in general may be quoted :—

1922 : September 8—" —the weather continues in the rainy season. The normal amount is 10 days rain this moon and 20 days last moon. With the end of this moon the rainy season closes. This year the rain at Auderas has been more than usual ; on the other hand practically none is said to have fallen in Ighazar, though further west at Zurika and Agellal it is normal."

" With the storms the wind moves round a good deal. It is generally blowing SW. when they come up. Then it comes from NE. moving to N., NW., W. and SW. again."

1922 : September 22—" E. wind still continues and with it a clear blue sky. The E. wind appears normal after the rains. To the south the rains are followed by a drying wind which dries the crops. The rains are certainly over."

1922 : November 16—" It is said that it used to rain in Aïr after the tropical or summer rains in the late autumn and in late October and November in the olden days, but it is 20 years or more since that happened. This second rain appears to be coincident with the rain in the Fezzan and Ghat areas in the late autumn and early winter corresponding with the European rainy season."

1922 : November 21—" It is noticeable that during the cloudy days that we have been having, the otherwise regular E. and SE. winds gave place to a SW. wind and that the clouds came from the N., much the same symptoms observed during the rainy season. This is probably the weather which used to come when the rains fell in Aïr in the late autumn."

1927 : October 14—" On the 2nd considerable quantities of cloud appeared and have been manifested almost daily since then, for the most part appearing some time after sunrise from the NE. or E. Occasionally higher clouds have been seen coming from the NW., but these have been difficult to remark as they have appeared on days when there was much cloud about at lower levels coming from the NE."

" These late, October, rains have been conspicuously absent in Aïr during the last 10 years by all accounts. When they occur they are supposed to betoken good autumn and winter rains in the Sahara subjected to the Mediterranean régime and good rains in Aïr during the next summer season following."

1927 : November 1—" The conclusion is that practically no rain has fallen this year between Tamgak (lat. 19) and Tarazit (lat. 20) though an almost exceptional amount in the latter area." (In the Tarazit area and rather east of the Tarazit massif is the Grebun massif which is probably the highest group in Aïr.)

1927 : December—" Throughout the last fortnight the weather has been cloudy nearly every day with skies often covered all day. . . . Drops of rain fell several times but although the sky was often very threatening no prolonged rain fell. The clouds seemed for the most part to be coming from N. or W. of N."

Sandstorms may occur alone, or as the precursors of rainstorms. Examples may be quoted from the weather diary :

1927 : June 15—" Dust storm from SE., wind force 4, but no rain : began 4 p.m., over by 4.40 p.m. Height of dust about 70 feet. Wind speed measured just before dust and wind arrived 1,490 ft. per min." (17 m.p.h.)

1927 : June 23—" 1/10 Ci. from NE. at 10 a.m. At noon cumulus appeared from NE. and E., by 3 p.m. heavy low nimbus approaching from E. with SW. and W. 1 wind in puffs. At 3.45 p.m. a cloud of sand probably 100 ft. high appeared, preceded by a calm. It suddenly commenced blowing E. 5 with much sand and went on for 20 minutes. Then steady rain. Most of the storm passed south of us ; storm went away west. Rain fell for about 45 minutes steadily and not hard, laying sandstorm which went on ahead of the rain."

Dust-devils were observed on many occasions. One which passed near the camp on July 26, 1927, caused a sudden drop in pressure of nearly 2 mb. Another on October 18, 1927, struck the camp at 15h. giving rise to a wind of force 8 momentarily, and then moved north at an estimated speed of 10 to 15 m.p.h.

Other phenomena.—The frequencies of thunder, lightning and zodiacal light are shown in Table XXIV. Very distant thunder and lightning were observed frequently but not recorded.

TABLE XXIV—FREQUENCY OF OCCURRENCE OF VARIOUS PHENOMENA

1922	Thunder	Lightning	Zodiacal light	No. of days	1927	Thunder	Lightning	Zodiacal light	No. of days
April ..	2	5	2	30					
May ..	2	2	—	31	May ..	1	3	—	10
June ..	—	1	—	30	June ..	1	2	—	30
July ..	1	1	—	31	July ..	—	1	—	23
Aug. ..	1	1	—	31	Aug. ..	5	5	—	31
Sept. ..	1	1	—	30	Sept. ..	2	—	6	30
Oct. ..	—	—	—	31	Oct. ..	—	—	—	31
Nov. ..	—	—	—	30	Nov. ..	—	—	4	30
Dec. ..	—	—	—	30	Dec. ..	—	1	—	15

§ 9—VISIBILITY

In 1927 several observations of visibility were made, the entries being usually descriptive, as " fair," " very hazy," and less commonly expressed as distances. These observations, being somewhat irregularly made, have not been summarised in the usual way, but have been classified broadly under two headings as shown in Table XXV.

TABLE XXV—SUMMARY OF VISIBILITY OBSERVATIONS 1927

Visibility	May		June		July		Aug.		Sept.		Oct.		Nov.		Dec.	
	6h	18h	6h	18h	6h	18h	6h	18h	6h	18h	6h	18h	6h	18h	6h	18h
" Very fair " and above ..	3	3	12	9	5	—	13	5	18	16	4	3	27	18	1	—
" Fair " and below ..	—	—	2	4	3	5	8	3	8	3	5	4	—	1	1	1
Total of observations ..	3	3	14	13	8	5	21	8	26	19	9	7	27	19	2	1

These observations indicate that visibility was best in May, June and November and worst from July to October. Low visibilities seem to be due to dust haze which often reduces the visibility to 1 mile or less. Sandstorms on occasion were noted as reducing visibility to a quarter of a mile and to 50 yards. There seems to be a considerable diurnal variation, haze increasing during the day on several occasions while morning and evening were clear, but on one or two days in July visibility was better about mid-day, and in August there was a tendency for haze in the mornings. In the latter part of October it was noted that " Visibility as usual with NE. winds has often been poor during the day but improved always to good and very good at sundown and at night when it has often been exceptionally good." In September, 1922, it was noted that " NW. wind brings haze all over the country, often very thick."

"*Heat flicker*" was noted on many occasions in May and June, but seldom afterwards.

Mirage was noted both in 1922 and 1927 wherever the ground was suitable after leaving latitude 15° N. It was of such frequent occurrence that only in exceptional cases is it alluded to in the diaries. It was seen in May (1922), June, July, September, October (1922 and 1927) and November (1927), both in the deserts south and west of Aïr and in the mountainous plateau itself, though not in narrow valleys.

Mirage on November 12, 13, 14 and 15 was so remarkably bad that at noon visibility fell at times to 200 yards in certain directions and was never more than two miles between 9h. and 15h. It extended all round the horizon. The desert here was exceedingly flat, the surface being small gravel lying on hard sand.

On November 14 the mirage was very bad even in the early morning. Some low hills called Ajir were seen for two hours flickering, but sufficiently formed to allow the natives to recognize their profile above the bank of mirage when the caravan was south of Tan Adar—a distance of at least 40 miles. Just before noon they disappeared and were not seen again until three days later from another direction 20 miles away. Normally when there is only a slight mirage they are not visible from the point south of Tan Adar on account both of distance and of intervening sand ridges. They are so low that in clear weather they only become visible at a distance of some 20 miles from a direction where no ridges intervene. The natives regarded this phenomenon as most interesting. The mirage lay in its correct bearing ; the mirage bank was perhaps 2° high and the hills some $1\frac{1}{2}$—2° above it.

APPENDIX

METEOROLOGICAL DIARIES KEPT BY F. R. RODD, 1922 AND 1927.

Day.	Station.	Lat. N.	Long. E.	Height *	Temperature. 6h.†	Temperature. 18h.†	Temperature. Max.	Temperature. Min.	Relative Humidity. 6h.	Relative Humidity. 18h.	Remarks.
April, 1922.		° ′	° ′	ft.	°F.	°F.	°F	°F.	%	%	
1	Kano	12 4	8 33	2000	82·1	91·1	94·0	81·6	74	46	Sun through haze all day.
2	.. ..	..	..	..	80·5	..	..	80·0	63	..	Fresh SW. wind all day.
3	Fanisau	12 5	8 33	1700	*80·1*	92·5	95·0	80·0	60	42	Hot day. Fresh SW. wind.
4	.. ..	..	..	..	76·0	95·5	96·0	76·0	75	49	Much cloud at night.
5	.. ..	..	..	..	74·0	*95·0*	96·0	74·0	93	25	Few drops rain 21h.
6	.. ..	..	..	..	75·5	90·2	98·0	75·5	84	40	Squalls at 15h. 55m. and 20h.
7	.. ..	..	..	..	74·0	95·1	95·4	74·0	95	38	Nb. over all sky 18h.
8	.. ..	..	..	..	76·0	94·0	97·5	76·0	82	27	Cloud disappeared in afternoon.
9	.. ..	..	..	..	67·2	91·0	99·0	67·2	56	30	Haze afternoon and night.
10	.. ..	..	..	..	64·0	95·1	100·3	64·0	..	..	Sky covered morning, clear afternoon.
11	Fanisau	..	..	..	70·0	89·0	96·2	70·0	..	..	Sky covered morning, clear afternoon.
12	.. ..	..	..	..	75·4	90·8	99·0	75·2	..	..	Afternoon clear.
13	.. ..	..	..	..	69·0	89·0	98·0	68·0	..	..	Haze morning, clear sky all day.
14	.. ..	..	..	..	67·1	91·0	98·3	67·1	..	..	Clear all day.
15	.. ..	..	..	..	65·3	97·7	99·0	65·3	..	..	Clear sky all day.
16	.. ..	..	..	..	67·0	*94·6*	99·2	67·0	94	19	Gusts of wind from E. and SE. p.m.
17	.. ..	..	..	..	64·0	88·6	100·1	64·0	100	25	Very hot in sun.
18	.. ..	..	..	..	74·8	91·8	100·1	72·2	55	31	Clear hot day.
19	.. ..	..	..	..	78·3	..	99·1	75·9	73	..	Sharp squall 16h. 30m. Rain 17h. and 18h. 55m.
20	.. ..	..	..	..	76·7	92·6	98·1	75·7	76	55	Sun hidden nearly all day.
21	.. ..	..	..	..	75·9	92·0	99·9	75·9	88	46	Much small Cu. cloud about.
22	.. ..	..	..	..	76·2	92·6	99·1	76·2	85	49	Hot and rather windless all day.
23	.. ..	..	..	..	77·7	97·5	100·9	77·7	76	40	Flecks of Cu. all day. Much St. sundown.
24	.. ..	..	..	..	..	96·0	101·4	78·4	..	51	Strong breeze with dust a.m. Very hot p.m.
25	.. ..	..	..	..	82·5	97·0	101·0	82·0	69	36	Nb. at 18h., but no rain came.
26	.. ..	..	..	..	80·3	100·6	103·5	80·3	71	..	Very sticky and hot last night.
27	.. ..	..	..	..	..	98·5	103·4	..	..	..	17h. wind changed SE. and white haze came up.
28	Dowano	..	..	*1780*	72·5	..	..	72·2	..	..	Visibility very bad all day.
28	Bechi	..	..	*1850*	..	96·2	..	..	..	..	——
29	Dan Zabua	..	..	1840	..	94·0	..	..	..	..	Sun hardly shining through haze and much dust.
30	.. ..	..	..	..	..	..	..	80·0	..	..	Less haze but visibility still bad.
30	Kusada	..	..	1820	..	93·5	..	..	..	..	——
May, 1922.											
1	Bindawa	..	..	*1800*	..	98·0	..	..	..	..	Sun shone strongly all day.
2	Bindawa	..	..	..	74·0	..	..	72·4	..	..	Clear day, hardly any haze.
2	Rimi	..	..	*1700*	..	98·0	..	..	..	..	——
3	Rimi	..	..	..	81·1	..	..	74·0	..	..	Westerly breeze from 9h.
3	Katsina	13 00	7 38	*1660*	..	98·0	..	..	..	..	——
4	.. ..	..	..	..	79·0	99·8	..	..	..	..	Clear day, some Cu. patches.
5	.. ..	..	..	..	..	96·4	..	..	..	..	White sky, though clear all day.
6	.. ..	..	..	..	76·9	95·0	99·5	..	..	15	White sky with much glare.
7	.. ..	..	..	..	81·0	93·4	98·0	80·9	15	27	Fresh E. breeze, white sky.
8	.. ..	..	..	..	..	..	..	68·6	..	..	Fresh E. wind after 9h.
8	Dan Kaba	13 13	7 45	*1470*	..	99·8	104·2	..	..	32	——
9	.. ..	..	..	..	79·0	91·2	98·4	78·8	65	47	White sky all day.
10	.. ..	..	..	..	75·2	*97·5*	102·5	76·0	70	32	Clear hot day.
11	.. ..	..	..	..	76·0	*84·2*	100·0	78·2	77	67	Showers 15h. 5m. to 19h. 30m.
12	.. ..	..	..	..	75·0	*93·0*	100·5	76·0	90	52	Very little breeze all day.
13	.. ..	..	..	..	75·3	97·9	103·2	75·6	76	18	Clear morning, very hazy afternoon.
14	.. ..	..	..	..	75·4	97·0	102·4	74·2	56	14	Visibility very poor all day.
15	.. ..	..	..	..	68·5	*100·0*	108·6	68·5	40	6	Puffs of hot wind from N. all afternoon.
16	.. ..	..	..	..	62·6	96·0	103·0	63·8	32	26	Much dust in the air.
17	.. ..	..	..	..	78·5	*97·0*	104·0	68·6	62	30	Very hot to-day.
18	.. ..	..	..	..	82·0	..	..	72·0	..	..	Looked very like rain ; rain fell to W.
18	Nr. Gangara	..	..	..	..	85·4	..	..	..	..	——
19	.. ..	..	..	..	74·4	..	..	73·0	..	..	Sky became 9/10 covered at 18h. 30m.
19	Nr. Yadawa	..	..	..	..	92·4	100·4	..	..	..	——
20	.. ..	..	..	..	80·0	..	..	..	..	..	Violent sandstorm from SW. preceded rain.
20	Tessawa	13 46	7 59	*1330*	..	*80·8*	99·8	..	..	67	——
21	.. ..	..	..	..	*77·5*	97·2	102·2	76·0	83	18	Violent tornado from E. 19h.
22	.. ..	..	..	..	*78·8*	..	106·0	76·0	74	..	Heavy Nb. 17h. but no rain.
23	.. ..	..	..	..	*81·0*	96·2	103·6	79·3	59	37	Little wind day, cool SE. wind evening.
24	.. ..	..	..	..	79·5	97·6	103·8	79·0	68	43	NW. breeze p.m. with flecks of Cu.
25	.. ..	..	..	..	*80·5*	92·0	97·2	80·5	60	44	Sky covered a.m., cleared p.m.
26	.. ..	..	..	..	76·4	..	..	74·8	..	..	Cloudy, clearing by noon, then rain 16h. 20m.
26	Matashi	..	..	..	..	98·0	..	..	..	..	——
27	.. ..	..	..	..	..	..	..	78·2	..	..	——
27	Urufan	14 05	8 06	*1380*	..	*98·0*	105·6	..	..	16	NW. breeze from 10h.
28	.. ..	..	..	..	77·0	98·0	107·5	75·4	61	28	All clouds apparently from E. and N.E.
29	.. ..	..	..	..	..	..	..	75·6	..	..	Wind SE. at noon, thin white cloud over sky.
29	Garari	..	..	*1450*	..	102·0	107·0	..	..	..	——
30	.. ..	..	..	..	73·2	98·1	108·0	71·0	..	..	Small Cu. from SE. all day.
31	.. ..	..	..	..	..	97·9	109·2	69·0	..	..	Some squalls from E. 15h.–16h.

* Heights printed in italics have been computed in the Meteorological Office from the pressure readings by aneroid in conjunction with any other available data.

† 1922 : Sling thermometer readings are given when available ; the readings in italics are from the sheltered thermometer (*see p. 7*).

Day.	Station.	Lat.	Long.	Height	Temperature.				Relative Humidity.		Remarks.
		N.	E.	*	† 6h.	† 18h.	Max.	Min.	6h.	18h.	
June, 1922.		° ′	° ′	ft.	°F.	°F.	°F.	°F.	%	%	
1	Garari	..	..	*1450*	..	..	..	77·6	..	..	Violent SE. wind with sand, 15h. 30m. to 16h. 10m. Wind then returned to SW.
1	Agaji	..	..	1500	..	99·7	105·2	..	..	..	——
2	Gangara	14 36	8 30	2057	..	91·7	100·4	..	..	35	Spots of rain 16h. 46m. and 17h. 15m.
3	.. ..	..	..	..	*81·2*	98·1	102·8	78·0	74	22	No gusts of wind to-day.
4	.. ..	..	..	..	*93·2*	*95·0*	101·0	80·6	17	22	Wind SW. till early p.m., then SE.–E.
5	.. ..	..	..	..	*84·0*	*99·0*	104·0	81·0	46	22	Small Cu. noon and p.m. St–Cu. sundown.
6	.. ..	..	..	..	82·2	*96·0*	106·0	81·0	38	2	SW. wind and clear sky all day.
7	.. ..	..	..	..	*85·2*	*100·2*	106·4	83·0	30	10	SW. wind, clear sky a.m. Much Cu. from E. p.m.
8	Gogowa	..	..	*1740*	..	101·0	104·0	..	..	..	Clear day till 16h., sandstorm 18h.
9	In Bush	..	..	..	76·0	..	..	74·5	..	..	SE. wind and white sky from 8h. onwards.
9	Tanut	14 58	8 52	*1720*	..	97·6	..	..	..	9	——
10	.. ..	..	..	..	77·9	*97·0*	103·0	76·2	31	3	SE. wind persisted, but haze less bad.
11	.. ..	..	..	..	79·8	94·9	98·0	78·6	52	2	One or two squalls from E. to NE.
12	.. ..	..	..	..	81·9	92·3	101·8	80·2	22	21	Rain fell a few miles off.
13	.. ..	..	..	..	77·0	..	..	74·8	56	..	Clear a.m., much Cu. and Cu–Nb. about 16h.
15	Garasu	14 27	9 33	1670	..	101·7	105·0	..	..	18	SE. wind and small Cu. from noon onwards.
17	Djom	14 35	9 56	*1650*	*82·0*	*101·6*	108·0	76·0	37	2	Clear day, SE. wind.
18	.. ..	..	..	..	*75·0*	..	..	73·0	36	..	E. wind all day, very hazy.
19	Bultum	14 37	10 12	1680	*82·0*	*99·8*	110·9	81·2	10	5	White haze and E. wind till 15h. when Nb. from NE.
20	In Bush	..	..	..	..	100·4	..	..	..	..	Strong gusts during day from E. and SE.
21	Tasr	14 55	10 45	1365	..	*98·2*	108·0	..	..	31	E. wind and white streaky sky all day.
22	Tasker	15 07	10 43	1434	..	96·0	106·0	..	..	4	Wind E. to NE. from noon.
23	In Desert	..	..	..	..	97·0	105·9	..	..	4	A little Ci. and Ci–St., otherwise clear all day.
24	.. ..	..	..	..	..	99·3	113·9	..	..	..	White haze: visibility never more than 1½ miles.
25	.. ..	..	..	..	..	..	113·0	..	..	..	No wind till 13h. then E. very hot.
26	Termet	16 04	11 09	2198	..	..	107·0	..	..	..	Strong E. wind all day, violent gusts 12h.–17h.
27	.. ..	..	..	..	..	94·0	..	..	..	..	Much haze afternoon.
28	.. ..	..	..	..	91·4	*91·8*	106·1	81·4	..	7	E. wind with haze noon till sunset.
29	.. ..	..	..	..	*74·6*	*99·0*	106·9	65·5	13	8	E. wind and some haze all day.
30	.. ..	..	..	..	*78·8*	..	107·7	72·7	22	..	SW. wind with Cu. till 15h. then ENE. with clear sky.
July, 1922.											
1	Termet	16 04	11 09	2198	*76·6*	*98·6*	107·0	69·9	27	16	W. wind with clear sky from noon. No clouds.
2	.. ..	..	..	..	*77·6*	..	..	67·5	41	..	No clouds, except small St. over sunset.
3	On March	..	..	..	75·2	..	..	..	..	..	SW. wind all day: no clouds.
4	Halt in Dunes ..	..	..	..	72·8	..	..	66·8	..	..	SW. breeze till 22h., when Nb. and Cu–Nb. from NE.
5	Tasker	15 07	10 43	1434	81·7	97·1	108·8	73·0	..	..	Wind varying SW. to NE., with much cloud from NE.
6	Bullum Baba.. ..	..	..	1388	78·2	..	..	..	..	..	W .wind all day with much cloud.
7	In Bush	..	..	..	79·5	..	..	78·2	..	..	Cloud all day from E.
7	On March	..	..	..	..	96·0	..	..	..	..	——
9	In Bush	..	..	..	..	..	..	64·0	..	..	——
9	Ighelaf	15 11	9 29	1420	..	86·4	..	..	..	..	West wind, but Cu. from E. all day.
10	.. ..	..	..	..	..	..	..	72·0	..	..	——
10	Guliski	15 02	9 12	1670	72·6	89·2	..	..	..	..	17h. heavy rainstorm from E. passed south.
11	Gamram	15 04	8 53	1590	..	85·0	..	..	..	..	Ci–St. till 13h., then Cu. and finally Nb.
12	.. ..	..	..	..	75·5	..	..	..	..	..	W. wind all day: Ci. and Ci–St. a.m., Cu. p.m.
12	Hannekar	15 09	8 44	*1475*	..	90·8	..	..	..	..	——
13	.. ..	..	..	..	80·8	83·4	94·0	78·0	..	..	Rain fell a.m. and p.m. Storms in progress all round.
14	.. ..	..	..	..	74·0	89·8	96·1	67·5	..	..	Many storms to S., coming from E.
18	Valley of Eghalgawen	..	..	..	..	91·8	..	..	..	..	Violent W. wind 8h. to 15h.
19	T'inwana	16 42	8 27	2218	..	..	104·0	..	..	..	River rose (rain from hills) 18h. 30m.
20	.. ..	..	..	..	..	..	98·0	83·0	..	..	Heavy rain clouds in evening.
21	.. ..	..	..	..	..	..	102·0	85·0	..	..	Heavy rainclouds to S. in evening.
22	.. ..	..	..	..	..	..	103·0	81·5	..	..	Less close but hot.
23	.. ..	..	..	..	..	..	106·0	80·0	..	..	W. wind all day.
24	.. ..	..	..	..	..	..	106·0	75·0	..	..	Rain 17h. 30m. to 18h. 15m.
25	Tebehic	16 48	8 21	*1645*	..	92·0	94·5	76·0	..	..	Rain 17h. 10m. to 19h.
26	.. ..	..	..	..	83·0	90·0	108·0	73·0	..	..	——
27	.. ..	..	..	..	..	76·0	102·0	80·0	..	..	——
28	.. ..	..	..	..	..	..	91·0	72·0	..	..	——
29	.. ..	..	..	..	..	82·0	96·0	73·0	..	..	——
30	Tintaborak	..	..	1560	..	..	..	76·0	..	..	Hurricane from NE. with sand, then rain 17h. 15m. [to 18h.
31	.. ..	..	..	..	..	..	..	..	..	..	——
31	Agades	16 59	7 59	2047	..	93·8	..	..	..	30	——

* Heights printed in italics have been computed in the Meteorological Office from the pressure readings by aneroid in conjunction with any other available data.
† 1922: Sling thermometer readings are given when available; the readings in italics are from the sheltered thermometer (*see p. 7*).

Day.	Station.	Lat. N.	Long. E.	Height *	Temperature. † 6h.	† 18h.	Max.	Min.	Relative Humidity. 6h.	18h.	Remarks.
		° ′	° ′	ft.	°F.	°F.	°F.	°F.	%	%	
August, 1922.											
1	Agades	16 59	7 59	2047	*82·0*	*95·0*	99·0	81·5	71	28	S. wind a.m. : hardly any wind p.m.
2	.. ..	..	..	..	*79·0*	*87·0*	97·0	77·0	65	39	SW. wind till evening, then NE. with raincloud.
3	.. ..	..	..	..	*82·0*	*87·9*	96·3	80·0	66	53	Sand and squalls 16h. 30m., then rain.
4	.. ..	..	..	..	*78·0*	*80·0*	89·0	74·0	84	78	Nb. over all W. sky at sunset. No rain.
5	.. ..	..	..	..	*77·5*	*79·7*	95·6	77·0	87	70	Heavy rain 15h. overcast till sunset.
6	.. ..	..	..	..	*75·0*	..	..	72·5	92	..	——
6	Nr. Azzal	..	..	..	..	87·9	..	..	..	..	21h. Cu-Nb. from E. : few drops rain 22h.
7	.. ..	..	..	..	74·0	..	..	74·0	..	..	9/10 Cu-Nb. from NE. all morning.
7	Solom Solom	17 18	8 4	1930	..	73·0	..	..	..	..	Cleared 12h., then Nb. and rain by 16h. 30m.
8	.. ..	..	..	..	69·0	..	..	68·0	..	..	Hot and damp ; no wind till 9h. then NW.
8	Assa	..	..	*2320*	..	77·0	..	..	..	..	Cu. from NE. at 12h., then Nb. Rain 13h. 35m.
9	.. ..	..	..	..	67·5	..	..	67·0	..	..	Ci-Cu. all morning, Nb. 12h.
9	Okuluf	..	..	..	..	81·7	..	..	..	..	Overcast with Nb. at sunset.
10	.. ..	..	..	..	67·5	..	..	67·0	..	..	Damp all morning. Heavy cloud overhead 13h. [Only light rain.
10	Auderas	17 38	8 25	2641	..	*75·0*	..	..	..	77	——
11	.. ..	..	..	..	*73·0*	*85·0*	92·0	71·5	82	50	Cloudy all day. Nb. and Cu. from E.
12	.. ..	..	..	..	*76·1*	*82·5*	88·0	74·3	81	60	22h. 30m. violent gale from NE., heavy rain.
13	.. ..	..	..	..	*76·5*	*75·0*	87·5	72·0	78	84	River in high flood.
14	.. ..	..	..	..	*71·0*	*74·0*	87·5	69·0	90	90	Little wind all day.
15	.. ..	..	..	..	*73·5*	*80·0*	..	72·0	88	69	Rain under uniform grey sky 12h. to 14h.
16	.. ..	..	..	..	*74·0*	*76·0*	82·0	71·5	83	83	Rain 13h. 50 m. and 16h.
17	.. ..	..	..	..	*74·0*	*83·8*	87·5	69·4	84	65	No rain to-day. 22h. violent gale from SE.
18	.. ..	..	..	..	*81·0*	*82·0*	88·0	72·0	48	51	SE. gale blowing all day.
19	.. ..	..	..	..	*77·0*	*79·3*	88·0	72·8	68	66	Heavy shower 18h. 35m. to 18h. 50 m.
20	.. ..	..	..	..	*74·0*	*74·0*	85·3	72·0	84	68	Very heavy rain 12h. 50m. to 14h. 15m.
21	.. ..	..	..	..	..	..	..	66·0	..	..	SW. breeze all day.
21	Towar	17 36	8 33	3327	..	84·0	..	..	..	..	——
22	.. ..	..	..	..	72·0	84·0	..	69·0	..	..	Nb. from NE. 12h. Drops of rain 13h. 50m.
23	.. ..	..	..	..	75·8	..	..	..	..	..	15h. haze appeared, lasting till sunset.
23	Auderas	17 38	8 25	2641	..	86·2	..	..	..	..	——
24	.. ..	..	..	..	*77·5*	*88·5*	92·5	73·0	52	23	Rather close.
25	.. ..	..	..	..	*75·0*	*90·0*	95·0	73·0	64	16	Very close and heavy.
26	.. ..	..	..	..	*78·3*	*83·0*	94·0	73·0	45	38	E. wind and haze a.m. Haze continued p.m.
27	.. ..	..	..	..	*79·0*	*76·8*	91·5	77·4	61	70	Rain about 15h.
28	.. ..	..	..	..	*75·6*	*87·4*	92·0	73·0	68	38	Some Nb. about 16h. but dissolved.
29	.. ..	..	..	..	*77·0*	*89·0*	95·5	75·0	63	23	Some haze a.m.
30	.. ..	..	..	..	*77·5*	*81·5*	96·0	77·0	59	54	Thunder-bolt fell to N.
31	.. ..	..	..	..	*75·4*	*76·6*	91·0	72·5	72	65	Rather close : very damp night.
Sept., 1922.											
1	Auderas	17 38	8 25	2641	*75·0*	*76·6*	91·0	73·0	66	65	Rain from E., hurricane wind 13h. 35m.
2	.. ..	..	..	..	*74·0*	*83·0*	86·5	71·8	74	54	Little wind all day.
3	.. ..	..	..	..	*78·0*	*76·5*	91·5	76·0	62	72	Light rain, covered sky all evening.
4	.. ..	..	..	..	*71·8*	*80·5*	86·8	71·0	84	56	W. wind till 15h., then Nb. from NE., and E. wind.
5	.. ..	..	..	..	*71·6*	..	..	71·0	90	..	SE. fresh wind all day.
5	Towar	17 36	8 33	3327	..	84·6	..	..	..	..	——
6	.. ..	..	..	..	72·6	80·0	..	71·5	..	..	Drops rain early and late p.m.
7	.. ..	..	..	..	74·5	..	..	67·5	..	..	NE. wind changed to NW. gale 8h.
7	Auderas	17 38	8 25	2641	..	76·2	..	..	..	..	14h. 20m. very strong E. wind, then calm till sunset.
8	.. ..	..	..	..	*73·0*	*87·0*	91·0	71·0	79	37	Very heavy rain to N. all afternoon.
9	.. ..	..	..	..	*75·8*	*71·2*	91·0	74·5	72	81	Heavy rain, river in high flood.
10	.. ..	..	..	..	*73·0*	..	88·5	69·5	91	..	W. wind all day.
11	.. ..	..	..	..	..	*87·0*	93·0	..	..	34	No clouds till noon, then Nb.
12	.. ..	..	..	..	*73·4*	*76·0*	89·0	71·5	88	58	No clouds till noon, then showers 14h. 30m. to 16h. 20 m.
13	.. ..	..	..	..	*76·0*	*86·2*	91·0	72·0	46	51	No wind all day, haze over all country.
14	.. ..	..	..	..	*86·4*	*89·0*	91·9	72·0	79	22	Clear day, with strong E. wind.
15	.. ..	..	..	..	*75·0*	*87·0*	93·0	73·9	64	65	Hot and close : some haze all round.
16	.. ..	..	..	..	*75·2*	*82·6*	95·8	74·3	60	52	Very close and heavy from 17h.
17	.. ..	..	..	..	*70·4*	*84·0*	94·7	68·8	91	59	Some Nb. early p.m., showers 15h. 40m.
18	.. ..	..	..	..	*72·4*	*89·0*	96·0	70·5	61	18	After 18h. steady E. wind. Very dry.
19	.. ..	..	..	..	*75·0*	*89·8*	94·5	70·5	56	13	Haze all day : fresh E. wind from 9h.
20	.. ..	..	..	..	*84·0*	*85·0*	94·0	77·9	15	23	Fresh E. wind all day (strong early a.m.).
21	.. ..	..	..	..	*82·7*	*87·8*	93·0	79·3	14	16	E. wind to 16h., then haze to 19h. 30m., when E. wind again.
22	.. ..	..	..	..	*75·7*	*88·0*	96·2	74·0	37	18	Hardly any haze.
23	.. ..	..	..	..	*82·0*	*89·0*	95·0	81·0	27	21	E. wind with intervals of W. wind all day.
24	.. ..	..	..	..	*78·0*	*90·0*	96·0	77·0	38	29	Very heavy and hot when no wind.
25	.. ..	..	..	..	*72·8*	*90·0*	97·2	71·0	48	57	Some cloud a.m., disappeared by noon.
26	.. ..	..	..	..	*77·7*	*88·6*	96·1	74·8	28	16	——
27	.. ..	..	..	..	*73·5*	*88·5*	94·4	68·0	37	20	Gentle E. wind, stronger in afternoon.
28	.. ..	..	..	..	*74·0*	*89·0*	94·5	73·0	43	22	Last two days sun remarkably clear.
29	.. ..	..	..	..	*83·0*	*90·0*	95·5	78·0	..	..	E. wind all day.
30	.. ..	..	..	..	*76·2*	*92·0*	100·0	75·7	34	23	Fine clear day.

* **Heights printed in italics have been computed in the Meteorological Office from the pressure readings by aneroid in conjunction with any other available data.**

† 1922 : Sling thermometer readings are given when available ; the readings in italics are from the sheltere thermometer (*see p.* 7).

Day.	Station.	Lat. N.	Long. E.	Height *	Temperature. † 6h.	Temperature. † 18h.	Temperature. Max.	Temperature. Min.	Relative Humidity. 6h.	Relative Humidity. 18h.	Remarks.
		° ′	° ′	ft.	°F.	°F.	°F.	°F.	%	%	
Oct., 1922.											
1	Auderas	17 38	8 25	2641	*82·0*	*91·0*	100·0	80·0	25	18	SE. to E. breeze all day.
2	..	..	..	..	*75·6*	*90·4*	100·0	72·0	32	20	——
3	..	..	..	..	*82·4*	*90·0*	95·0	72·5	20	..	——
4	..	..	..	..	62·3	..	..	60·0	..	..	SE. wind from 9h.
4	El Baghdadi	..	..	..	..	82·0	..	..	..	..	——
5	..	..	..	..	74·0	..	..	65·0	..	..	SE. wind from 7h. Very pleasant travelling.
5	Assada Vall.	17 49	8 18	*2805*	..	88·6	..	..	..	..	——
6	..	..	..	..	73·0	..	..	66·5	..	..	Fresh E. wind all day. No clouds. till 17h. when
6	Elazzas Vall.	..	..	..	..	86·2	..	..	..	..	—— [small patches in W.
7	..	..	..	..	*82·0*	*88·0*	95·4	68·5	3	9	Fresh E. wind all day.
8	..	..	..	..	77·5	..	..	71·8	..	..	Fresh E. wind all day.
8	Abarakan	18 03	8 42	*2950*	..	86·2	..	..	..	..	No clouds at all.
9	..	..	..	..	77·0	..	..	68·5	..	..	Clear day ; no clouds.
9	Timia	18 07	?	3470	..	*86·0*	..	..	..	4	——
10	..	..	..	..	*73·0*	*86·0*	90·5	69·6	22	7	Clear day ; no clouds.
11	..	..	..	..	*74·5*	..	91·4	70·0	9	..	No clouds.
12	..	..	..	..	68·5	..	..	67·5	..	..	A little Cu. noon to sunset, increasing to N. from
12	Abarakan	18 03	8 42	*2950*	..	88·2	..	..	..	..	—— [16h.
13	..	..	..	..	75·0	..	..	60·5	..	..	Wind E. to ESE. all day.
13	Teginjir	17 59	..	3520	..	83·2	..	..	..	..	A little thin St. or Ci–St. at times.
14	..	..	..	..	57·0	..	..	51·5	..	..	Very little wind all day.
14	Tamanet	..	..	3220	..	85·0	..	..	..	..	——
15	..	..	..	..	52·5	..	..	51·5	..	..	Rather hot travelling.
15	Tellia	17 47	8 53	*3130*	..	86·2	..	..	..	..	A little small Cu. p.m. Clear sunset.
16	..	..	..	..	*69·0*	*85·0*	99·0	58·0	24	4	Hot. No clouds all day.
17	..	..	..	..	59·0	..	..	59·0	..	..	S.E. wind all day from 9h. A little Ci. after 15h.
17	Teloas Valley ..	..	..	3130	..	86·2	..	..	..	..	—— [till sunset.
18	..	..	..	..	59·0	..	..	59·0	..	..	Light SE. wind from 9h. ; no cloud.
18	Tabello	17 35	8 55	2690	..	86·0	..	..	..	..	——
19	..	..	..	..	*61·0*	*87·0*	95·0	59·3	45	5	SE. wind ; no cloud.
20	..	..	..	..	*61·7*	*61·2*	92·0	60·0	26	27	Light SE. wind from 10h. ; no cloud.
21	..	..	..	..	*61·2*	*85·0*	93·0	57·2	29	..	SE. wind from 9h.
22	..	..	..	..	*61·0*	*84·0*	92·0	58·3	32	8	Very little wind all day.
23	..	..	..	..	*65·0*	*83·0*	90·0	59·6	22	9	Slight haze.
24	..	..	..	..	*59·0*	..	91·2	58·5	51	..	Clear sky ; hot day.
25	..	..	..	..	*59·2*	..	..	58·8	25	..	Clear a.m. ; some St. to S. and W. p.m.
25	Nr. Adkakit	..	..	..	..	85·6	..	..	..	..	——
26	Nr. Adkakit	..	..	..	61·8	..	..	61·7	..	..	Light E. to SE. winds.
26	Towar	17 36	8 33	3327	..	85·4	..	..	..	..	——
27	..	..	..	..	73·7	87·2	..	70·4	..	..	SE. wind all day ; some Ci. a.m.
28	..	..	..	..	80·3	..	..	79·4	..	..	SE. wind ; Ci. afternoon and sunset ; some haze all
28	Auderas	17 38	8 25	2641	..	87·4	..	..	..	..	—— [day.
29	..	..	..	..	*77·0*	*87·0*	..	72·2	12	2	Dust-devil (clockwise) over camp 15h.
30	..	..	..	..	*71·2*	*87·0*	92·0	69·0	34	10	Clear day ; no haze ; no clouds.
31	..	..	..	..	*66·2*	*81·2*	93·0	65·0	33	23	No clouds ; cool and clear.
Nov., 1922.											
1	Auderas	17 38	8 25	2641	*76·7*	*85·5*	93·0	69·0	16	17	SE. breeze steady all day.
2	..	..	..	..	*75·0*	*87·0*	95·7	69·0	22	10	SE. wind, no clouds.
3	..	..	..	..	58·0	..	..	58·0	..	..	No clouds ; visibility good.
3	Ighaghar	..	..	3075	..	86·2	..	..	..	..	——
4	..	..	..	..	56·4	..	..	..	..	..	Much Ci. all day.
4	Assada	17 49	8 18	2805	..	82·5	..	..	..	..	——
5	..	..	..	..	43·0	..	..	43·0	..	..	No wind till 13h. then fresh SW. till sundown ; no
5	Aggata	18 09	8 33	*2525*	..	86·2	..	..	..	..	—— [clouds.
6	..	..	..	..	45·0	..	..	43·4	..	..	Light SW. breeze 12h. till sunset ; fresh E. wind
6	Assode	18 27	8 29	*2395*	..	78·0	..	..	..	..	—— [sprang up 19h.
7	..	..	..	..	71·5	*87·0*	..	62·3	..	18	E. wind all day ; less cold.
8	..	..	..	..	*69·4*	..	..	68·0	24	..	SE. to E. wind from 6h.
8	Anusamad	..	..	2630	..	88·8	..	..	..	..	——
9	..	..	..	..	58·0	..	..	52·5	..	..	Moderate E. wind all day ; no clouds, but visibility
9	Assarara	18 36	8 35	2615	..	85·0	..	..	..	..	—— [not good.
10	..	..	..	..	62·0	..	..	62·0	..	..	E. wind from 11h. became NW. at 16h. Some haze
10	Assode	18 27	8 29	*2395*	..	*72·0*	..	..	..	24	—— [all day.
11	..	..	..	..	*63·0*	..	..	62·3	25	..	No cloud except at sunset, when much Ci.
11	Afis	18 37	8 38	2540	..	80·5	..	..	..	..	E. gale from 19h. all night.
12	..	..	..	..	69·2	..	..	68·0	..	..	No clouds except a little St. at sunset.
12	Fodet	18 47	8 37	*2690*	..	83·6	..	..	..	..	——
13	..	..	..	..	73·0	..	..	..	..	..	From noon on more and more Ci. covering sky.
13	Tanutmolet	..	..	2310	..	80·4	..	..	..	..	——
14	..	..	..	..	60·8	..	..	58·0	..	..	More and more Ci. from 14h. onward.
14	Iferuan	19 05	8 25	*2190*	..	82·0	..	..	..	..	——
15	..	..	..	..	*58·3*	*84·5*	93·0	56·5	33	14	Very little breeze ; Ci. from noon onwards.
16	..	..	..	..	*57·0*	*84·0*	90·0	55·8	40	19	Weather as yesterday.
17	..	..	..	..	*59·0*	*86·8*	93·0	55·5	36	14	Clear day.

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† 1922 : Sling thermometer readings are given when available ; the readings in italics are from the sheltered thermometer (*see p.* 7).

Day.	Station.	Lat. N.	Long. E.	Height *	Temperature. † 6h.	Temperature. † 18h.	Temperature. Max.	Temperature. Min.	Relative Humidity. 6h.	Relative Humidity. 18h.	Remarks.
		° ′	° ′	ft.	°F.	°F.	°F.	°F.	%	%	
Nov., 1922.											
18	..	..	..	..	*58·3*	*86·0*	96·0	57·8	40	16	Much Ci. from dawn onward.
19	..	..	..	..	*59·6*	*83·0*	..	56·8	41	25	SW. breeze afternoon.
20	..	..	..	..	*60·0*	*85·4*	..	57·0	36	26	Some squalls and dust-devils p.m.
21	..	..	..	..	*63·4*	*87·0*	96·0	60·0	45	35	SW. wind, very light a.m., moderate p.m.
22	..	..	..	..	*69·0*	*86·6*	95·0	66·8	34	31	Much Ci. and St. to N. and NW.
23	..	..	..	..	*70·2*	*86·5*	94·0	65·6	39	32	NW. wind ; hot all day.
24	..	..	..	..	*66·6*	*83·0*	91·6	63·6	52	46	Ci. all over sky p.m.
25	..	..	..	..	*65·0*	80·0	..	62·0	62	..	Some Ci. all day.
26	..	..	..	..	49·0	..	..	48·0	..	..	Some Ci. all day ; W. breeze all day from about 8h.
26	Areitun	..	..	1960	..	79·0	..	..	..	..	——
27	..	..	..	..	43·0	..	..	43·0	..	..	Scarcely any cloud, but thin St. to W. at Sunset.
27	Agellal ..	18 43	8 10	2011	..	80·0	..	..	..	..	——
28	..	..	..	..	42·0	..	..	41·0	..	..	Light SW. breeze all day ; no clouds.
28	Anuwisheran ..	..	..	1990	..	82·0	..	..	..	..	——
29	..	..	..	..	63·0	..	..	..	..	..	SE. breeze ; clear sky.
29	Garet ..	..	..	1960	..	78·0	..	..	..	..	Calm from 15h. onwards.
30	..	..	..	..	59·0	..	..	58·8	..	..	Easterly breeze till sunset. No cloud except a little [Ci. at sunset.
30	Anu Maqaran ..	..	..	2050	..	76·2	..	..	..	..	——
Dec., 1922.											
1	Anu Maqaran ..	..	..	2050	43·0	..	..	42·0	..	..	No clouds ; hot marching at times.
1	Tamenzaret ..	..	..	2560	..	76·3	..	..	..	..	——
3	Auderas	17 38	8 25	2641	..	75·8	..	..	..	..	SE. wind, very light all day.
4	..	..	..	..	49·0	80·0	..	46·4	..	..	No cloud.
5	..	..	..	..	49·0	78·6	..	47·3	..	..	——
6	..	..	..	..	60·3	..	..	60·0	..	..	Moderate W. wind all day, clear sky sunset.
6	Arawat	..	..	2600	..	68·6	..	..	..	..	——
7	..	..	..	..	38·8	..	..	37·0	..	..	Heavy low haze till 14h. ; then cleared with Westerly [wind.
7	In Watsa	..	..	2405	..	75·0	..	..	..	..	——
8	..	..	..	..	45·5	..	..	45·4	..	..	Ci. all day ; W. wind from 9h. veering N.W. p.m.
8	In Delawin	..	..	2110	..	77·7	..	..	..	..	——
9	..	..	..	..	..	..	..	53·0	..	..	——
9	Akaraq	..	..	1760	..	79·2	..	..	..	..	Ci. lasted all night and all to-day.
10	..	..	..	..	53·7	..	..	52·5	..	..	Thin Ci. over all sky all day, cleared at sunset.
10	Eghalgawen ..	16 48	8 32	*1720*	..	79·3	..	..	..	..	——
11	..	..	..	..	..	..	..	61·5	..	..	——
11	Milen ..	16 29	8 29	1630	..	79·6	..	..	..	..	Some Ci. all day.
12	..	..	..	..	..	..	..	54·3	..	..	NE. wind with much sand and dust all day from 8h.
12	Anu Banka	..	..	1600	..	71·5	..	..	..	..	——
13	..	..	..	..	53·0	..	..	52·0	..	..	Strong NE. wind all day ; much dust in air.
13	Nr. Keta	..	..	1585	..	64·0	..	..	..	..	——
14	..	..	..	..	49·0	..	..	48·0	..	..	NE. wind less strong ; less dust.
15	Tiworshekaken	..	..	1640	40·4	..	..	31·0	..	..	NE. wind less strong, a little Ci. all day.
15	Kidigi ..	..	..	1440	..	65·6	..	..	..	..	——
16	..	..	..	..	39·0	..	..	37·0	..	..	NE. wind. Less cold ; more normal weather.
16	Hannekar	..	..	1475	..	71·0	..	..	..	..	——
18	Mazzia ..	..	..	1515	..	72·2	..	..	..	..	Clear till 11h. ; then haze from NE. and N.
19	..	..	..	..	53·8	..	..	49·0	..	..	NE. breeze ; moderate to light ; scarcely any haze.
19	Kallilua	..	..	1410	..	71·3	..	..	..	..	——
20	..	..	..	..	44·0	..	..	37·0	..	..	NE. breeze ; light all day ; a little haze.
20	Zurawa	..	..	1340	..	71·0	..	..	..	..	——
21	..	..	..	..	49·1	..	..	47·3	..	..	Light NE. breeze all day.
21	Takaka	..	..	1410	..	70·4	..	..	..	..	——
22	..	..	..	..	38·0	..	..	37·5	..	..	Light NE. wind, no cloud.
22	Dambida	..	..	1420	..	70·8	..	..	..	..	——
23	..	..	..	..	54·0	..	..	52·5	..	..	Light NE. breeze in fitful intervals. No cloud.
23	Beinaka	..	..	1440	..	70·4	..	..	..	..	——
24	..	..	..	..	42·0	69·6	..	41·0	..	..	E. breeze till 16h. No cloud.
25	..	..	..	..	54·0	..	..	46·0	..	..	NE. wind with much haze.
25	Kukasamu	..	..	1450	..	72·2	..	..	..	..	No cloud.
26	..	..	..	..	45·6	..	..	45·0	..	..	Light NE. breeze. Thin high St about all day.
26	Zongo ..	..	..	1610	..	77·0	..	..	..	..	——
27	..	..	..	..	50·6	..	..	47·0	..	..	Light NE. wind ; a good deal of Ci.
27	Dankwashi	..	..	1440	..	75·6	..	..	..	..	——
28	..	..	..	..	40·8	..	..	40·0	..	..	Scarcely any wind. Much St. 4h.–12h. Much Ci. [all p.m.
28	Damberta	..	..	1525	..	75·0	..	..	..	..	——
29	..	..	..	..	54·0	..	..	40·0	..	..	E. winds ; some Ci. all day.
29	Nr. Kano	..	..	1555	..	66·5	..	..	..	..	——
30	..	..	..	..	42·0	..	..	40·0	..	..	E. wind ; some haze.
31	Kano ..	..	..	2000	..	..	..	..	..	..	——

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Day.	Station.	Lat. N.	Long. E.	Ht. *	Temperature. 6h.	Temperature. 18h.	Temperature. Max.	Temperature. Min.	Relative Humidity. 6h.	Relative Humidity. 18h.	Cloud Amount. 6h.	Cloud Amount. 18h.	Wind. 6h. Dir.	Wind. 6h. Force	Wind. 18h. Dir.	Wind. 18h. Force	Remarks.
		° ′	° ′	ft.	°F.	°F.	°F.	°F.	%	%							
May, 1927.																	
22	Katsina	13 00	7 38	1660	..	86·5	..	..	..	41	..	..	..		Calm		Drops of rain 20h.
23	.. .. ..	..	..	..	72·5	80·5	86·9	71·6	95	69	10	..	Calm		Calm		Small tornado at 22h. 30m.
24	.. .. ..	..	..	..	71·4	83·5	89·3	73·6	83	57	10	5	SSW	1	..		18h. St. from SW., Ci. from NE.
25	.. .. ..	..	..	..	78·5	91·7	99·0	76·1	72	30	10	0	NE	2	Calm		10 St. at 7h., clearing by 9h.
26	.. .. ..	..	..	..	77·5	..	..	..	76	..	0	..	SW	2	Calm		Wind calm after 17h. 10m.
27	.. .. ..	..	..	..	85·3	83·5	99·0	82·3	41	62	0	10	SSE	2	Calm		Nly. squall 15h. 27m.
28	.. .. ..	..	..	..	74·5	89·5	91·0	73·6	79	42	8	0	Calm		Calm		Much Ci–Cu. a.m., clear p.m.
29	.. .. ..	..	..	..	81·5	..	99·0	79·1	73	..	0	..	SW	1	..		Heavy rain seen in distance.
30	.. .. ..	..	..	..	80·5	..	..	81·3	73	..	9	..	E	2	..		9/10 cloud till 10h., clearing later.
30	Dankaba	13 13	7 45	*1470*	..	92·2	..	..	..	43	..	..	..		SE	1	——
31	.. .. ..	..	..	..	..	..	..	75·1	..	..	4	..	W	1	..		——
June, 1927.																	
1	Dan Kama ..	13 15	7 48	*1450*	75·5	86·5	96·6	69·9	78	52	7	8	Calm		Calm		Scarcely any wind all day.
2	.. .. ..	..	..	..	79·2	80·5	98·5	71·1	78	54	0	..	Calm		SW	1	Dust storm about 18h.
3	Gazawa	13 32	7 57	*1360*	..	88·7	96·6	70·7	..	48	..	0	..		Calm		No heat flicker.
4	.. .. ..	..	..	..	76·0	..	..	74·7	83	..	0	..	SE	1	..		Clear a.m., 10 Nb. by 15h. 40m.; then [rain.
4	Tessawa	13 46	7 59	1330	..	79·7	..	..	..	66	..	10	..		SW	3	——
5	.. .. ..	..	..	..	..	..	..	..	..	..	5	..	..		..		Visibility very good all round, after [rain.
5	5 miles NNE. Tessawa	..	..	*1260*	..	72·5	..	..	..	78	..	..	..		..		——
6	.. .. ..	..	..	..	71·3	..	..	67·6	93	..	1	..	S	1	..		St. 9 at 10h., clear by noon.
6	Urufan	14 05	8 06	*1380*	..	89·5	..	..	..	37	..	0	..		SW	1	——
7	.. .. ..	..	..	..	80·7	96·5	..	72·3	71	30	0	..	..		..		Hot day, heat lasted late.
8	.. .. ..	..	..	..	82·0	..	..	79·1	67	..	0	..	Calm		..		Several storms p.m., clear sky by 24h.
8	Giddan Yaro ..	..	..	*1450*	..	..	104·0	..	..	..	..	..	..		..		——
9	.. .. ..	..	..	..	75·5	..	98·2	73·1	80	..	0	8	..		Calm		Several storms after 16h.
10	Nr. Yagaji	..	..	*1450*	74·0	..	..	70·1	..	..	..	..	..		..		Very hot day with scarcely any breeze.
10	.. .. ..	..	..	..	..	89·5	99·2	..	..	50	..	..	..		Calm		——
11	Yagaji	..	..	..	78·7	..	..	79·3	67	..	..	..	W	1	..		Fresh dry breeze all day; hot evening.
11	Kurdidifi	14 31	8 28	*1470*	..	94·7	102·5	..	..	40	..	..	..		..		——
12	.. .. ..	..	..	..	80·1	..	..	76·1	69	..	6	..	SW	1	..		Became overcast (thin cloud) about 16h.; cleared later.
12	Gangara	14 36	8 30	2057	..	91·5	98·0	..	..	33	..	1	..		SW	1	——
13	.. .. ..	..	..	..	80·5	89·0	93·5	80·6	65	31	10	3	SSW	3	Calm		Duststorm 6h. 30m.; no rain.
14	.. .. ..	..	..	..	81·5	92·9	100·4	80·3	61	33	10	8	Calm		Calm		No wind; much heat flicker.
15	.. .. ..	..	..	..	83·5	90·3	102·5	83·1	52	36	10	10	Calm		SW	1	Dust storm 16h. 40m.; no rain.
16	.. .. ..	..	..	..	81·9	91·5	102·7	80·1	54	39	1	0	W	1	SW	1	Drops of rain 13h. 30m.
17	.. .. ..	..	..	..	81·0	94·5	102·0	80·6	53	21	1	3	WSW	2	Calm		18h. driest air yet recorded.
18	.. .. ..	..	..	..	77·5	77·3	101·9	76·9	60	77	9	10	W	1	W	1	Rain p.m.
19	.. .. ..	..	..	..	74·5	86·7	96·4	72·6	83	49	0	..	SW	1	..		Excellent visibility a.m.
20	.. .. ..	..	..	..	75·0	..	..	72·5	69	..	0	..	W	1	..		Little cloud all day.
20	Nr. Tagelal ..	..	..	*1500*	..	92·0	..	..	..	32	..	2	..		SSW	2	——
21	.. .. ..	..	..	..	77·7	..	..	73·6	63	..	..	..	W	1	..		Very hot p.m.
21	Nr. Eliki	..	..	..	..	92·5	105·5	..	..	21	..	..	..		Calm		——
22	.. .. ..	..	..	..	73·5	..	..	73·6	65	..	0	..	Calm		..		——
22	Tinawgarakan ..	15 18	8 16	*1500*	..	98·3	105·5	..	..	16	..	0	..		Calm		Repeated dry and wet bulb readings.
23	.. .. ..	..	..	..	81·5	80·5	..	70·1	52	..	0	..	Calm		..		Sand and rainstorm p.m.
24	.. .. ..	..	..	..	74·6	93·5	102·0	..	..	37	10	1	..		..		Rain to W. after 16h.; much lightning.
25	.. .. ..	..	..	..	77·7	..	..	72·1	70	..	9	..	SW	2	..		Overcast 6h. 30m. till 10h. then clearing.
25	Bush Camp, Tinawgarakan Valley.	..	..	*1520*	..	94·0	..	..	..	16	..	0	..		Calm		——
26	.. .. ..	..	..	..	83·5	98·0	103·0	..	45	18	1	0	SW	2	NW	1	Grey bank of haze and dust at sunset.
27	.. .. ..	..	..	..	79·0	..	..	76·1	53	..	10	..	SW	1	..		Hazy all day.
28	.. .. ..	..	..	..	77·5	..	..	75·6	75	..	0	..	..		..		——
28	Yofaghazwa Valley	..	..	..	..	94·5	108·5	..	..	14	..	0	..		Calm		Max. thermometer set up at 13h. 30m.
29	.. .. ..	..	..	..	80·5	..	..	79·6	48	..	2	..	SW	1	..		Hazy sky during day.
29	Desert Camp ..	..	..	..	..	93·0	..	..	..	37	..	1	..		SW	3	——
30	Desert Camp ..	..	..	..	77·5	..	..	77·6	59	..	1	..	Calm		..		Visibility fair; much dust.
30	Tagedufat	16 06	8·24	1634	..	95·0	105·5	..	..	23	..	0	..		SW	1	——

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Day.	Station.	Lat. N.	Long. E.	Ht. *	Temperature. 6h.	Temperature. 18h.	Temperature. Max.	Temperature. Min.	Relative Humidity. 6h.	Relative Humidity. 18h.	Cloud Amount 6h.	Cloud Amount 18h.	Wind. 6h. Dir. Force.	Wind. 18h. Dir. Force.	Remarks.
		° ′	° ′	ft.	°F.	°F.	°F.	°F.	%	%					
July, 1927.															
1	Tagedufat	16 06	8 24	1634	80·0	..	110·6	..	47	..	4	..	..	..	Dust and rain storms afternoon.
3	Milen	16 29	8 29	1630	..	..	..	..	..	..	0	..	Calm	..	Visibility very poor p.m.
3	T'inwana	16 42	8 27	2218	..	89·5	..	..	..	37	..	..	..	SW 3	—
4	.. .. ..	..	..	..	81·5	96·8	101·6	75·1	47	17	0	0	W 1	W 1	Much dust from 16h. onward.
5	.. .. ..	..	..	..	86·5	97·0	103·4	87·7	40	24	0	0	W 1	WNW 1	Heavy Cu. round horizon 14h. 30m. to 17h.
6	.. .. ..	..	..	..	83·5	92·0	..	84·1	53	33	1	1	WNW 3	W 2	Wind velocity measured 800 ft./min. 13h.
7	.. .. ..	..	..	..	82·5	81·5	103·0	83·1	52	58	0	5	W 1	..	Squalls ceased just before 17h.
8	.. .. ..	..	..	..	77·5	93·5	100·0	76·6	63	25	0	6	Calm	NW 2	Visibility poor all day.
9	.. .. ..	..	..	..	82·5	94·0	101·5	82·4	..	34	0	9	W 1	W 1	Storm p.m. preceded by cloud of sand.
10	.. .. ..	..	..	..	83·5	90·9	102·0	82·6	45	33	0	0	W 1	SW 1	Last night still and hot.
11	.. .. ..	..	..	..	82·5	93·5	94·5	83·9	52	32	5	0	SW 1	Calm	Dull sunset behind grey St.
12	.. .. ..	..	..	..	82·5	..	..	80·3	48	..	2	..	NW 1	..	16h. 15m. sandstorm from NE.
12	Nr. Agades.. ..	..	..	..	..	93·5	..	..	..	28	..	9	..	SW 2	—
20	Azzal	..	..	..	..	98·0	..	..	..	37	..	0	..	WNW 2	Pale yellow sunset.
21	.. .. ..	..	..	..	80·7	..	..	82·1	15	..	8	..	W 1	..	Very hot gusts of wind from E. 12h. [to 13h.
21	Dabaga	..	..	*2110*	..	97·5	..	..	..	11	..	3	..	ENE 1	—
22	.. .. ..	..	..	..	80·5	..	..	69·0	66	..	..	..	Calm	..	Shower 12h. 15m. to 12h. 30m.
22	Aghejabjab.. ..	..	..	*2250*	..	88·5	..	..	..	37	..	3	..	Calm	—
23	.. .. ..	..	..	..	78·8	..	..	73·7	55	..	8	..	SW 1	..	Showers 16h. to 18h. 45m.
23	Tilisdak	..	..	*2380*	..	83·5	..	..	..	..	..	..	..	..	—
24	.. .. ..	..	..	..	78·0	..	..	..	67	..	0	..	..	..	16h. storm over Todra, passed south.
24	Auderas	17 38	8 25	2641	..	87·3	..	..	..	33	..	..	..	..	—
25	.. .. ..	..	..	..	82·2	90·0	107·3	75·1	45	31	7	2	Calm	Calm	Sun heavily veiled at noon.
26	.. .. ..	..	..	..	79·0	94·5	109·0	76·3	51	23	0	8	W 1	Calm	Dust devil from west p.m.
27	.. .. ..	..	..	..	79·5	94·0	104·8	79·5	57	17	0	4	NW 1	Calm	Nb. from north-east passed south 16h.–17h.
28	.. .. ..	..	..	..	79·9	87·5	101·2	80·0	55	33	0	1	SW 1	SSW 3	Few drops rain 13h. 30m.
29	.. .. ..	..	..	..	77·5	82·5	96·0	74·3	59	38	10	4	Calm	W 3	Storm 12h.; wind measured 25.8 [m.p.h.
30	.. .. ..	..	..	..	71·5	88·5	97·2	69·7	71	16	0	9	Calm	N 1	18h. heavy dark cloud, no rain visible.
31	.. .. ..	..	..	..	75·5	89·3	..	75·1	67	31	8	..	W 3	WNW ..	Very clear at 6h.
Aug., 1927.															
1	Auderas	17 38	8 25	2641	77·5	87·5	102·0	75·3	63	..	1	9	NNW 1	E 5	Thunderstorm and rainbow 16h.
2	.. .. ..	..	..	..	79·7	84·5	95·5	..	60	47	0	..	W 1	SW 1	Storm; showers 11h. 50m. to 13h. 30m.
3	.. .. ..	..	..	..	76·5	72·5	93·2	74·1	60	78	9	10	Calm	W 1	Showers p.m.
4	.. .. ..	..	..	..	70·5	78·0	99·0	..	93	65	6	8	SW 1	SW 1	Rain storms all day in various parts.
5	.. .. ..	..	..	..	75·5	77·0	93·5	78·7	78	77	1	7	W 1	Calm	Storm; rain 13h. 35m. to 14h 45m.
6	.. .. ..	..	..	..	70·0	73·5	87·4	68·1	85	80	2	10	Calm	Calm	Storm from E. 16h. 30m.
7	.. .. ..	..	..	..	76·5	76·1	86·9	71·9	69	75	..	..	..	..	Sharp showers 11h. 50m. to 17h. 30m.
8	.. .. ..	..	..	..	71·3	85·2	93·0	79·6	85	44	0	..	Calm	..	Detached Cu. from E. all day.
9	.. .. ..	..	..	..	76·2	76·3	93·0	73·5	74	..	0	10	NE 1	SE 1	Light showers from NE. p.m.
10	.. .. ..	..	..	..	75·1	75·3	98·5	73·3	75	73	3	10	Calm	..	17h. mist came down over south flank of Todra.
11	.. .. ..	..	..	..	73·2	91·5	99·5	72·1	57	29	8	8	E 3	NE 2	Very little breeze all day.
12	.. .. ..	..	..	..	73·5	89·5	98·5	69·9	70	27	0	1	Calm	ESE 2	Considerable dew 6h.
13	.. .. ..	..	..	..	74·5	79·5	95·5	72·7	72	57	0	4	Calm	W 1	Storm from E. p.m.
14	.. .. ..	..	..	..	72·2	78·0	93·5	71·6	..	..	2	4	E 1	NE 3	Rainstorm p.m.
15	.. .. ..	..	..	..	75·0	80·0	100·0	70·1	65	..	2	8	Calm	..	Storm 16h. 30m.
16	.. .. ..	..	..	..	73·0	84·1	95·5	71·1	67	33	7	..	Calm	NW 1	Grey sunset behind Cu. and St.
17	.. .. ..	..	..	..	73·5	79·3	96·5	70·1	70	63	4	9	Calm	Calm	River began running 20h. 30m.
18	.. .. ..	..	..	..	73·5	76·1	94·0	70·6	78	66	9	9	NE 1	Calm	Storms from E. and NE. p.m.
19	.. .. ..	..	..	..	74·5	82·0	96·5	68·0	66	43	0	..	Calm	..	p.m. biggest storm yet seen.
20	.. .. ..	..	..	..	80·0	91·5	94·5	74·1	43	9	0	..	W 1	..	Very hazy all day.
21	.. .. ..	..	..	..	77·5	84·5	100·0	74·1	58	31	..	..	NW 2	SW 2	Hot day till wind changed at 16h.
22	.. .. ..	..	..	..	77·5	77·5	94·6	71·1	63	67	0	..	N 1	NW 1	Both rivers running by 16h.
23	.. .. ..	..	..	..	72·5	..	96·0	66·0	65	..	3	..	NW 1	NW 1	Rain storm p.m.
24	.. .. ..	..	..	..	76·0	81·5	97·0	69·6	65	45	0	..	NW 1	N 1	Rain p.m.
25	.. .. ..	..	..	..	75·8	74·5	92·0	..	66	..	1	..	Calm	..	Rain late afternoon and evening.
26	.. .. ..	..	..	..	71·5	76·5	94·0	69·0	74	63	..	9	Calm	N 1	Showers p.m.
27	.. .. ..	..	..	..	71·5	77·5	95·0	67·0	81	68	0	..	Calm	Calm	Showers 12h. 50m. to 16h.
28	.. .. ..	..	..	..	71·0	75·9	92·0	67·5	84	69	1	0	Calm	N 1	Heaviest dew yet seen.
29	.. .. ..	..	..	..	69·1	84·5	95·0	68·5	89	36	2	0	Calm	SE 2	Very hazy p.m.
30	.. .. ..	..	..	..	75·5	91·3	99·0	71·6	66	17	0	1	E 1	E 2	Hazy p.m.
31	.. .. ..	..	..	..	75·5	91·8	..	72·8	62	12	1	..	Calm	Calm	Very clear evening.

* Heights printed in italics have been computed in the Meteorological Office from the pressure readings by aneroid in conjunction with any other available data.

Day.	Station.	Lat. N.	Long. E.	Ht. *	Temperature. 6h.	18h.	Max.	Min.	Relative Humidity. 6h.	18h.	Cloud Amount. 6h.	18h.	Wind. 6h. Dir. Force	18h. Dir. Force	Remarks.
		° ′	° ′	ft.	°F.	°F.	°F.	°F.	%	%					
Sept., 1927.															
1	Auderas	17 38	8 25	2641	80·5	90·2	104·0	77·1	18	13	4	..	Calm	E 3	Scarcely any cloud all day.
2	..	..	..	..	77·5	79·0	98·5	73·6	56	59	1	3	E 2	Calm	Showers p.m.
3	..	..	..	..	74·5	82·5	94·0	68·0	71	41	10	10	Calm	Calm	Showers 15h. 30m. to 17h.
4	..	..	..	..	71·0	94·5	102·5	65·5	81	18	10	10	Calm	E 2	Clear sky till noon.
5	..	..	..	..	77·0	..	..	71·1	43	..	..	..	Calm	..	Thick haze all day, visibility often lower
5	Tegbisheri	..	..	*2860*	..	91·5	..	..	..	17	..	..	..	E 2	—— [than 1 mile.
6	..	..	..	..	72·5	..	..	69·0	43	..	..	..	Calm	..	Haze dawn to sunset, less thick than
6	Towar	17 36	8 33	3327	..	92·2	..	..	..	15	..	..	..	..	—— [yesterday.
7	..	..	..	..	83·0	90·0	95·0	64·5	19	36	..	..	SE 3	NE 2	Haze cleared by 9h.
8	..	..	..	..	83·0	88·0	94·5	63·5	18	19	0	..	NE 2	SE 1	Very hazy in afternoon.
9	..	..	..	..	82·2	83·0	94·0	61·0	29	..	8	10	Calm	Calm	Showers 17h. 30m. to 18h. 45m.
10	..	..	..	..	73·1	..	..	65·0	67	..	4	..	N 1	..	Shower p.m. then cleared, no cloud by
10	Adkakit	..	..	2740	..	86·0	98·0	..	..	36	..	5	..	Calm	—— [19h.
11	..	..	..	..	68·5	..	..	57·0	45	..	0	..	Calm	..	——
11	Teloas	..	..	..	..	88·5	..	..	..	9	..	..	..	Calm	Extraordinarily clear evening.
12	..	..	..	..	72·5	..	..	59·3	63	..	2	..	Calm	..	Very clear early; Some Nb. 16h. to
12	Emilial	..	..	3667	..	88·0	98·0	..	..	7	..	0	..	E 1	—— [17h. 30m.
13	..	..	..	..	72·0	..	..	55·0	27	..	0	..	Calm	..	Hot day, very little air moving, but
13	Wellek	..	..	*3090*	..	89·0	..	..	..	16	..	0	..	SE 2	—— [clear.
14	..	..	..	..	73·5	..	..	62·0	27	..	9	..	Calm	..	Much glare to-day. Drops of rain at
14	Telleichina	..	..	3656	..	87·0	..	..	..	16	..	..	..	E 2	—— [14h.
15	..	..	..	..	76·0	..	..	70·1	24	..	8	..	Calm	..	Cloudy on and off all day.
15	Tintaralle	18 27	8 56	3149	..	86·0	..	..	..	25	..	..	..	..	Drops of rain 11h.
16	..	..	..	..	78·8	86·0	99·0	72·1	34	27	3	5	Calm	N 1	13h. thunder to W. and N.W
17	..	..	..	..	82·2	88·5	..	65·0	27	9	0	0	NE 1	NE 1	Slight zodiacal light 18h.
18	..	..	..	..	74·2	..	..	69·6	17	..	0	..	NE 1	..	Thin Ci. over all sky all day.
18	Main Valley	..	..	*2820*	..	85·5	..	..	..	13	..	..	..	NE 1	——
19	..	..	..	..	64·7	..	..	55·0	45	..	0	..	Calm	..	Some rain 16h.–16h. 30m.
19	Agaragar Valley	..	..	*2770*	..	87·2	..	..	..	63	..	..	..	NE 1	——
20	..	..	..	..	68·5	..	..	64·0	45	..	..	..	Calm	..	Hot travelling.
20	Iberkom	..	..	..	..	91·5	..	..	..	17	..	8	..	NE 2	——
21	..	..	..	..	83·5	..	..	60·5	16	..	0	..	ENE 3	..	Very hazy day.
21	Iferuan	19 05	8 25	*2190*	..	91·5	..	..	..	7	..	0	..	Calm	——
22	..	..	..	..	78·0	94·3	114·0	76·6	20	19	0	2	Calm	NE 1	Very hot day.
23	..	..	..	..	76·3	89·2	109·0	74·1	51	27	2	0	Calm	Calm	Shower 14h. to 15h. 30 m.
24	..	..	..	..	72·5	92·7	108·0	73·1	53	15	0	3	Calm	Calm	Visibility exceptionally good all day.
25	..	..	..	..	77·5	89·9	107·0	74·1	59	..	2	9	Calm	E 3	Showers 11h. 30m. to 17h.
26	..	..	..	..	73·4	93·9	107·0	70·1	61	16	..	0	Calm	Calm	Very clear 18h.
27	..	..	..	..	74·5	95·1	110·0	71·1	48	14	0	0	Calm	ENE 2	Very clear at sunset.
28	..	..	..	..	72·1	93·5	110·0	71·1	34	9	0	0	Calm	ENE 2	Visibility good 18h.
29	..	..	..	..	82·5	96·5	113·0	80·1	12	8	0	0	Calm	..	No cloud all day.
30	..	..	..	..	68·5	..	..	65·5	34	..	0	..	Calm	..	Not a trace of cloud all day.
30	Tegidda Mellen	19 12	8 21	2150	..	91·0	102·0	..	..	8	..	0	..	NE 3	——
Oct., 1927.															
1	Tegidda Mellen	19 12	8 21	2150	73·5	92·5	107·0	71·1	16	7	0	0	NE 1	NE 3	Visibility very good 18h.
2	..	..	..	..	74·5	93·5	102·5	69·6	21	8	0	5	Calm	NE 2	High cloud during day.
3	..	..	..	..	82·5	88·5	100·0	75·6	27	25	9	8	ESE 1	WNW 1	Shower 14h. 30m. to 14h. 50m.
4	..	..	..	..	78·3	92·5	102·5	76·1	36	12	6	5	NE 2	NE 3	Visibility very poor all day.
5	..	..	..	..	73·5	93·5	103·0	71·6	24	9	0	0	Calm	NNE 3	Very hazy all day.
6	..	..	..	..	77·3	93·5	103·0	72·1	18	8	..	..	NE 2	N 1	Scarcely any breeze all day.
7	..	..	..	..	79·3	91·5	102·0	74·1	26	16	..	..	NE 3	N 2	Strong gusts at times 8h.–16h.
8	..	..	..	..	79·5	93·0	..	73·1	26	19	6	7	NE 3	NW 2	A little rain 19h. to 19h. 10m.
9	..	..	..	..	78·0	91·5	111·0	68·0	25	12	..	..	N 2	NE 1	Detached Cu. from ENE. 11h.–17h.
10	..	..	..	..	76·5	92·5	..	73·1	21	14	..	..	NE 2	NNE 1	Sky covered with St. nearly all day.
11	..	..	..	..	79·5	92·0	..	73·6	23	14	2	1	N 1	N 1	Showers seen falling to E.
12	..	..	..	..	79·0	89·7	101·0	77·1	17	15	..	0	..	Calm	Cu. and Nb. from NE. 11h. onwards.
13	..	..	..	..	76·5	87·0	..	77·1	21	25	7	3	..	ENE 3	Rain–storm 10h. 30m.
14	..	..	..	..	75·5	89·7	100·0	72·1	34	20	..	..	N 2	NE 2	No cloud.
15	..	..	..	..	81·8	90·3	102·0	76·1	21	14	..	..	NE 2	NNE 2	Dust storm from NE. 11h. 30m
16	..	..	..	..	73·5	88·0	93·2	70·1	27	14	..	..	NNE 1	..	No cloud.
17	..	..	..	..	72·5	91·5	109·0	70·6	25	19	0	..	Calm	..	17h. appearance of rain to E.
18	..	..	..	..	79·5	94·5	106·0	80·1	29	14	4	7	ENE 1	S 3	Whirlwind struck camp 15h.
19	..	..	..	..	75·5	90·5	106·0	75·1	29	12	4	..	..	NE 2	12h.–17h. wind NE. force 5.
20	..	..	..	..	77·3	88·7	..	75·6	37	14	..	..	NE 6	NE 1	Strong NE. wind 4h.–6h.
21	..	..	..	..	75·0	..	..	..	..	..	..	..	NE 2	..	Strong NE. wind morning.
22	Aberkot Valley	..	..	..	71·5	..	..	..	23	..	..	..	..	..	Fresh NE. wind all day.
23	Tarazit Pool	..	..	*2520*	..	86·5	..	..	..	13	..	..	..	..	Warm night.
24	..	..	..	..	..	77·5	..	..	..	21	..	..	..	..	——
25	..	..	..	..	75·5	88·5	..	..	14	8	1	..	..	..	——
26	..	..	..	..	..	..	..	..	..	..	0	..	..	..	——
27	..	..	..	..	80·0	..	..	..	17	..	5	..	..	..	——
28	Desert	..	..	..	72·5	..	..	..	..	..	..	..	..	..	Fresh E. wind all day. Very cold night.
29	Desert N. of Tamgak	..	..	..	68·5	..	..	..	45	..	..	..	NE 5	..	14h. sky almost covered with St from —— [SW.
31	Iferuan	19 05	8 25	*2190*	63·0	82·5	98·0	..	49	17	..	..	..	..	Slight Easterly wind most of day.

* Heights printed in italics have been computed in the Meteorological Office from the pressure readings by aneroid in conjunction with any other available data

Day.	Station.	Lat. N.	Long. E.	Ht. *	Temperature. 6h.	Temperature. 18h.	Temperature. Max.	Temperature. Min.	Relative Humidity. 6h.	Relative Humidity. 18h.	Cloud Amount 6h.	Cloud Amount 18h.	Wind. 6h. Dir. Force	Wind. 18h. Dir. Force	Remarks.
		° ′	° ′	ft.	°F.	°F.	°F.	°F.	%	%					
Nov., 1927.															
1	Iferuan	19 05	8 25	*2190*	59·5	81·0	105·0	59·0	55	19	..	..	..	N 1	—
2	.. .. ..	..	..	..	62·5	78·0	102·5	57·0	41	20	0	1	Calm	..	—
3	.. .. ..	..	..	..	68·0	..	..	64·0	30	..	2	..	Calm	..	—
3	Anefok	..	..	*1960*	..	78·5	..	..	..	19	..	10	..	ENE 4	A few drops of rain in night.
4	.. .. ..	..	..	..	70·3	..	..	69·0	28	..	9	..	NNE 3	..	A few drops of rain 7h. 20m.
4	Tedekel	..	..	*1750*	..	77·2	..	..	..	23	..	0	..	E 2	—
5	.. .. ..	..	..	..	70·5	..	..	65·5	35	..	..	..	Calm	..	No cloud.
5	Lower Taruei ..	..	..	1620	..	..	..	..	..	..	..	0	..	Calm	—
6	.. .. ..	..	..	..	64·5	..	..	55·0	37	..	0	..	Calm	..	No cloud all day.
6	Arli	19 00	7 38	1543	..	83·1	99·0	..	..	17	..	0	..	Calm	—
7	.. .. ..	..	..	..	64·8	84·5	94·5	61·0	33	10	0	0	Calm	ENE 3	No cloud.
8	.. .. ..	..	..	..	67·7	84·0	98·0	54·0	27	10	0	0	Calm	ENE 3	No cloud.
9	.. .. ..	..	..	..	74·9	81·0	93·5	..	18	15	0	0	Calm	NE 3	No cloud.
10	.. .. ..	..	..	..	65·5	..	..	64·0	19	..	0	..	NE 1	..	No cloud.
10	Tagellalt	..	..	*1550*	..	82·1	..	..	..	10	..	0	..	NE 2	—
11	.. .. ..	..	..	..	64·5	..	..	55·0	33	..	0	..	Calm	..	Much mirage.
11	Efenghalen ..	..	..	..	..	79·5	..	..	..	12	..	0	..	NE 1	—
12	.. .. ..	..	..	..	59·3	..	..	48·0	21	..	0	..	Calm	..	
12	Adar Valley ..	..	..	..	..	77·5	98·5	..	..	23	..	0	..	Calm	Strong zodiacal light 18h.
13	Desert Camp ..	..	..	*1400*	53·0	..	..	46·0	25	..	0	..	Calm	..	Mirage 6h. 30m. till sundown.
13	D. Camp	..	..	*1310*	..	77·2	..	..	..	12	..	0	..	Calm	—
14	.. .. ..	..	..	..	..	..	..	45·0	..	..	0	..	Calm	..	Mirage 6h. 30m. to 15h.
14	Inallaren Valley ..	18 16	..	..	..	77·3	..	..	..	13	..	0	..	NE 1	—
15	D. Camp	..	..	*1270*	58·5	..	..	51·0	22	..	0	..	Calm	..	Mirage began 7h. 30m.; very strong to [S. 13h.
15	Buttel	18 11	6 11	1149	..	79·0	..	..	..	12	..	0	..	Calm	—
16	.. .. ..	..	..	..	58·0	81·0	100·0	56·0	27	17	0	0	Calm	Calm	High zodiacal light 18h.
17	.. .. ..	..	..	..	59·7	..	..	50·0	25	..	0	..	Calm	..	No cloud.
17	D. Camp	..	..	*1210*	..	76·5	..	..	..	17	..	0	..	Calm	—
18	.. .. ..	..	..	..	57·7	..	..	49·0	27	..	0	..	N 1	..	18h. slight cloud to W. first seen since [leaving Air.
18	D. Camp	..	..	*1160*	..	78·5	..	..	..	14	..	0	..	NNE 1	—
19	.. .. ..	..	..	..	58·5	..	..	49·0	26	..	0	..	NNE 1	..	Hazy all day from 7h.
19	In Nuggaren Wells	17 59	5 18	1270	..	81·0	..	..	..	14	..	5	..	..	—
20	.. .. ..	..	..	..	62·0	..	..	55·0	32	..	0	..	Calm	..	Day slightly hazy.
20	D. Camp	..	..	*1090*	..	81·1	..	..	..	18	..	0	..	NE 1	—
21	.. .. ..	..	..	..	60·8	..	..	52·5	31	..	2	..	E 1	..	—
21	Nr. Indunan ..	..	..	..	..	77·3	..	..	..	20	..	0	..	Calm	—
22	.. .. ..	..	..	..	60·5	..	..	48·0	28	..	8	..	Calm	..	Some mirage mid-day.
22	In Aridel	17 45	4 25	1152	..	73·0	..	..	..	27	..	0	..	Calm	—
23	.. .. ..	..	..	..	61·0	76·9	86·9	57·0	26	22	2	0	Calm	Calm	Haze at sunset.
24	.. .. ..	..	..	..	54·5	..	..	53·5	55	..	9	..	Calm	..	—
24	Tiriken Valley ..	..	..	*1170*	..	76·3	..	..	..	24	..	3	..	Calm	
25	.. .. ..	..	..	..	53·9	..	..	47·0	38	..	9	..	Calm	..	6/10–7/10 cloud all day.
25	Nr. Temakkas ..	..	..	..	..	81·3	..	..	..	17	..	7	..	..	—
26	Temakkas	..	..	..	59·3	..	..	56·0	31	..	10	..	NE 1	..	Sun veiled nearly all day.
26	D. Camp	..	..	*1230*	..	76·5	..	..	..	16	..	..	..	..	—
27	.. .. ..	..	..	..	56·5	..	..	51·5	22	..	..	..	NE 1	..	Cool day marching.
27	Tanekert Well ..	17 49	3 11	1205	..	74·5	..	..	..	12	..	..	..	NW 1	—
28	.. .. ..	..	..	..	54·5	73·9	96·0	46·0	19	15	10	..	NNE 2	Calm	Much mirage to N. 12h. to 15h.
29	,, ..	..	..	..	56·2	..	..	47·0	22	..	9	..	N 1	..	Sky covered with St all day.
29	Nr. Tesa tan Tiklatin	..	..	*1450*	..	78·5	..	..	..	19	..	10	..	..	—
30	.. .. ..	..	..	..	64·3	..	..	61·0	17	..	7	..	NNW 2	..	Sky completely overcast all day.
30	Akalu Valley ..	18 08	2 16	*1480*	..	72·9	..	..	..	20	..	10	..	Calm	—
Dec., 1927.															
1	Akalu Valley ..	..	..	..	67·0	..	..	56·0	21	..	10	..	Calm	..	10/10 St. nearly all day.
1	Upper Akalu ..	..	..	*1530*	..	78·7	..	..	..	19	..	10	..	Calm	—
2	.. .. ..	..	..	..	66·5	..	..	56·5	21	..	10	..	Calm	..	Cool and cloudy all day.
2	D. Camp	..	..	*1500*	..	75·5	..	..	..	34	..	..	..	Calm	—
3	.. .. ..	..	..	..	64·5	..	..	55·5	53	..	10	..	Calm	..	Cold trekking; low St. all day.
3	D. Camp	..	..	*1650*	..	75·1	..	..	..	37	..	..	..	..	—
4	.. .. ..	..	..	..	63·7	..	..	59·0	62	..	10	..	NE 3	..	10/10 St. all day; drops of rain 16h. [30m.
4	D. Camp	..	..	*1480*	..	69·5	..	..	..	57	..	..	..	NE 2	—
5	.. .. ..	..	..	..	66·3	..	..	60·5	66	..	10	..	ENE 1	..	10/10 cloud all day.
5	Kidal	18 26	1 21	*1520*	..	75·5	..	..	..	51	..	..	..	Calm	—
6	.. .. ..	..	..	..	63·5	71·5	94·0	..	78	48	8	10	..	..	—
7	.. .. ..	..	..	..	58·1	..	..	..	76	..	2	..	SW 1	..	—
7	Bush Camp.. ..	..	..	*1360*	..	71·5	..	..	..	48	..	1	..	..	—
8	.. .. ..	..	..	..	58·0	..	..	?51·0	53	..	9	..	E 1	..	—
8	Camp	..	..	*1320*	..	71·5	..	..	..	48	..	2	..	NW 2	—
9	.. .. ..	..	..	..	59·0	..	..	47·0	54	..	10	..	NE 1	..	—
9	Camp	..	..	*1160*	..	68·5	81·8	..	..	41	..	1	..	..	—
10	.. .. ..	..	..	..	49·0	..	..	41·0	54	..	3	..	..	..	—
10	Camp	..	..	*1090*	..	75·5	86·9	..	..	21	..	0	..	Calm	—
11	.. .. ..	..	..	..	58·0	79·5	93·0	..	31	11	8	3	NE 1	..	Lightning all round horizon after 18h.
12	.. .. ..	..	..	..	63·0	..	..	57·0	40	..	9	..	..	..	—
12	Camp	..	..	*1050*	..	79·5	..	..	..	25	..	10	..	..	—
13	.. .. ..	..	..	..	67·0	..	..	60·0	51	..	..	..	W 1	..	Sky covered with St–Cu. most of day; spots of rain about 16h.
13	Intaset	..	..	*1010*	..	77·5	..	..	..	59	..	9	..	Calm	—
14	Camp	..	..	..	56·5	..	..	49·0	78	..	..	..	N 1	..	—
14	Camp	..	..	*1110*	..	76·5	..	..	..	44	..	..	..	NE 1	—
15	.. .. ..	..	..	..	60·5	..	..	48·0	47	..	10	..	N 2	..	—
16	Burem on Niger ..	..	..	886	..	..	..	..	..	..	..	..	..	..	

* Heights printed in italics have been computed in the Meteorological Office from the pressure readings by aneroid in conjunction with any other available data.

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Two Notes on the Operation of Galitzin Seismographs

By F. J. SCRASE, M.A., B.Sc.

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TWO NOTES ON THE OPERATION OF GALITZIN SEISMOGRAPHS

I.—AN ISOPLETH DIAGRAM FOR THE RAPID EVALUATION OF THE DAMPING CONSTANT AND THE FREE PERIOD OF A GALITZIN SEISMOGRAPH PENDULUM

The chief feature of the Galitzin seismograph is that the motion of the pendulum is recorded galvanometrically. The displacement of the galvanometer coil is proportional to the angular velocity, and not to the displacement, of the pendulum. On this account, the interpretation of the record in terms of earth movement is a difficult matter except under certain conditions. The differential equation of the motion of the pendulum under the influence of an earth movement may be expressed—

$$\theta''+2\varepsilon\theta'+n^2\theta+\frac{x''}{l}=0,$$

where θ is the angular displacement of the pendulum, ε is the coefficient of damping, n depends on the free period T of the pendulum $\left(n=\frac{2\pi}{T}\right)$, x is the displacement of the ground and l is the length of the equivalent simple pendulum. Similarly, the equation for the motion of the galvanometer coil may be written—

$$\phi''+2\,\varepsilon_1\,\phi'+n_1^2\,\phi+k\cdot\theta'=0.$$

Here ϕ, ε_1, and n_1 have the same meanings as θ, ε and n, but with reference to the galvanometer; k is a constant depending on the strength of the inductive coupling and may be called the transmission coefficient.

The solution of these equations when x is a prescribed function of time is worked out fully by Prince Galitzin[1], and the relation between the galvanometer record and the earth movement is considerably simplified if both pendulum and galvanometer are made to have the same free period and to be critically aperiodic within very narrow limits. The attainment of these ideal conditions is aimed at, therefore, when an instrument is installed.

The first step is to make the galvanometer strictly aperiodic. This is simply a matter of adjusting the electrical resistance of the circuit, and need not be discussed here. When the condition is reached $\varepsilon_1=n_1=\frac{2\pi}{T_1}$ and no appreciable changes are likely to take place. It remains to make the pendulum aperiodic and to give it a free period T equal to that of the galvanometer T_1. When these conditions are fulfilled $\varepsilon_1=n_1=\varepsilon=n$. For convenience the departure from aperiodicity may be written—

$$\mu^2=1-\frac{\varepsilon^2}{n^2}\quad\text{(Galitzin calls } \mu^2 \text{ the damping constant[2])}$$

and the ideal is attained for $\mu^2=0$, and $n=n_1$.

The free period of the pendulum is altered by adjusting the tilt of the supporting frame, and may be measured directly if the damping system is removed. It is not difficult to bring T near to T_1 by this direct method, and having done this, the damping magnets can then be closed in until the pendulum just ceases to oscillate on being given a small displacement.

The next proceeding is to make an accurate determination of T and μ^2 to see how near the pendulum is to the ideal conditions. This is done by giving the pendulum a small impulse and by making observations of the movement recorded by the galvanometer. The displacement of the pendulum due to the impulse is given by

$$\theta=\frac{\theta'_0}{\mu n}e^{-\varepsilon t}\sin\mu nt$$

---

[1] Vorlesungen über Seismometrie, 1914 (Leipzig).

[2] *The significance of* μ.—It may be recalled that when aperiodicity has not been attained the displacement of the pendulum after an initial impulse is a multiple of $e^{-\varepsilon t}\sin\mu nt$. When the pendulum is overdamped μ is imaginary and the sine is hyperbolic. As long as μ is real it may be defined as the ratio of the periods of undamped and damped oscillations of the pendulum.

where θ_0' is the initial angular velocity. The motion takes the form shown by the full curve in Fig. 1.

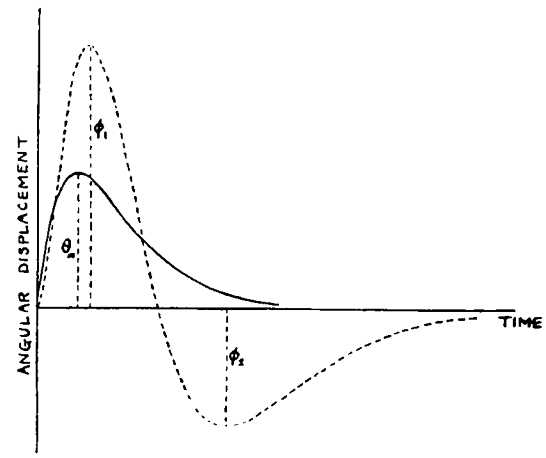


FIG. 1

The solution of the equation of motion of the galvanometer coil corresponding to the above form of pendulum movement is very complicated and is given fully by Galitzin. The broken curve in Fig. 1 shows the displacement followed by the coil; the measurements which are made are of the two maximum amplitudes ϕ_1 and ϕ_2 and the interval t_0 between the time of giving the impulse and the time when the coil crosses the zero line after the first half of the oscillation. Galitzin derives two expressions which enable μ^2 and T to be determined from these observations. Thus—

$$\xi = \frac{n_1 t_0 - a + c\xi^2}{b}; \qquad \text{where } \xi = \frac{T - T_1}{T}$$

$$a = 3 - 0{\cdot}15\,\mu^2$$
$$b = 1{\cdot}5 + 0{\cdot}225\,\mu^2$$
$$c = 0{\cdot}3 + 0{\cdot}0171\,\mu^2$$

$$\mu^2 = \frac{\beta - a}{a\psi_2 - \beta\psi_1}; \qquad \text{where } \beta = 2{\cdot}2937\,(1 + 0{\cdot}1732\,\xi^2)$$

$$a = \frac{\phi_1}{\phi_2}$$
$$\psi_1 = -0{\cdot}0065377\,(1 + 5{\cdot}5981\,\xi + 1{\cdot}5556\,\xi^2)$$
$$\psi_2 = 0{\cdot}33988\,(1 + 0{\cdot}40192\,\xi - 0{\cdot}63417\,\xi^2)$$

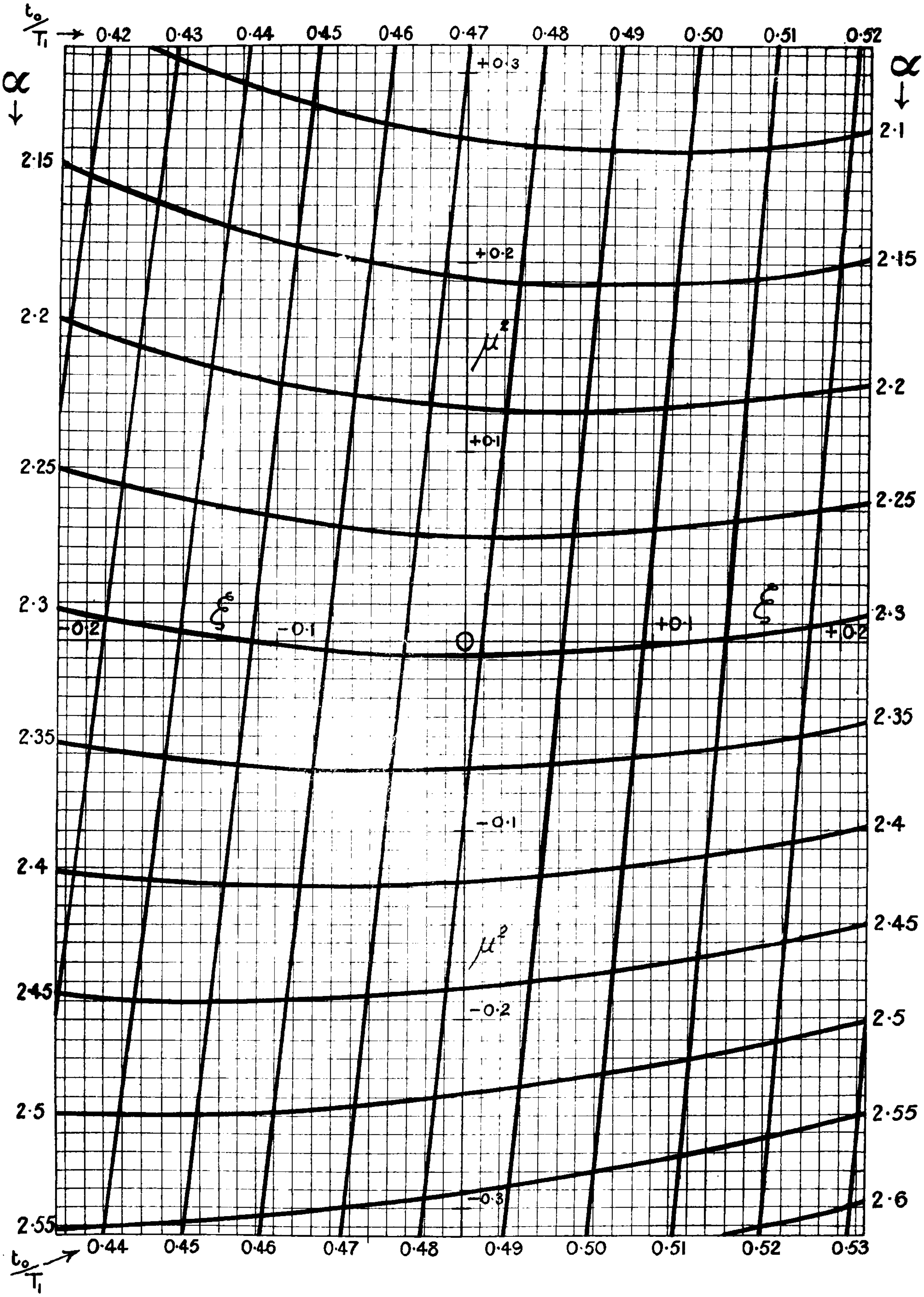
It will be seen that the computation of μ^2 and ξ is not very straightforward. The method suggested by Galitzin is that of successive approximation, μ^2 being calculated first on the assumption that $\xi = 0$ and then this value of μ^2 is used to determine the approximate value of ξ. The process is repeated using this value of ξ. It will be seen that the critical conditions are attained when, simultaneously

$$a = \beta = 2{\cdot}2937 \text{ and } t_0 = \frac{3T_1}{2\pi}$$

Now when an instrument is in the process of being adjusted to the critical condition it is a distinct advantage to be able to convert the observations of a $\left(\text{i.e. } \frac{\phi_1}{\phi_2}\right)$ and t_0 into μ^2 and ξ by some direct method. In this way the adjustment may be attained in quite a short space of time. With this object in view, an isopleth diagram has been constructed connecting μ^2, ξ, a and t_0. (Actually t_0/T_1 has been used as one of the variables so that the diagram is not restricted to instruments in which the galvanometers have the same free period.) The diagram has been made by giving t_0/T_1 and a a series of values and then making the calculations of μ^2 and ξ by Galitzin's method outlined above. The values of μ^2 and ξ have been plotted as abscissae and ordinates respectively and the isopleths of t_0/T_1 and a have been drawn.

Fig. 2

To face p. 4.



ISOPLETH DIAGRAM FOR OBTAINING DIRECTLY VALUES OF μ^2 AND ξ FROM OBSERVED VALUES OF t_0/T_1 AND α

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A reproduction of the diagram is given in Fig. 2. Having obtained a few observations of α and t_0 it is a simple matter to read off the corresponding values of μ^2 and ξ, T then being obtained by the relation

$$T = (1+\xi)\ T_1$$

The meshes formed by the isopleths have been made of such size that linear interpolation can be used without introducing any appreciable error in μ^2 or ξ. The diagram covers a range of values of μ^2 from about $+0{\cdot}3$ to $-0{\cdot}3$ and a range of values of ξ from about 0·2 to −0·2.

It should be pointed out that by making approximations in the solution of the differential equation for the motion of the galvanometer much simpler expressions can be derived for μ^2 and ξ. Thus O. Somville[3] finds that provided the pendulum is very near to being critically aperiodic the following formulæ give sufficiently accurate values :

$$\mu^2 = \frac{2{\cdot}294 - \alpha}{0{\cdot}795}$$

$$\xi = \frac{4\ \pi\ t_0}{3\ T_1} - 2 + \tfrac{1}{10}\ \mu^2$$

Similarly G. W. Walker[4] gives

$$\mu^2 = 2{\cdot}294\ \left(\frac{2{\cdot}294}{\alpha} - 1\right)$$

$$\xi = \tfrac{2}{3}\ \left(\frac{2\ \pi\ t_0}{T_1} - 3\right)$$

when ξ and μ^2 are not greater than 0·1.

The use of these simple formulæ presupposes that the ideal conditions of tuning and damping have almost been reached, whereas the diagram based on the more exact theory is valid when the departure from critical conditions is large. The diagram is specially useful, therefore, when adjustments are being attempted after a rough tuning has been made by direct observations on the pendulum.

Since the departure from critical damping is dependent on the free period of the pendulum, it is best to complete the final adjustment of the period (using the impulse method and not the direct method for measuring the period[5]) before attempting fine adjustment of the damping. If the latter is attempted first then the critical condition of damping will be upset by final adjustment of the period.

For the benefit of workers who desire to construct a diagram on a scale larger than that reproduced the necessary numerical data are given in the accompanying tables.

VALUES OF μ^2.

α \ ξ	−·20	−·15	−·10	−0·5	0	+·05	+·10	+·15	+·20
2·1 ..	+·329	+·305	+·288	+·275	+·266	+·261	+·260	+·261	+·267
2·15 ..	+·245	+·225	+·210	+·199	+·193	+·189	+·190	+·192	+·199
2·2 ..	+·164	+·148	+·136	+·128	+·123	+·121	+·123	+·127	+·133
2·25 ..	+·087	+·074	+·065	+·059	+·056	+·056	+·059	+·064	+·071
2·3 ..	+·014	+·004	−·003	−·007	−·008	−·007	−·003	+·003	+·011
2·35 ..	−·057	−·064	−·068	−·070	−·069	−·066	−·062	−·055	−·046
2·4 ..	−·124	−·128	−·130	−·130	−·128	−·124	−·118	−·111	−·101
2·45 ..	−·188	−·191	−·190	−·188	−·184	−·179	−·172	−·164	−·154
2·5 ..	−·250	−·250	−·248	−·244	−·239	−·232	−·224	−·215	−·205
2·55 ..	−·311	−·307	−·303	−·297	−·291	−·283	−·274	−·265	−·254

3 Constants des Sismographes Galitzin.—*Annales de l'Observatoire Royal de Belgique*, 1922 (Brussels).

4 Modern Seismology, 1913 (London).

5 Somville (loc. cit.) points out that the free period as obtained by direct measurement, with the damping magnets removed, differs appreciably from the value given by the impulse method, in which the damping magnets are in position, and shows that the discrepancy is due to the pendulum not being magnetically neutral.

VALUES OF ξ.

t_0/π \ μ^2	+0·3	+0·2	+0·1	0	−0·1	−0·2	−0·3
0·43 ..	−·156	−·168	−·179	−·191	−·202	−·215	−·227
0·44 ..	−·118	−·129	−·141	−·152	−·163	−·175	−·188
0·45 ..	−·080	−·091	−·102	−·113	−·124	−·135	−·147
0·46 ..	−·041	−·051	−·062	−·072	−·083	−·094	−·106
0·47 ..	−·001	−·011	−·021	−·031	−·041	−·052	−·063
0·48 ..	+·039	+·030	+·020	+·011	+·001	−·010	−·020
0·49 ..	+·080	+·071	+·062	+·053	+·044	+·034	+·024
0·50 ..	+·122	+·114	+·105	+·097	+·087	+·078	+·068
0·51 ..	+·164	+·156	+·148	+·140	+·131	+·122	+·114
0·52 ..	+·207	+·199	+·192	+·184	+·177	+·168	+·160

II—SOME PRACTICAL CONSIDERATIONS ARISING FROM THE VARIATION OF THE PERIOD OF THE PENDULUM OF A GALITZIN VERTICAL SEISMOGRAPH

§ 1—Introduction

The variation of the period of the pendulum of the Galitzin vertical seismograph with deviation from the normal position has been discussed by L. F. Richardson[1] and by J. Wilip[2]. They advocate the use of a modified design of instrument embodying two (or more) control springs instead of one, as a means of obtaining a more uniform period over the range of amplitudes usually encountered. T. Tamaru[3] also has dealt with the theory of vertical pendulums in which more than one spring is employed. The excuse for a further discussion of the same subject is that there must be a number of seismological stations where, although the merits of the two-spring system are fully appreciated, the original pattern of Galitzin vertical seismograph is retained in order to avoid the expense of alterations and therefore it may be of interest to deal with some of the practical limitations of the original type of instrument.

§ 2—Variation of Period with Displacement

It is necessary first of all to outline briefly the theory of the instrument. In Fig. 1 the moving part of the pendulum is represented by OMB.

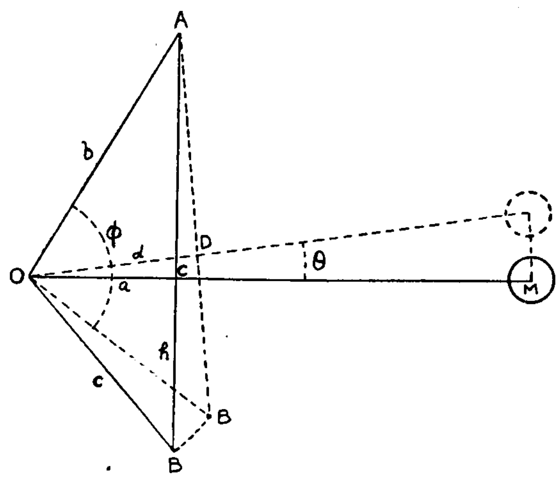

Fig. 1.

O is the turning axis and M the centre of mass. AB is the spiral spring which is fixed at A. The elastic constant of the spring is β given by

$$P-P_0=\beta\,(L-L_0)$$

where P_0 and L_0 are the tension and length of the spring respectively in the normal position, and P and L are the corresponding quantities when the boom is displaced through a small angle θ.

Referring to Fig. 1 it will be seen that the length of the spring in any position is given by:

$$L^2=b^2+c^2-2\,bc\cos\phi \qquad \ldots \quad \ldots \qquad (1)$$

where ϕ is the variable angle AOB, b is the fixed distance OA and c is the fixed length of the arm OB. The couple due to the spring is Pd where d is the length of the perpendicular from O to the axis of the spring and is equal to $\frac{bc\sin\phi}{L}$ (in the normal position $d_0=a$).

$$Pd=[P_0+\beta\,(L-L_0)]\,\frac{bc\sin\phi}{L} \qquad \ldots \quad \ldots \qquad (2)$$

[1] *Monthly Notices, R.A.S.*, Geophys. Suppl **1**, No 8, 1926.
[2] *Gerlands Beiträge zur Geophysik.*, *Leipzig*, **19**, Heft 4, 1928.
[3] *Physikalische Zeitschrift, Leipzig*, **4**, 1903, p. 638.

The couple due to the weight is $Mgr_0 \cos\theta$ ($\theta = \phi - \phi_0$), where r_0 is the distance of the centre of mass M from the axis of rotation. The net restoring couple is therefore:

$$C = Pd - Mgr_0 \cos\theta \quad \ldots \quad (3)$$

and the period is given by:

$$T = 2\pi\sqrt{\frac{I}{dC/d\phi}} \quad \ldots \quad (4)$$

I being the moment of inertia. This is the theory which is further developed by Richardson (loc. cit.).

By neglecting second-order quantities Galitzin obtained a simple formula for the period given by

$$\frac{4\pi^2}{T^2} = n^2 = \frac{\beta a^2}{I} - \frac{P_0 h}{I}\left(1 - \frac{h}{L_0}\right) \quad \ldots \quad (5)$$

This expression gives an apparently uniform period. Richardson, however, shows that the higher derivatives of the restoring couple are by no means negligible. The effect of this on the period can be seen by inserting numerical values, obtained from the dimensions of the pendulum, in the expressions (1) to (4). The theoretical curve connecting the period with the deviation has been worked out in the case of the Kew instrument. It is not reproduced here since it is exactly similar to the curve in Fig. 2A which was obtained experimentally.

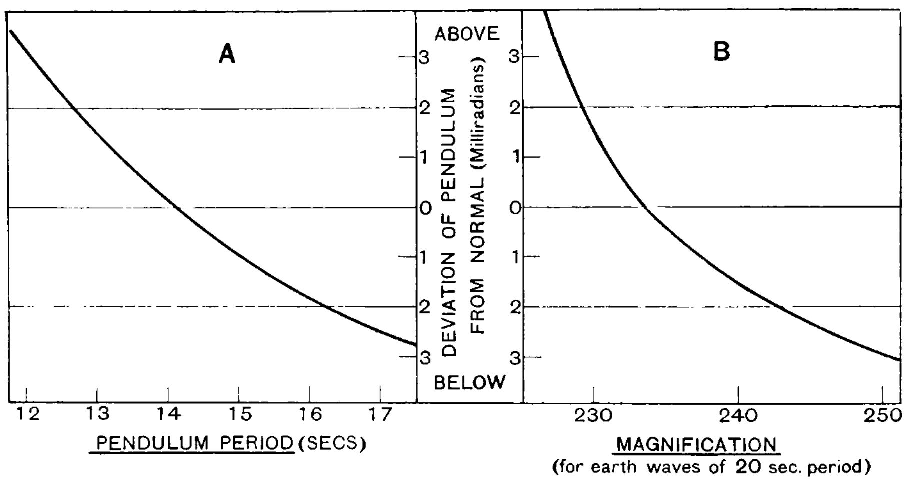

FIG. 2.

It will be seen that the variation of the period is extremely large, especially when the pendulum is displaced below its normal position. In practice when the displacement reaches about 0·02 radian below the normal position the pendulum becomes unstable. This is the most serious consequence of the variation in period since it causes a complete loss of record until the pendulum is readjusted to its normal position. The amount of the variation can be reduced by using a lower working period but this is considered disadvantageous for recording distant earthquakes.

3—Effects of Variation of Period on Magnification

One effect of the variation of the period is to make the determination of the angle of emergence of a seismic ray very difficult and inaccurate. In order to achieve reliable results in this direction it is essential that the periods of all three components of the seismograph installation should be the same. With the period of the vertical pendulum varying as it does, it is impossible to obtain an accurate measure of the amplitude of an impulse and it is seldom attempted.

The amplitudes of the sinusoidal waves in the main phase of an earthquake are, however, measured as a routine procedure at a number of stations, and it is of interest to see what reliance can be placed on measurements obtained from records of the Galitzin vertical seismograph. The magnification given by the galvanometer record for a sinusoidal wave is expressed by the formula :

$$M = \frac{T_p K A}{\pi l} \quad \frac{1}{(1+u_1^2)(1+u^2)\sqrt{1-\mu^2 f(u)}} \quad \cdots \quad \cdots \quad (6)$$

where T_p is the period of the earth wave, K is the transmission coefficient depending chiefly on the strength of the inductive coupling between the pendulum and the galvanometer circuit, $u_1 = T_p/T_1$ (T_1 being the galvanometer period), $u = T_p/T$; μ^2 is the damping constant and is equal to $1 - \frac{\varepsilon^2 T^2}{4\pi^2}$, ε being the ordinary damping coefficient and $f(u)$ is $\left[\frac{2u}{1+u^2}\right]^2$. Now when the boom of the vertical pendulum shifts its equilibrium position (usually on account of temperature change), causing an alteration in the period T, it is clear that the magnification will not be the same as for the true equilibrium position. In the above formula both u and μ^2 are altered. Differentiating M with respect to T we get :

$$\frac{dM}{dT} = -\frac{2\,C\,u^2\,(1-u^2)}{T\,(1+u^2)^3\,[1-\mu^2 f(u)]^{3/2}} \quad \cdots \quad \cdots \quad (7)$$

where C replaces $\frac{1}{T_p} \; \frac{\pi l}{K A} \; (1+u_1^2)$.

We can express the proportional change in the magnification as a factor (γ) of the proportional change in the period thus :

$$\frac{\delta M}{M} = -\frac{2\,u^2\,(1-u^2)}{(1+u^2)\,[1-\mu^2 f(u)]} \; \frac{\delta T}{T} = \gamma \frac{\delta T}{T} \quad \cdots \quad \cdots \quad (8)$$

The ratio of the corresponding changes therefore is dependent on the period of the earth wave (since $u = \frac{T_p}{T}$) as is the magnification itself. In the following table values of γ have been calculated for some given values of u, also the earth-wave periods T_p, corresponding to these values of u and a pendulum period in the normal position of 14 seconds. To simplify the calculations μ^2, in the normal position, has been taken as zero (i.e., the damping as being critically aperiodic).

$u\left(=\frac{T_p}{T}\right)$	0·2	0·5	0·6	0·8	1·0	2·0	3·0	4·0	infinite
T_p (for T 14 secs.)	2·8	7	8·4	11·2	14	28	42	56	infinite
γ	−0·07	−0·24	−0·25	−0·17	0	+0·96	+1·44	+1·66	+2·0

These figures are shown graphically in Fig. 3. It will be seen that so long as u is less than unity an increase in pendulum period causes a decrease in magnification. When u is less than 1·2 the change in magnification is not more than one quarter of the change in pendulum period, but when u is greater than 2 the change in M is even greater than the change in T. It must be remembered, however, that the above values of γ do not apply strictly to large increments.

Some measurements obtained in a series of standardisation tests on the Kew vertical seismograph show how much the magnification (for sinusoidal waves of fixed period) is affected by large changes in the pendulum period due to the deviation of the equilibrium position from normal. The variations are shown in Fig. 2B in which magnifications for waves of 20-seconds period are plotted against angular deviation of the pendulum ; in Fig. 2A the corresponding pendulum periods are plotted. In the operation of the Kew seismograph the former practice was to limit the drift of the pendulum (due to temperature change) to $\pm 3\cdot7$ milliradians, an adjustment being made if this amount was reached. The magnification factors corresponding to the period of the pendulum in the normal equilibrium position were assumed to apply over the whole range of this drift. Referring to Fig. 2 it will be seen that in the normal position the pendulum period is about 14 seconds and the magnification (for $T_p = 20$ seconds) is 233. If the pendulum rises $3\cdot7$ milliradians the period falls to 12 seconds, i.e., a change of about -16 per cent, while the magnification decreases by only 2 per cent. If the pendulum falls through the same angle the period increases by 30 per cent, and the corresponding increase in magnification is 10 per cent. Thus

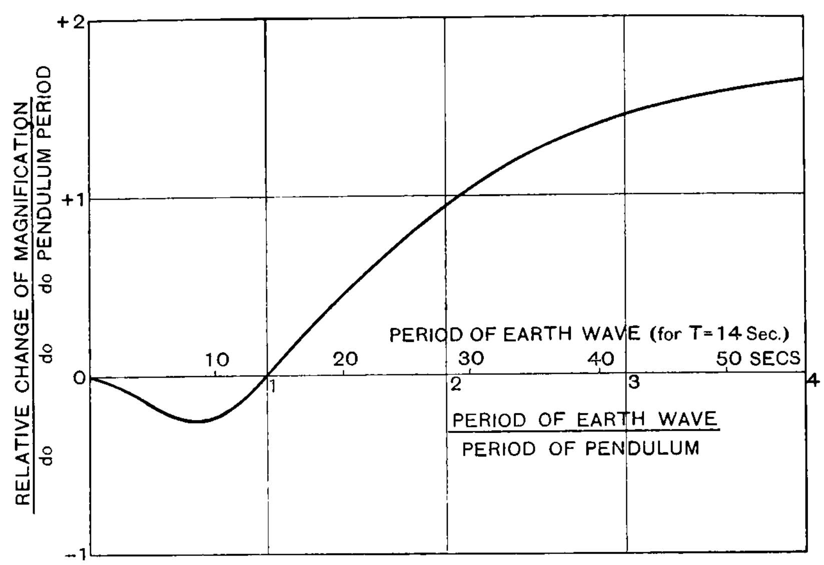

FIG. 3.

in applying the magnification corresponding to the normal position to any other position within the range of drift permitted an error of 10 per cent may occur. In view of the asymmetry of the variation of the period it is clearly better to reduce the permissible drift below normal and, if necessary, allow a larger drift above normal. Thus, if the drift is limited to 2 milliradians above normal and 1 milliradian below, the error of the magnification factor for earth waves of 20-seconds period does not exceed about 2 per cent, or for earth waves of 30-seconds period about 3 per cent. These limits are now in use at Kew.

In addition to the variation due to change in the equilibrium position of the pendulum there is the fact that the oscillations of large amplitude about any mean position are not simple harmonic. While we cannot avoid this last consequence, except by incorporating additional springs, we can improve the accuracy of measurements of small amplitudes by keeping the drift of the pendulum within narrower limits.

§ 4—ADJUSTMENT OF PENDULUM ZERO

The usual cause of the drift of the pendulum from its normal position is the change in the elastic constant of the spring due to change of temperature. The temperature effect in the case of the steel spring as ordinarily used is very great. Thus for the spring originally fitted to the seismograph at Kew the elastic constant β is $21\cdot2 \times 10^5$ gm./cm, and the temperature coefficient of β is about $-2\cdot2 \times 10^4$ per degree C. The steel spring[4] has recently been replaced by one made of elinvar alloy, of which the temperature coefficient of the elastic constant is only about one-tenth of that of the original spring. This is a decided improvement since large drifts occur much less frequently and the pendulum requires less adjustment.

[4] F. J. Scrase; *London Inst. Physics, J. Sci. Instr.* **6**, No. 12, 1929, p. 385.

On referring back to the formulæ for the period of the pendulum it will be seen that a change in β affects the period. We did not take account of this before, since we assumed β was constant. This effect, however, is small compared with the variation in period due to displacement but it persists after the pendulum has been readjusted to its normal position provided the temperature remains different from the original temperature.

Now there are two ways of correcting the drift of the pendulum due to the effect of temperature on the elastic constant of the spring. The first is by altering the moment of the moving system and the second by altering the length of the spring. Some calculations show that it is better to adopt the former method since it causes less alteration to the working period.

The turning moment is adjusted by moving a small weight along a screw thread attached to the pendulum frame. If the whole of this adjustment has been utilised then the main mass of the pendulum can be moved. To take the case of the Kew instrument, a rise of 1°C. causes a reduction by 0·022 per cent in β, the elastic constant of the steel spring. In order to restore the balance in the normal position the small weight (100 gm.), which is about 50 cm. from the turning axis must be moved one cm. To find the effect on the period in the normal position we can use Galitzin's formula (5) which can be taken as valid in this position. The rise in temperature and the necessary adjustment affect β, P_0 and I. P_0 is affected in the same ratio as β since the length of the spring L_0 is kept constant and, assuming that the unstretched length is unchanged, the extension is unaltered. The change in I is $m\ (r_1^2-r_2^2)$. i.e. 100 (50^2-49^2) or 10^4 gm. cm.^{2} and since I is about 156×10^5 gm. cm.^{2} the percentage decrease is 0·06. Thus the net effect on n^2 $(=4\ \pi^2/T^2)$ is an increase of about 0·04 per cent. The period T therefore is decreased by about 0·02 per cent for 1°C. rise in temperature. So that even for a change of 15°C. (the annual range of temperature in the seismograph room at Kew) the alteration in the working period due to this method of maintaining the pendulum near its normal position is negligible compared with the variation with the deviation from normal. Moreover, if necessary, the mean position of the adjustable weight could be so arranged that the change in I would counterbalance those of β and P_0. For the relative change of β or P_0 is equal to the relative change of the moment which is $mg\ (r_1-r_2)/Mgr_0$ and this can be made equal to $m\ (r_1^2-r_2^2)/I$, m being the mass of the small weight and $\frac{1}{2}(r_1+r_2)$ its mean distance. In our case equality would occur if the adjustable weight were fitted at about 20 cm. instead of 50 cm. from the turning axis.

The second method of adjustment can be examined in a similar manner. In this case we keep P_0, I and the turning moment constant but alter L_0 in order to counteract the change in β. A decrease of 0·02 per cent in β (corresponding to a rise of 1°C.) necessitates an increase in L_0 of half this amount to support the same load in the case of the Kew instrument for if $P_0=\beta\ (L_0-l_0)$, l_0 being the unstretched length of the spring, then $\frac{\delta L_0}{L_0}=-\frac{P_0}{\beta L_0}\ \frac{\delta\beta}{\beta}$. Using the Galitzin formula again we find that these changes cause an increase in the period of 0·75 per cent for a rise of 1°C. The annual range of temperature therefore may cause a change of 11 per cent in the working period and this effect is additional to the variation of the period with deviation from the normal. It is clear then that this method of adjustment is not to be recommended.

§ 5—Summary

The single-spring system employed in the Galitzin vertical seismograph involves a variation in the period of the pendulum with deviation from the normal position. The variation is much more pronounced at high periods than at low periods. It can only be eliminated by fitting additional springs.

The relative change in magnification is less than that of the pendulum period for earth waves having periods less than double that of the pendulum. Since the variations are symmetrical about the normal equilibrium position the limit for the drift of the pendulum should be less when the deviation is below normal than when it is above normal.

In correcting the drift of the pendulum it is better to alter the turning moment (by moving the adjustable weight or, when necessary, the main weight) than to alter the length of the spring. The latter method causes an appreciable change in the period at the normal equilibrium position, and this effect is in addition to the change in period with deviation.

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PRACTICAL EXAMPLES OF POLAR-FRONT ANALYSIS OVER THE BRITISH ISLES IN 1925-6

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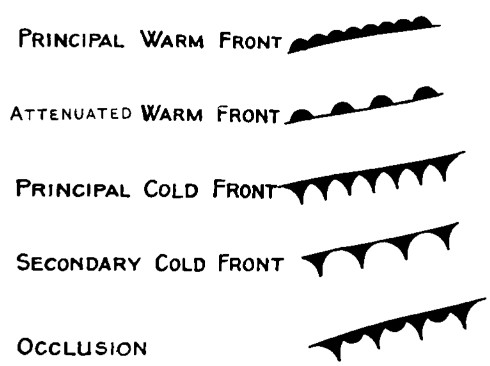
PRACTICAL EXAMPLES OF POLAR-FRONT ANALYSIS OVER THE BRITISH ISLES IN 1925-6

INTRODUCTION

The following three weather sketches are intended to show the use of polar-front method on actual weather situations. Attempts are made to understand some of the physical processes responsible for the development of events observed on weather maps and autographic records. The explanations are of course not infallible and may be modified by continued research with more powerful technical aids. One such modification of the original theories is for the first time being introduced through this publication, namely : the explanation of fronts becoming diffuse as a result of adiabatic heating by descending motion on the cold side, and fronts becoming sharp by an ascending motion in the air of the zone of transition.

For the convenience of the reader the maps are enumerated with a letter, A, B or C, referring to each one of the series, and with numbers in chronological order within each series. The photographs of autographic records have the same system of letters. Their numbers within each series are in the order of first occurrence in the text. The symbols on the maps are the following :—



Hatching indicates the areas where rain is falling at the time of observation.

The maps are only of limited extent and it is therefore advisable to consult, for instance, the " International Section " of the *Daily Weather Report.*

A. MARCH 30 TO APRIL 1, 1925

On the 30th of March, 1925, a high pressure system extended from the region of Madeira to Central Europe. The British Isles were in the mild subtropical current north-west of the high. Over the Atlantic, colder air of polar origin was pushing southwards and eastwards. This colder air reached Stornoway during the forenoon of the 30th (drop of temperature from 47°F. at 7h. to 42°F. at 13h). According to the autographic records, Lerwick was reached by the cold air between 15h. and 16h. Aberdeen at 21h. 25m., Leuchars and Renfrew just before midnight between the 30th and 31st. Also Malin Head came into the cold current between 18h. on the 30th and 1h. on the 31st, the wind changing from SW. to N. and the temperature dropping from 48° to 39°F. In the latter part of the night, Blacksod got the change from S.

wind with 50° to N. wind with 41°, so that on the morning of the 31st (map A 1), we may trace the polar front running south of Blacksod, Malin Head, Renfrew and Edinburgh, but north of Birr Castle, Donaghadee and Eskdalemuir. The lowest pressure was near Blacksod, so that the cold air could not push farther south from Scotland to England. Probably there was even a counter attack going on from the side of the warm air, east of the centre of low pressure, but it did not reach any of the synoptic stations north of the front. During the 31st, the low off Blacksod moved east-north-east to the North Sea and reached Norway on the 1st of April. A trough extending southwards from the centre passed meanwhile over Ireland and England. As it will be seen the passage of the trough line also marked the arrival of the cold air. Some selected autographic records will show the structure of the cold front which accompanied the trough in the various stages of its development.

The Valentia autographic records (Record A 1) show the passage of the cold front on the morning of the 31st at 4h. 45m. The sudden drop of temperature is not big, only a little more than 2°F., but it is followed by a gradual fall of about the same amount. The maximum temperature of the 31st reached only 48° (4·6 hours sunshine), whereas the 30th, when the warm current reigned, had a maximum of 53° (4·1 hours of sunshine). 5°F. can therefore be considered as the true temperature difference, between the interiors of the cold and warm currents at the surface. Higher up the difference was probably somewhat greater, because the cold air was in the state of being heated from below, which usually involves a steep lapse rate. The warm current had on the other hand, at any rate in south-east England, a small lapse rate, as can be seen from the Duxford ascents of the 31st.

The anemogram at Valentia shows a fairly steady wind direction, S. by W., up to 4h. 45m., then a somewhat irregular veer in the course of half an hour, to a little beyond SW. Later on a gradual veer continued until the wind had become northerly in the evening. Also the wind force showed a decided change at 4h. 45m. Up to then, the velocity was approximately constant about 12 m.p.h., but from 4h. 45m. to 5h. 30m. it dropped down to about 6 m.p.h.

Since the thermogram definitely fixes the arrival of the cold air at 4h. 45m., we have the result :—

(1) The warm current had steady direction and approximately constant speed just up to the cold front itself.

(2) The change of wind direction and wind velocity was going on within the foremost part of the cold wedge.

In this case it happened that the warm current had a greater average velocity than the cold. This is of course, not a general rule, it depends on the orientation of the cold front relatively to the isobars of the warm and cold currents. If the front is in the middle of the angle formed between the two sets of isobars (Fig. 1 b.), the horizontal pressure gradients on both sides become equal, which implies that the wind speeds are approximately the same in both currents. In our case the front direction was nearer to the direction of the isobars on the warm side (Fig. 1 a.), and the gradient must therefore have been stronger on the warm side. In the other case (Fig. 1 c.), when the front direction is nearer to the direction of

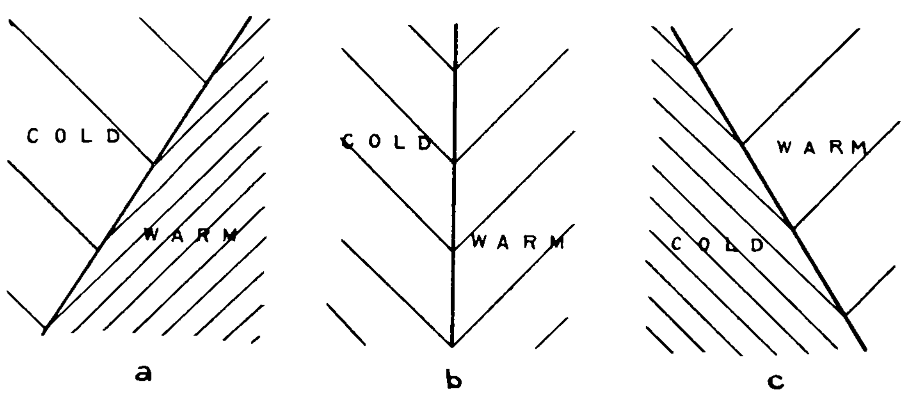


FIG. 1.—Orientation of cold front with reference to the isobars of the warm and cold currents.

isobars on the cold side, the cold current will be stronger than the warm. These purely geometrical relationships, which can easily be extended also to warm fronts, decide whether the wind speed shall increase or decrease at the passage of the front.

The typical gust at the arrival of the cold air does not appear on the Valentia anemogram, for the obvious reason that the wind was too strong before. The distribution of wind speed in the cold wedge was nevertheless normal—strongest at the foremost part and decreasing from there backwards. The rain at Valentia started 20 minutes before the cold front, but did not become heavy before 5h., that is 15 minutes after the cold air arrived at the surface. The rain then continued with decreasing intensity till about 7h. 30m. The greatest part of the rain must therefore have originated from the warm air while being lifted by the cold wedge. Also the barogram shows the cold front at 4h. 45m. The fall of pressure is at that moment suddenly replaced by a slow rise. This corner in the barogram entitles us to make a corresponding corner in the isobars where they pass the trough line.

The characteristic form of the barogram enables us to fix the time of the passage of the cold front at Roche's Point, 9h. 30m. and at Belfast, 12h. The anemogram, (only speed) at Weaver Point, close to Roche's Point, shows at 9h. 30m. the same characteristic decrease of wind force as that of Valentia.

The next synoptic station to be reached was Holyhead, the autographic records of which are given on Record A 2.

On the Holyhead anemogram the veer does not start suddenly. Already at 17h. there is a very slight veer, then a quicker one at 17h. 50m. to 18h. After some backing and renewed veer there is a sudden veer at 20h. 10m. marking the arrival of the NW. current. The thermogram shows the sudden drop of temperature at 20h. 10m. simultaneously with the last and most conspicuous veer. The temperature changes before then must have been quite minute, as the greatest part of the fall in the afternoon must be ascribed to the diurnal period.

The surprising feature is, however, that the rain is falling during the first slow veer of the wind, from 17h. 25m. to 18h. 50m. The sudden veer at 20h. 10., which also in the thermogram seems to be the most important part of the cold front, is accompanied by no rain whatever.

The results from Holyhead are verified by the other stations farther east. As an example the Andover autographics are reproduced (Record A 3). They show differences from the Holyhead ones in detail, but the two veers appear quite clearly. In the thermogram the first veer corresponds to a gradual fall, the second to a sudden fall of temperature. The entire drop of temperature appears small, because insolation starts soon after the second veer. The rain starts and is fairly strong during the first veer. At the time of the second veer the last slight rainfall has just stopped. The Scilly anemogram (Record A 4), shows the two veers farther apart, 23h. 35m. and 4h. 40m, but both well marked.

The Holyhead type of record is found on most of the stations farther east. Birmingham and Cranwell (not reproduced) have a slow veer and slow fall of temperature during the rain. A sudden veer and corresponding sudden fall of temperature comes afterwards without any clear connection with the rain strip. At Sealand (Record A 5), the first veer is accompanied by a more distinct fall of temperature, probably because that veer brought a sudden termination of the foehn from the Welsh mountains.

Southport, Fleetwood and Spurn Head (anemographs only) show two separate veers of a kind, similar to that in Holyhead—the first gradual, the second more sudden. Taking Spurn Head (Record A 6) as an example, the first cold front is represented by the gradual veer stopping at 3h. 15m., whereas the second cold front gives the much sharper veer at about 4h. (There is a variable time correction to be applied to the Spurn Head anemogram, therefore the times put on the map are a little different from those in the text.)

On maps A 6 and A 7, the times at which the two veers occurred at the various stations are shown. The first figures indicate the start of the veer, the figures after the hyphen indicate the end of the veer. The isochrones are drawn for each two hours, their breadth indicates the breadth of the zone of veer. In the case of the first veer (map A 6), the greatest breadth is found in the region Cranwell—Spurn Head. Farther south it decreases and at Scilly, Croydon, Felixstowe and Lympne, the duration of the veer is only a few minutes.

The Spurn Head anemogram (Record A 6) shows further veers at 5h. 25m. and 7h. The probable origin of these secondary cold fronts is to be found on the Eskdalemuir diagram (Record A 7). The first cold front at 17h. 20m. brings the wind round from SSW. to WSW., whereafter a period of slight SW follows. At 20h. 35m. another cold front brings a sudden veer to N. and an equally sudden increase of wind speed. Since Eskdalemuir is far from the other stations with self-recording instruments there are several possibilities of connecting up the passages of the fronts at Eskdalemuir with those farther south. The solution given on the map for 18h. on the 31st, appears however the most likely one. The first cold front is assumed to be single just as it was when passing Valentia, and the second cold front at Eskdalemuir would then really be a third cold front formed behind the centre. The shape of the cyclone on the 13h. map (map A 2), already suggests a cold front extending west-south-west through north Ireland. The cold air has completed the occlusion nearest to the centre, but there is still sufficient contrast of temperature between the cold NE. current and the air which has curved round and now moves from SW. In principle this cold front is really part of an occlusion, and is therefore indicated as such on the map.

The further movement of this third cold front can be followed on the synoptic maps and the map of isochrones (map A 8). At Spurn Head it arrives as the already mentioned couple of fronts, at Cranwell and Gorleston, it is more like one broad front, and at Felixstowe (Record A 8), it is again as sharp as it was at Eskdalemuir and has a very abrupt fall of temperature.

If this diagnosis is right, the third cold front offers an interesting example of a sharp slow-moving front being transformed to a broad (or double) front while accelerating, and again becoming sharp when slowing down.

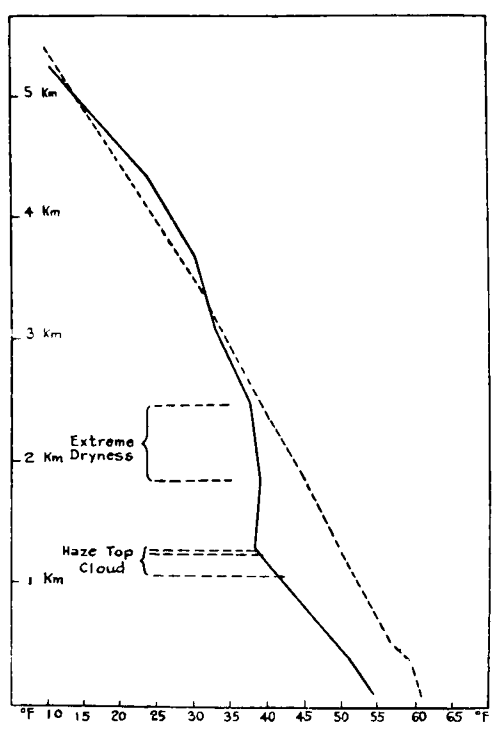


FIG. 2.—Lapse-lines before and after the passage of a line-squall.
...............observations taken in an ascent in front of the squall.
————observations taken in an ascent after the passage of the squall.

On the stations farther west, Fleetwood, Southport, Sealand and Birmingham there are only slight indications of the third cold front, and farther west and south no trace at all. This is quite natural when considering the way this front was formed —as the back-bent top of an occlusion.

SUGGESTED EXPLANATION OF THE DOUBLE COLD FRONTS

The change from the single cold front at Valentia to the double cold front at Holyhead, Scilly, Andover and stations farther east, and likewise the change from a single cold front at Eskdalemuir to double at Spurn Head, requires explanation. An attempt is made here to see whether the subsidence in the cold wedge may account for these phenomena.

The subsidence in the air behind a cold front has been revealed by several aerological ascents. A good description of the phenomenon has been given by M. A. Giblett in " Upper air conditions after a line squall," *Nature* 112, 1923, p. 863. In that case two aeroplane ascents were made, one immediately before and another some hours after the cold front. The two lapse-lines (temperature-height curve) are reproduced from Giblett's paper in Fig. 2. The temperature fell during the time between the two ascents in all heights below 3 km. The lowest part of the cold air up to 1·3 km. was in turbulent equilibrium with a fairly steep lapse rate. From 1·3 to 3 km., there was an almost isothermal layer with extreme dryness, which shows that this air must have descended from a considerable height. Moreover, the fact that the temperature in the dry layer was lower than that in the warm air, at the same level, shows that the descended air must have been derived exclusively from the polar air. A descending part of the warm current would naturally be warmer than those parts of the same current which have not descended.

Giblett's investigation thus proves (see Fig. 3) that the upper dry part of the cold wedge was descending (or at any rate had descended) and thereby had a temperature higher than that of the non-descending cold air at the same level, but colder than the warm air at the same level.

If the case described by Giblett is a frequent one (and there is much evidence for that especially brought forward by the Lindenburg school) it is only natural that one should occasionally find traces of the downward-sliding cold air also at the ground. On a thermogram that would appear as a dividing of the cold front into two. (See

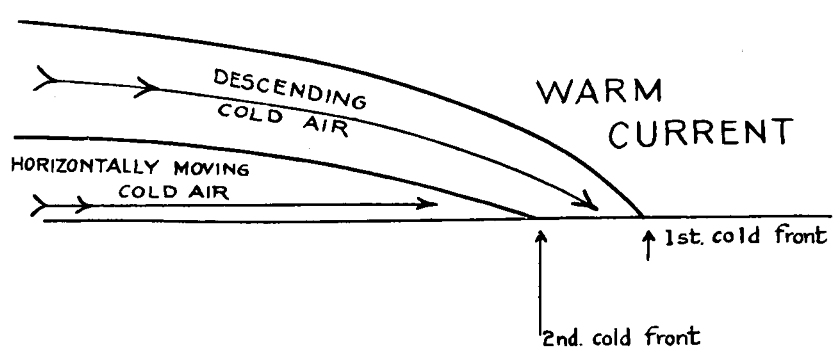


FIG. 3.—Diagrammatic representation of a double cold front.

Fig. 3). The air between the two cold fronts would have a temperature between that of the cold and warm currents. The greater the height from which the air had descended, the warmer it would be and the smaller the temperature contrast at the original cold front. The temperature contrast may eventually be completely transferred to the second cold front which separates the descended cold air from the horizontally-moving main cold current. On a hygrogram the air between the two cold fronts ought to appear drier than the air on both sides. This is shown in the case described by R. S. Read in the *Quarterly Journal of the Royal Meteorological Society*, October, 1925, p. 416, where the same dividing up of the cold front was found. It must, however, not be expected that dry air will always be found, because the air which has descended near the cold front is constantly travelling in the cold-front rain. It is therefore quite likely that the same air may have been heated by descending but yet has been kept wet by the rain. This seems to have been so in the case considered, so that the humidity registrations can neither prove nor disprove the assumed descending motion down to the ground behind the cold front.

On an anemogram both the cold fronts ought to appear as separate veers, this being a necessary effect of the close connection between temperature, pressure, and wind.

The simpler case with only one cold front can be represented schematically by Fig. 4. The vertical distance between unit isobaric surfaces must be greater on the warm side than on the cold, hence the refraction of the isobaric surfaces where they pass through the cold-front surface, hence also the sudden change of wind direction and force at the same boundary surface.

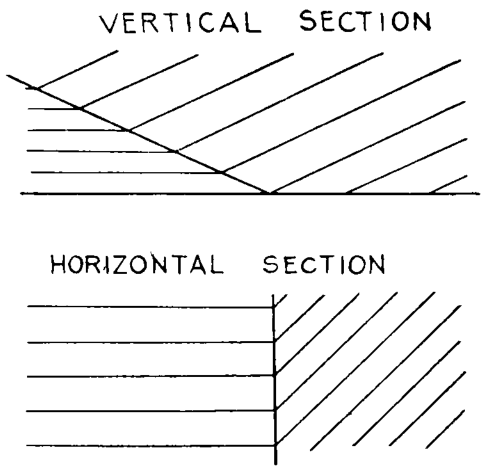


FIG. 4.—Sections across a cold front.

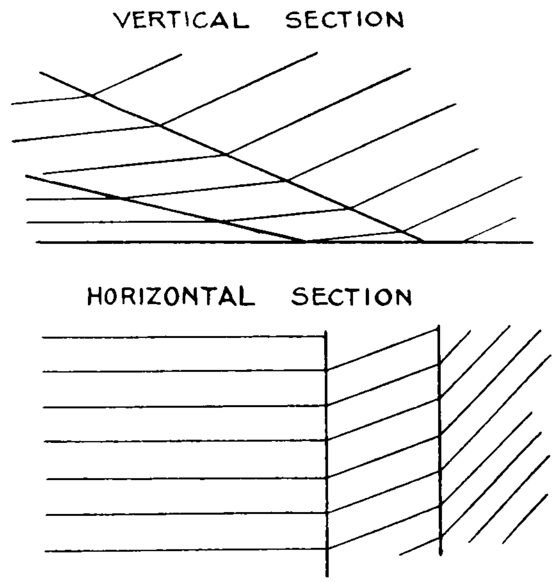


FIG. 5.—Sections across a double cold front.

If we now introduce a slab of intermediate temperature between the cold and warm currents (Fig. 5) the isobaric surfaces, will be refracted at both surfaces of discontinuity, and in the horizontal, the isobars will show the corresponding changes in direction when passing each one of the two fronts. The nearer the temperature of the intermediate air approaches that of the warm air, the smaller the refraction of isobars and the slighter the veer of wind at the original cold front. The wind contrast, like the temperature contrast, may therefore be transferred to the second cold front.

The complete knowledge of the horizontal field of motion at the cold front would enable us to use the equation of continuity for constructing the field of vertical motion in the layer nearest the ground. That can be done on any synoptic chart with a sufficient number of well observed winds, but even with the densest networks in use much detail gets lost especially at the fronts where the change from place to place is so great. We therefore get a better analysis of the structure of the front when using the particular anemograms at stations where the front has passed. This indirect method is not quite exact because it assumes :—

(1) That the structure of the front does not change materially during the passage, so that the winds as a function of time on the anemogram can be taken as representing winds as function of space in the atmosphere.

(2) That the derivatives of the wind parallel to the front (which cannot be found from the anemogram of one station alone) should be negligible as compared with the derivatives across the front.

Both conditions are likely to be reasonably fulfilled at most well marked and not too slow-moving fronts. Taking this as granted, we may build up the picture of the front as follows. Instead of the time scale on the anemogram we put a scale showing the distance run by the front simply by multiplying the time by the speed of the front perpendicular to its own direction. From this we may plot the winds at any point of a line perpendicularly across the front (Fig. 6).

Assuming that this cross-section of winds is not much different at neighbouring cross-sections to the front, we get the two-dimensional distribution of winds which is the nearest approximation to the real field of motion obtainable from one station only.

For the construction of the vertical velocity component it suffices for our rough purpose to use the simplified form of the equation of continuity: $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$

When placing the y axis along the front the derivative $\frac{\partial v}{\partial y}$ becomes negligible and we may write $\frac{\partial w}{\partial z} = -\frac{\partial u}{\partial x}$

By the aid of this equation we can find the vertical motion in the layers near the ground, positive $\frac{\partial w}{\partial z}$ means upward motion, negative $\frac{\partial w}{\partial z}$ downward motion.

We will apply this method on an ordinary cold front (Fig. 7), where we for simplicity assume the direction of the cold current everywhere perpendicular to the front, and the wind speed in the same current represented by the length of the arrows.

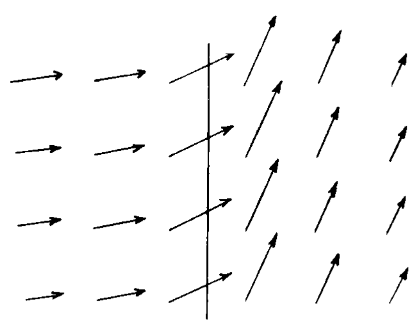


FIG. 6.—Diagram of winds across a cold front.

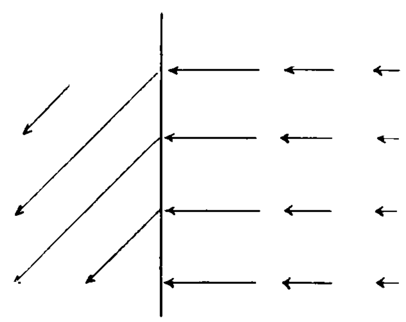


FIG. 7.—Diagram of winds across a cold front.

The vertical motion in the cold air will in this case depend merely on the distribution of wind velocity along the stream lines. We get downward velocity because on one and the same stream line a strong wind is followed by a lighter one. This will be the general case behind the gust which is so frequently found at the first arrival of the cold air (the case also included where the "gust" has a lighter wind than the warm current just before).

In the more general case where the stream lines of the cold air are not perpendicular to the front and where the veer may extend over some period of time, the gust is in itself not sufficient evidence for downward motion behind. After the decomposition in u and v components the point of strongest gust on the anemogram is not necessarily the point of the greatest u, and the region of downward motion $\left(\frac{\partial u}{\partial x} = +, \frac{\partial w}{\partial z} = -\right)$ may start farther behind the cold front. In most cases, however, the point of strongest gust is also the point of greatest u, so that the downward motion starts immediately at the cold-air gust on the anemogram.

The first cold front at Sealand (Record A 5) shows rather well the descending motion on the cold side. The orientation of the front was about north-east to south-west, so that the u component perpendicular to that direction (in this case NW. component) had its maximum at about 21h. 50m. and decreased from there to a minimum at about 22h. 40m. During these 50 minutes $\frac{\partial u}{\partial x}$ was positive and therefore $\frac{\partial w}{\partial z}$ negative; in other words there was downward motion in a zone commencing just behind the cold front. Since the front moved with a speed of 35 miles per hour the breadth of the zone of downward motion must have been about 30 miles.

The second cold front on the same diagram has not so much downward motion behind. There is a cold-front gust at 23h. 15m. but at that moment the wind has not completed the cold-front veer. At 23h. 30m., when the veer has finished, the wind speed is less than at 23h. 15m., but the u component perpendicular to the front is practically as big as it was at the time of strongest gust, 23h. 15m. Also in the subsequent hours u keeps almost constant so that the vertical motion must be insignificant in the current following the second cold front.

Such a couple of cold fronts—the first with downward motion behind, the second without—is rather often found. At Scilly (Record A 4) the first cold front at 23h. 30m. is followed by downward motion lasting $1\frac{1}{2}$ hours (breadth of zone again 30 miles) whereas the second cold front at 4h. 40m. has no appreciable downward motion behind. The same sort of couple is found at Spurn Head, the first cold front at 5h. 25m. is followed by downward motion, the one at 7h. is not.

The structure of the wind field in these and several more cases brings evidence for a zone of descending air just behind the first cold front. The descending air is colder than the warm current but warmer than the main cold current which arrives after a second cold front. This in conjunction with the previously mentioned results from aerology makes the scheme of Fig 3, the most likely structure of a cold front which has descending air in the foremost and uppermost part of the cold wedge. Since the vertical velocity must be zero at the ground, the only way to bring air particles from the free atmosphere down to the level of the instruments of ordinary observing stations is through turbulence. When we speak of heating at the ground as a consequence of subsidence in the free atmosphere, we must imagine the turbulence to be the intervening link which transports the heat down to the very bottom of the atmosphere.

Although most of the changes occurring with the cold-front system while moving from Valentia to Holyhead are accounted for in this manner, there has been given no satisfactory reason why the boundary between sinking cold air and horozontally-moving cold air should necessarily develop into such a sharp surface of discontinuity. One might just as well have expected a gradual transition. As a matter of fact the latter case is also often found and will be referred to in the other notes. It is difficult to tell what are the necessary conditions for the creation of a sharp surface of subsidence and a corresponding sharp second cold front. Perhaps it is the combined effect of sinking in the layer above, and turbulent up and down currents in the layer below the surface of subsidence. Once the surface has been formed the difference in the horizontal advection above and below may also help to keep up the existing discontinuity.

It may be of interest to consider what ought to happen if the sinking air becomes almost as warm as the adjacent warm current. While the difference in temperature decreases, the angle of inclination which gives equilibrium for the cold-front surface increases. When the difference decreases towards zero the inclination increases towards the vertical. We must therefore admit the possibility that a cold front surface becomes vertical at the places where the temperature contrast vanishes. It is true that where the temperature contrast vanishes there is no longer a thermal boundary surface. But other elements as humidity and wind (horizontal and vertical) are not likely to lose their discontinuity exactly at the same moment as the temperature. Also for temperature the perfect vanishing of the contrast is only a transitory state. A little more subsiding continuing by inertia would reverse the sign of the original temperature contrast and would let the boundary surface pass through the vertical state and assume the inclination of a warm-front surface.

This may appear rather speculative but a fairly frequent case of the kind may easily be imagined. Suppose that we have to begin with a cold front where the cold wedge in every level is colder than the adjacent warm current (Fig. 8 a). The warm current, however, will have a cooled surface layer of, say, 1 kilometre thickness (for instance as shown by Duxford on the 31st of March). The horizontal temperature

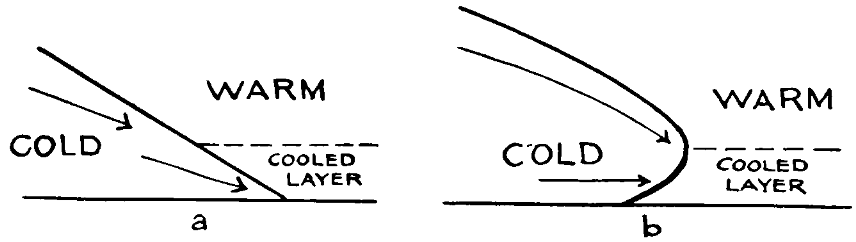


FIG. 8.—Diagram illustrating the degeneration of a cold front.

difference across the cold front will then be smaller near the ground than higher up. Let us now assume that the downwards sliding motion starts on the cold side in all levels. Provided that the cold wedge has a uniform lapse-rate smaller than the dry adiabatic, the downwards sliding will produce a uniform rise in temperature at all levels. The temperature contrast, thus being diminished by the same amount at all levels, will first vanish in the bottom layers where it was from the beginning small. The subsiding, which is still favoured by the remaining temperature contrast in the upper layers, will not stop immediately the bottom layers have had enough of it, and that will bring down air from the cold wedge which will be warmer than the cooled surface layer of the warm current. The boundary surface in that level will then have to pass through the vertical state to the forwards-tilting position of Fig. 8 b.

Such a cold front will at the surface bring a slight rise of temperature, followed later by a fall as soon as the zone of subsiding air has passed by. At a sufficiently high mountain station it would appear as a regular cold front, only more or less attenuated by subsiding on the cold side.

A cold front which has arrived in this stage of degeneration will have no sharp veer, but a zone of gradual veer. That is what we find represented where the first cold front passes Holyhead, Birmingham, Cranwell and Spurn Head.

The *rise* of temperature at the arrival of a " cold front " is not shown on any of the diagrams mentioned, but the case is quite frequent, especially in winter when the maritime polar air meets the continental air. The former may be the warmer at the ground, but the difference of temperature is very soon reversed higher up, so that we are entitled to speak of a *cold front* which is disguised by the local surface conditions.

It is a question of some importance to know when a cold front is going to degenerate in the above-mentioned way, and when it is going to retain sharpness. The full mathematical theory for these phenomena cannot yet be given, but some qualitative relationships may be indicated.

When the downward current reaches the ground it must spread forward over the region occupied by the warm air. A boundary surface which was at rest will thus start moving as a cold front as soon as the downward current reaches the ground. In the case when the cold wedge is already advancing, the start of the downward current would mean an increase of the velocity of propagation. Generally speaking the subsidence in the cold wedge should in the first instance lead to an acceleration of the cold front, and the persistence of subsidence will maintain a high speed of the front ; most fast-moving cold fronts should therefore have had so much subsidence in the cold wedge that the discontinuity at the front ought to be replaced by a zone of gradual transition (both in temperature and wind). The term " frontolysis," has been introduced by Dr. Bergeron for this transformation, from discontinuity to continuity.

For the diffuse cold front resulting from frontolysis to be transformed into a sharp one again, it is necessary for the air in the transitional zone to escape. Genuine cold and warm currents of air are then brought close to one another and the sharp front is re-established (" frontogenesis " in the terminology of Dr. Bergeron). Frontogenesis may also start in situations where no pre-existing diffuse front can be traced. It is sufficient for the field of motion to act in such a way that the isotherms aproach one another ; the final result is then a front. Fronts in the state of frontogenesis are usually slow-moving ones.

The second cold front is in this respect an exception as it was fast moving, but nevertheless sharp. This is, however, reasonable because the second cold front was formed within the moving cold current and was never accelerated afterwards. The isochrones of the third cold front furthermore show the change from sharp to broad front while accelerating, and the reverse while slowing down.

This knowledge of the behaviour of accelerated and retarding cold fronts adds new features to the picture of the " ideal cyclone."

Taking first the case of a cyclone at the moment of its birth, (Fig 9).

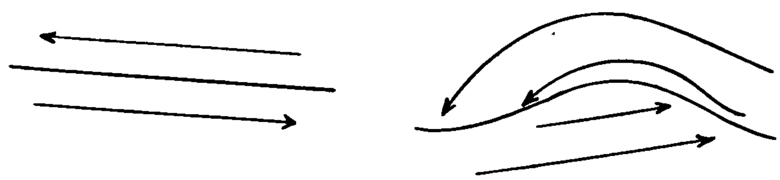


FIG. 9.—Birth of a cyclone.

The front is then to begin with stationary, with both the warm and cold currents flowing parallel to their mutual boundary. The part of the stationary front which becomes a cold front, is therefore from the first moment an accelerated cold front. While the " cyclone wave " moves east along the front, the cold air particles just north of the centre have an instantaneous motion from the E., which changes for the same particle to NE. and N. wind, when the centre has passed. This means acceleration of cold air particles perpendicularly to the front towards the warm region. The cold front immediately behind the centre is therefore an accelerated one, also after the cyclone wave has attained a finite amplitude, and should show the phenomena of downward motion and adiabatic heating in the foremost part of the cold wedge. During the further development of the cyclone the acceleration of the cold front goes on simultaneously with a further smoothing out of the discontinuity, so that as a rule in a fully developed cyclone the first cold front is fast moving but ill defined.

If a second cold front is formed behind the subsiding part of the cold current, it is usually more sharply defined than the first cold front. The precipitation is however missing, unless the subsiding air has had opportunity to pick up enough moisture after its descent to the ground. It is possible that, just as the original cold front has divided into two, one or both fronts may again subdivide. That case, however, seems to be rather rare and has not come into evidence in the examined situations.

More frequent is the case where the subsiding in the cold wedge creates a field of linearly decreasing temperature from the cold front to the interior of the cold current. This state would result from a maximum downward displacement of particles near the cold front, and gradually smaller downward displacement with increasing distance from the front. A priori that is perhaps more likely than the subdivision of the original cold front into separate small ones. It is not yet clear what conditions determine whether a cold front is to degenerate in the discontinuous or the continuous way.

Another very frequent type of cold fronts is that of the third cold front (maps A 2—A 5 occlusion) in the case discussed above. It is formed according to the scheme in Fig. 10.

The cold air near the centre has only a short distance to travel in order to complete the occlusion of the top part of the warm sector. It therefore often happens that this part of the warm sector disappears earlier than the rest. At the same time the lowest pressure will have a tendency to move to the north end of the remaining warm sector (Fig. 10 b and c). Once that has taken place the occlusion moves down behind the centre, as a secondary cold front.

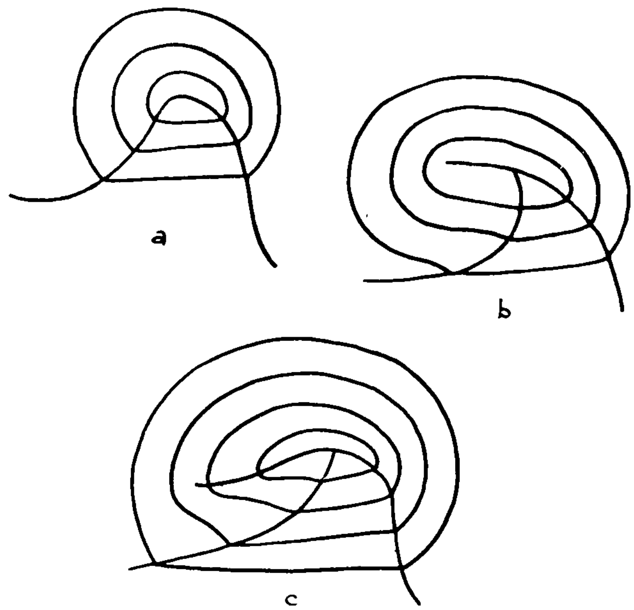


FIG. 10.—Occlusion as a secondary cold front.

This secondary cold front, which is really the top of the occlusion bent back, will have to be of limited length. In the case discussed, it was well pronounced only at Eskdalemuir and on the east coast stations down to Felixstowe, hardly visible at Sealand and not to be found farther west and south. No rain occurred with this cold front, but that must rather be considered as an exception. The rain might in the general case be quite abundant and long lasting in the part nearest the centre, but will naturally decrease towards the outer end of the cold front (see C, January 22–23, 1926).

B. FEBRUARY 10–11, 1925.

The weather situation the 10th and 11th of February, 1925, has been chosen especially to demonstrate the case in which a sharp front is formed where there was originally only a diffuse one.*

Valentia (Record B 1) shows the arrival of the cold air between 11h. and 12h. The fall of temperature is irregular and extends over more than 12 hours. (In cases like this we may agree to place the cold front at the beginning of the fall of temperature thus taking as a working hypothesis that all the air in the transitional zone originates from the cold supply. This rule has been followed in the drawing of maps. The rain lasts about 18 hours, which indicates a very broad cold-front rain. The barogram which gives a slight indication of the front between 11h. and 12h. deviates from the normal type in that a negative "surge" is superimposed. (The wind record is unfortunately defective just in the region of the front. There was evidently a veer although probably not a sharp one).

At Eskdalemuir (Record B 2) conditions were similar, with a considerable fall of temperature irregularly distributed over about 10 hours. Only the barogram shows distinctly at what time the cold front passed, namely at 14h. on the 10th. There is one noteworthy singularity in the thermogram and in the wind force at 19h.

At Holyhead (Record B 3) there is already more sign of discontinuity at 1h. on the 11th, there is a conspicuous veer coinciding with the steepest part of the fall of temperature. The cold front in the sense defined above is, however, at Holyhead already by 21h. of the 10th. At that time the fall of temperature starts and the rain begins. The quick fall of temperature at 1h. occurs in the middle of the rain ; it

* The same case has been treated from a slightly different point of view by N. K. Johnson in an interesting note in the *Meteorological Magazine*, April, 1925, p. 53. Moreover the 11th of February, 1925, is of interest because of the upper air data available. A balloon released from Sealand that day, showed a relatively high tropopause at the spot where a cyclone was being formed.

is a heavier downpour just then, but that is only a small episode in the non-stop rain from 21h. on the 10th to 6h. 20m. on the 11th. Also Southport (Record B 4) shows the same type—slight fall of temperature at 20h. 30m. where the rain starts, followed by a more marked fall at 3h. 45m. during the rain. Andover (Record B 5) also shows the same type but the sudden fall has grown immensely and there is only a little left of the gradual fall before it. Finally, at Croydon (Record B 6), where we must fix the beginning of the sudden fall at 22h. 45m., there are only small irregularities before the big drop of temperature, and the pre-frontal rain which was still to be found at Andover has practically disappeared.

Combining these observational facts, we may infer what happened.

The cold front arrived with a broad zone of transitional air through which there is on the thermogram an approximately linear fall of temperature (Fig. 11a).

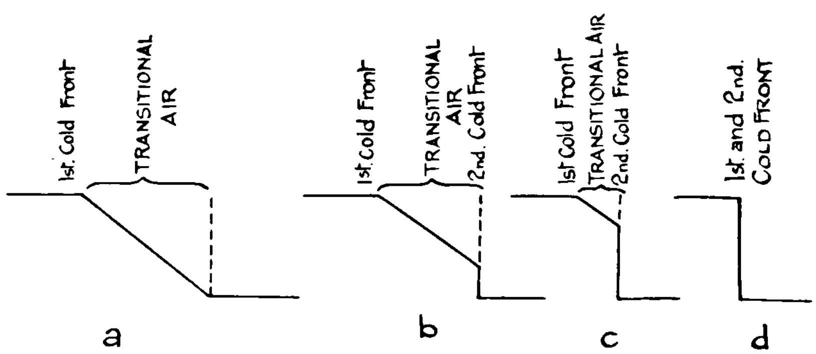


FIG. 11.—Types of thermograms corresponding with diffuse and sharp fronts.

Then the homogeneous part of the cold current pushed under the transitional air, which was forced to ascend. Once a certain part of the transitional air has ascended, a thermogram of the type in Fig. 11b will result. The cold current which is penetrating into the transitional air has met gradually warmer air and a temperature discontinuity now marks how far it has penetrated. If this process continues, there will gradually be less left of the transitional air at the ground (type of Fig. 11c), and the final effect may be that the whole change of temperature is concentrated at one point of the thermogram (type of Fig. 11d). (Hereunder we have assumed that the cold air, which pushes away the transitional air, itself retains constant temperature. This will of course only be fulfilled under special conditions and is not completely fulfilled in our case as we find a good deal of gradual fall after the sudden fall of temperature. It was probably again the adiabatic process which heated the foremost part of the cold wedge).

Fig. 11 exemplifies the essential part of the process of front formation. A diffuse front, or in other words a zone of gradual transition in temperature between a homogeneous warm and a homogeneous cold mass, becomes a sharp front if the intermediate air escapes upwards. This escaping upwards seems to start where the cold air undermines the transitional air. This new " cold front " penetrates across the zone of transition, so that cold and warm air finally come into direct contact with each other.

The veer of wind at the limit between the warm air and transitional air seems to get lost very soon, at any rate near the ground. Valentia and Eskdalemuir had some veer at that time, but Holyhead and likewise Andover already showed steady wind direction until the limit between the transitional air and the cold air passed by. In these circumstances it is quite natural that a rapid change from a diffuse to a sharp cold front took place. One can easily ascertain that the transitional air, which moved almost parallel to the front, could not escape horizontally from the cold air, which cut in at almost right angles to the same front. Consequently the transitional air had to ascend and let cold and warm air approach each other on the ground.

It might here be appropriate to remind ourselves of the limited validity of these qualitative considerations. In the equation of continuity with which we derived the formula for the vertical component of the wind in the neighbourhood of fronts, the term $\frac{\partial v}{\partial y}$ was neglected in order to get a formula merely containing quantities which could be read off autographic records at isolated stations. We are just discussing a case where the neglected term $\frac{\partial v}{\partial y}$ is perhaps not negligible, $\frac{\partial v}{\partial y} = 0$, means that when following along the front at any particular moment, the component of motion parallel to the front should be constant (although of course different on either side of the front). If tested that condition would in most cases prove unfulfilled. Taking map B 1 for 13h. of the 10th, one finds on the cold side a greater v, in the region of Edinburgh than at Valentia. To make a rough estimate, we may assume $v = 20$ mi./hr. at Valentia and 40 mi./hr. at Edinburgh. The body of air, 400 miles long, between the two places, thus during its motion becomes 20 miles or 5 per cent longer for every hour. The transitional air which covers a narrow zone along the front is thus dilating by 5 per cent per hour in the direction parallel to the front. If we for the instant abstract from the vertical motion this 5 per cent. dilation parallel to the front would correspond to a 5 per cent. contraction perpendicular to the front. In other words, without any transitional air escaping upwards, the breadth of the zone of transition would decrease at a rate of 5 per cent per hour. The term $\frac{\partial v}{\partial y}$ thus in our case assists in creating a sharp front out of a diffuse one. If starting with a thermogram of the type Fig. 12a characterised by a slow linear fall, one would subsequently get the transformation to the types b and c with a steeper linear fall. The true discontinuity would be reached asymptotically, viz., theoretically after an indefinite period of time. In this respect the thermograms of Fig. 12, differ from those of Fig. 11, where a discontinuity was created by penetrating of the cold air under the transitional air. The shape of the actual thermograms seems to indicate that the process of Fig. 11 after all has been the most important one.

Summing up we may state that the horizontal motion alone would, in the absence of other factors, have increased the temperature gradient across the zone of transition. But the discontinuity of temperature which suddenly appears together with the

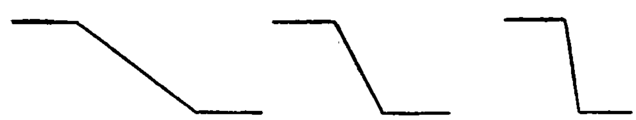


FIG. 12.—Types of thermograms corresponding with diffuse and sharp fronts.

linear fall, is a sign that some transitional air has ascended at that place and made it possible for cold and warm air to come into direct contact with each other. The latter process seems to be the quickest way to create discontinuities.

At all the stations mentioned hitherto the cold front passed once only; Sealand, however (Record B 7) represents an exception in that respect. The cold front arrived at 21h., indicated on the diagram by the beginning of slight rain and by a 2·5° fall of temperature. (Just as in the case first discussed the sudden fall of temperature is largely due to the abnormally high foehn temperature prevailing before. If Sealand had started with the same temperature as Holyhead, the cold front would have produced nothing but a continuous linear fall of temperature). After a second slight rainfall there is a sudden rise of temperature at 1h. The wind has for a while been very light from NE., but the warmer air which arrives at 1h. belongs to the SW current. In other words the cold front, after having passed Sealand, becomes retrograde and passes back as a warm front. After a rainless spell of 5 hours the cold front arrives again a little before 6h., this time accompanied by heavy rain, which becomes moderate continuous rain. The wind veers NW. and decreases.

The described succession of events shows that the cold front, which had already slowed down generally, had a wave-like disturbance travelling along it from SW. to NE. On the morning map of the 11th (map B 3) this disturbance is entered on the map as a little warm-sector cyclone north-east of Sealand. It is interesting to compare the rain records of Sealand and Southport. At the time when Sealand had the rain-free warm sector, it was raining continuously in Southport, because this latter place remained on the cold side during the passage of the small cyclone. The perfect absence of rain in the warm sector is far from being the rule, but it seems to occur rather often at Sealand, where the Welsh hills provide shelter against the lighter sorts of precipitation from SW

During the time when the warm sector passed Sealand, Southport had the afore-mentioned sudden fall of temperature which finished the " zone of transition." This shows that the zone of transition had then become a very narrow strip, a fact which is also indicated by the very sudden fall of temperature when the cold air arrived the second time at Sealand. The zone of transition which was much broader when passing Ireland, had thus contracted during the period of retardation which preceded the quasi-stationary conditions of the 11th of February. We have here one more verification of the rule that retarding cold fronts tend to become gradually sharper.

On the noon map of the 11th (map B 4) another young cyclone appears on the quasi-stationary front over the Bristol Channel. In the evening it has moved to the Midlands and has grown rapidly deeper. This time the warm sector is not entirely free from rain, at any rate we find it over a zone preceding the cold front. As already indicated, this might be the same phenomenon as we had at Valentia, Eskdalemuir and Holyhead. The original cold front may be at the beginning of the rain (gradual fall of temperature at Andover already from 18h.), although strongly masked at the ground, and the following cold front in the trough might be the one which appeared where the cold air pushed under the transitional air. But it may well be that the cold front in the trough is the only cold front, grown sharp because all transitional air has been lifted away. The gradual fall of temperature before it might be partly due to the rain itself and partly due to the time of day. For the pre-frontal rain one would then have to seek another justification which might be the following. The rapid fall of pressure increases the relative humidity of the already rather moist southerly current. This acts, at all levels, simultaneously, and thus prepares the possibility of thick cloud masses. In such a current a slight convergence might suffice for rain formation. No doubt there is always some general convergence towards the centre of a depression. The accelerated winds of the warm sector must transport air across the isobars towards the centre, and since the centre is not filling up, these masses must ascend and be transported away at some higher level.

This kind of pre-frontal cold-front rain, which is certainly very frequent in the British Isles, presents a very difficult but important problem. Upper air observations, close in time and space, would be necessary in order to see what is really happening in the layers from which the rain falls.

The newly-formed cyclone over the Midlands continued north-eastwards, and was next day a deep storm centre off the Norwegian coast. The cold front swept during the night with accelerating speed across south-east England and began to show the usual signs of degeneration met with during acceleration. The extraordinary sharpness observed at Andover (Record B 5) has already got lost a little at Croydon (Record B 6). The wind does not turn so quickly and the temperature does not fall quite so abruptly as at Andover. At Lympne (Record B 8) the entire veer lasts more than an hour, and two separate cold fronts may be distinguished both in wind direction and in temperature. We have here the same phenomenon which was discussed in the first part—a further verification that accelerating cold fronts become diffuse, or occasionally divide into two under the influence of the downward motion in the cold wedge.

The same phenomenon can be observed also on the diagrams for Cranwell (Record B 9) and Spurn Head (Record B 10). Cranwell has one cold front at 22h. 15m. and already a slight indication of a second one in the trace of wind direction just before 23h. At Spurn Head the second front at 23h. 50m. is already quite distinct and there are well defined relationships between direction and velocity variations. The first front is characterised by a quick decrease of speed which is indicative of descending motion in the foremost part of the cold wedge. The second one has constant speed of wind in the nearest region after the veer—in other words, no descending motion.

It is of interest to note that the cold-front couple does not necessarily occur all along one and the same cold front. In Felixstowe and Gorleston (not reproduced) there was instead a continuous half-hour veer. There must have been descending motion of a kind which gives continuous distribution of temperature and therefore also a continuous veer of wind instead of two separate veers.

C. JANUARY 22–23, 1926.

The series 22–23 of January, 1926, presents some typical events in the south-westerly type.

After a spell of cold weather, warm Atlantic air pushed in from WSW., climbed on the wedge of retreating cold air and produced warm-front precipitation. On the first map (map C 1) the warm air has already reached south-west Ireland, where temperatures have risen to 50° or above. The eastern part of the British Isles is still cold with slight frost inland. The temperature increases gradually from east to west through the rain area, so that the warm front does not concentrate in itself all the east-west contrast of temperature. The warm front is the line where the gradual rise of temperature is followed by a constant temperature.

The Valentia thermogram (Record C 1) exemplifies these conditions. There is a rise of altogether about 7° distributed from 21h. on the 21st to 4h. on the 22nd. In such circumstances it is only by an arbitrary definition that we can fix the position of the warm front on the thermogram. It will, just as with the cold fronts, be a rational principle to place the warm front so that it separates air of *cold origin* from air of *warm origin*. Taking this as our working principle the question arises: is the transitional air of cold or of warm origin?

There are several reasons in favour of ascribing all the transitional air to the cold origin. In analogy with the cold fronts we must expect an upward motion on the warm side and a tendency for downward motion on the cold side. There is aerological evidence for the downward motion of the cold air under the alto-stratus of the warm front; such downward motion will tend to raise the temperature of the cold side. The transitional air can accordingly be derived from the cold source by adiabatic processes but not from the warm. If the transitional air were cooled masses from the warm source, one would have to look for other processes than the adiabatic ones to explain the loss of heat which has taken place. The loss of heat in contact with the ground might be thought of, but it is not before the very end of the period of transition that the air temperature has risen above that of the sea. Through the greatest part of the zone of transition the air exhibits the usual " polar-air criterion "— air temperature below that of the sea. The trajectories must therefore lead back to a cold source, although the air is just for the moment flowing from south.

The possibility of the transitional air being a mixing product of warm and cold air deserves careful consideration. Mixing is always present, and since it works ceaselessly in destroying discontinuities its accumulated effects may be of importance. Nevertheless I am not inclined to believe that mixing alone would be able to create a zone of transition several hundred miles broad. The limited importance of mixing is best seen in the case of a front which changes from a diffuse to a sharp structure. Mixing is then present all the time and tries to hinder the creation of discontinuity, but there are obviously factors stronger than mixing which in that case determine the result. These are the air transports which bring into contact air with different life histories. The sharpest discontinuities are formed when the vertical motion also enters into action and makes the transitional air ascend. If we take the opposite case, when a downward motion on the cold side is creating transitional air, then the air transport and mixing act in the same destructive sense on the discontinuities. In this case we cannot directly see which factor is the strongest, but it seems to be a fair conclusion that then also the vertical motion with consequent adiabatic process is a much more powerful factor than pure mixing.

Although many of these questions need further and more exact investigation, we may retain as the most probable working hypothesis that the greatest part of the transitional air is of cold origin also in the case of warm fronts.

In the case of Valentia we therefore place the warm front at 3h. or perhaps even 4h., the earliest time at which the temperature reaches the level where it remains throughout the warm sector. This time also fits well with the time for the end of the veer and the end of the measurable rain. The agreement is not so good with the barogram, which indicates the change from falling to steady pressure already at 2h. There must have been something up above which has compensated the last part of the fall to be expected from surface conditions.

Perhaps the most likely explanation is that the warm front we are describing was really some time ago an occlusion. Occlusions are often shown by a trough in the barogram under the point A of Fig. 13, that is before the arrival of the front on the ground. If this is right the warm air in our case has not been warm air for a very long time. But the essential for us is to state that the air in the south-west corner of the map C 1 is the warmest air we shall have to deal with in the following development of events.

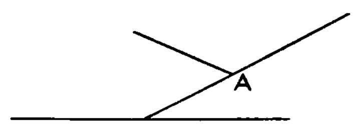


FIG. 13.—Vertical section through an occlusion.

The conditions described for Valentia are found to be rather similar at Holyhead (Record C 2). Thermogram and wind-direction trace analysed according to the above principles fix the warm front passage at 13h. A difference from Valentia is the early cessation of the rain—two hours before the warm front. On the whole the rain in this section of the warm front has been slight. Sealand (Record C 3) with its well defined warm front at 15h. only reports traces of rain during the whole passage, and several stations on the 13h. and 18h. maps have intermittent or no rain in the region where a normal warm front ought to have given continuous rain. It must be considered as an exception that the Wales and Cumberland hills are able to afford shelter against warm-front rain as they did in this case.

At Andover (Record C 4) the anemogram indicates a sort of front at 17h. and the quickest rise of temperature also occurs at that time. But there is a further slow veer and slow rise of temperature going on till 2h. in the night. It seems to be a thin layer of cold air near the surface which drags behind and only slowly becomes mixed with the air of the warm current above. This phenomenon is still more pronounced farther away from the depression, where the surface wind velocities are smaller.

Over France and south-east England a layer of relatively cold air persisted even the following day. The attenuated warm fronts on the 7h. and 13h. charts of the 23rd are intended as a reminder of the cold surface layer over the south-eastern corner of the map. Only west and north of that line was the ground swept clean of remnants of cold air. Slight rain and drizzle occurred over the region where the remnants of cold air were being absorbed and also in the warm current itself.

In the north the development of the weather was essentially different. The Hebrides also had the rain on the morning of the 22nd, but immediately behind it there is broken sky with clouds of Cu. type and occasional showers. Although this air arrives from WSW. it must evidently be polar air. At the same time the dull and drizzly type of weather persists in the south, where there is a current of the same direction (WSW.) but of subtropical origin. The limit between the two almost parallel currents can best be found by the cloudiness itself, but the temperature also gives some indication. Blacksod has 51° in the morning and 49° at noon, so that air of colder origin must have arrived during the forenoon at that place. This cold front, which is also characterised by a rise of pressure behind, is on the noon map to be found between Blacksod and Valentia and extends from there to the region of Donaghadee, where it joins with the warm front. North of the point of junction we have an occluded front as line of separation between the continental polar air from the south and the maritime polar air from the west.

The two diagrams, Eskdalemuir (Record C 5) and Aberdeen (Record C 6), show the passage of that occlusion. Eskdalemuir was rather near the point of junction, so that the beginning of the diagram is like that of stations farther south when the warm front was approaching. There is a gradual rise of temperature simultaneous with a slow veer. At 17h. the maximum of temperature is reached, but this maximum (44°) is low relatively to that of Valentia (52°) even if the greater altitude of Eskdalemuir is allowed for. But immediately afterwards the fall of temperature begins under the influence of the arriving maritime polar air from the west.

The Eskdalemuir thermogram can be considered as typical for the passage of fronts which are just recently occluded—first a gradual rise, as that experienced during the approach of warm fronts, then a gradual fall as that behind the cold fronts. In this case the rise was greater than the fall, but that is different from one case to another ; in summer one would usually find more fall behind than rise in front.

The typical little maximum at the passage of the occlusion is also found at Aberdeen, where the temperature reaches 41° at 15h. (simultaneous trough in the barogram). This is obviously a polar-air temperature for that place and it is a considerably lower maximum than that reached at Eskdalemuir. Even the second maximum, 43° at 18h. caused by sunshine and foehn, is lower than that of Eskdalemuir in spite of the difference of altitude.

The only measurable rain at Aberdeen fell very early from alto-stratus, which had passed the Scotch mountains without being affected by downward currents on the lee side. The latter part of the rain which should presumably fall from lower alto-stratus has been very slight because of the sheltering influence of the mountains.

A situation like that of the 22nd at 13h. (map C 2) with a polar westerly current in the north and a sub-tropical westerly in the south is an almost unmistakable sign that a new disturbance in the shape of a young deepening depression is due to arrive. In this case the depression must have formed not very far off the Irish coast on the continuation of the quasi-stationary front which separates cold and warm westerlies. The next morning the depression is over northern Ireland and continues north-eastwards during the day, becoming deeper from map to map.

The diagram of Valentia gives a good example of the front structure of a young depression.

The afore-mentioned limit between the polar and the sub-tropical part of the westerly current went slowly southwards during the day of the 22nd. At about 13h. the temperature starts falling at Valentia and at 19h. 30m. the temperature has gone down 4°F. It is a cold front at which all discontinuity is smoothed out. According to our previous rules the cold front is drawn at the beginning of the fall of temperature, and is thus the limit between the field of quasi-constant temperature in the warm sector and the sloping field of temperature in the nearest part of the cold air.

It is interesting to see how this diffuse cold front returns as a rather sharp warm front only some few hours afterwards. A sudden rise of temperature starts at 20h. 35m. and in less than half an hour the temperature of the warm sector is re-established. The corresponding changes in wind direction and force are also fairly sharp. This change of structure from diffuse to sharp front is in reality the same as we have seen with retarding cold fronts in the two previous cases. A cold front which slows down and then moves retrograde as a warm front is physically the same as a retarding cold front.

If we generalize this principle, a warm front which is slowing down and then changes into a cold front should be physically analogous to an accelerated cold front. In this case the structure of the front should change from sharp to diffuse. That is just what we see on the Valentia diagram at the next return of the front at 4h. of the 23rd. Although the front is then moving much more quickly, the fall of temperature is going on at a slower rate than the previous rise ; likewise the veer lasts more than 2 hours, whereas it was only 20 minutes when the same front was a warm front.

These conditions ought to be found generally near the centre of young depressions. The first cold front which arrives behind the centre has recently been a warm front during the approach of the centre. It is therefore an accelerating cold front which is changing from sharp to diffuse structure.

Eskdalemuir which was very near the path of the centre of the depression gives a further verification of the rule. There is a warm front at 7h. 20m. which is very sharp both in respect of temperature and wind. But the return of the same front as a cold front between 12h. and 13h. is much more diffuse, the veer is insignificant, and the fall of temperature is spread out to a linear fall lasting several hours.

The same cold front passed Holyhead, 10h. 30m., Sealand at 12h. 30m. and Andover at about 15h. The fall of temperature at all three places is smaller and less abrupt than at Valentia. Sealand has most left of the fall of temperature, but that is again an effect of the high temperature which is there reached in the warmer sector. From 1h. to 6h. 30m. and again just before the cold front Sealand had a foehn.

At Scilly (Record C 7, anemogram only) we find the cold-front couple typical for accelerated cold fronts; the first one at 9h. 30m. with decreasing velocity behind the second at 12h. with constant velocity behind. The second cold front is just visible at Holyhead at 12h. so that it has been possible to fix its position on the 13h. map.

It is important as well to notice the shape of the barograms. At Valentia the warm front marks a point where a rapid fall of pressure changes into less rapid fall. The static effect of the warm front alone would be a fall of pressure as long as cold air is replaced by warm air, and then no further change of pressure. In all cases where the warm front is part of a deepening depression there is, however, a negative surge superimposed, so that a fall of pressure continues all through the warm sector. The arrival of the cold air brings at Valentia a rise which just over-compensates the negative surge due to the deepening of the depression so that a slow rise results.

At Eskdalemuir it is already different; the cold front at 13h. only just suffices to stop the fall of pressure for a while, whereafter a new slight fall begins. Since the fall of pressure through the warm sector was approximately the same at Eskdalemuir as at Valentia, we may conclude that the wedge of cold air arriving at Eskdalemuir was less steep and contained probably more degenerated heated cold air than that which had arrived over Valentia. The latter is also supported by the thermograms, the fall of temperature is relatively quicker at Valentia than at Eskdalemuir. A wedge of cold air which undergoes a change in that sense must necessarily produce less pressure effect.

Both barograms suggest a further singularity: Valentia a sudden change from slow rise to rapid rise at 10h. and Eskdalemuir a change from slow fall to rapid rise at 16h. There is a corresponding veer at both places, most pronounced at Eskdalemuir. The temperature is falling during the time in question, but there is nothing particular to show a really sharp cold front at the time when the barograms indicate the troughs.

At Holyhead the same system has developed into a real cold front of great sharpness (passing at 15h.). This third cold front (if the secondary cold front on map C 5 is counted as the second) is indicated on the maps by a line of occlusion. In analogy with the third cold front in the case first described (pages 6 and 12) it can be considered as the back-bent northern end of the occlusion. In the beginning there is little contrast of temperature at this front because of the similar life histories of the various parts of the cold air close to the centre. But the more the trough develops in the region of the back-bent occlusion (maps C 5 and C 6), the more difference there will be in the life history of the air on both sides. The final temperature after the third cold front, is the same at Valentia and Holyhead—about 44°—but the temperature before it is 1° warmer at Holyhead than at Valentia; 1° has thus been added to the temperature contrast. At Sealand the temperature is still 1° higher before the arrival of the third cold front (17h. 15m.), so that a discontinuous fall of 4° and a very brisk rise of pressure result. It will usually be found that the contrast of temperature at the back-bent occlusion develops as a result of an increase of temperature in front, while it remains more or less constant behind. With the development of the trough the air in front of it, although of polar origin, has to move along a curved trajectory ending up with a motion from SW. That obviously must give a higher temperature than for the particles which arrive more directly from the N.

At Andover one might have expected a further accentuation of the third cold front, but that is not so. The fall of temperature at 21h. is probably the remainder of what was on the other stations the third cold front, but the barogram does not show any sign of a trough at that place, nor is there any rain or well marked veer connected with it. Also the other southern stations from Scilly to south-east England show the third cold front very faintly or not at all. The *third cold front* is thus *of limited length* as a back-bent occlusion ought to be.

These conditions are important to remember when analysing synoptic maps. It is often found that the cold front which has the most conspicuous trough near the centre fades away already at a limited distance from it. That is then usually the back-bent occlusion. The first cold front is in such a case to be found in a masked state without a distinct trough nearest to the centre, but farther away it may be the only important cold front with a good contrast of temperature and occasionally with a V-shaped trough.

The rainfall in the last depression needs to be specially mentioned, because there are several departures from normal conditions.

The warm-front rain was at Valentia, Holyhead and Sealand quite according to rules. It stopped just at the passage of the warm front itself and the rain in the adjacent part of the warm sector was slight and intermittent. But Eskdalemuir which was quite close to the passing centre has heavy continuous rainfall all through the warm sector. Such a downpour is only possible if the air in the warm sector is ascending bodily at a considerable velocity. That kind of ascending motion in the part of the warm sector nearest the centre must undoubtedly be admitted in many depressions.

The rain at the first cold front is chiefly pre-frontal. At Valentia for instance, the bulk of the rain is about 3h., but the cold front does not arrive before 4h. when the rain has already become very slight. An explanation may be that the veer starts somewhat earlier, which would indicate some convergence in the warm current before the arrival of the cold front. Holyhead and Andover have the same pre-frontal rain at the first cold front.

The rain of the back-bent occlusion was heavy and long-lasting at Valentia and equally long-lasting but slighter at Eskdalemuir. At both places the rain was falling both before and after the proper cold front. At Holyhead and Sealand finally one finds the classical cold-front rain—beginning exactly with the arrival of the cold front, short duration, heavy at first and then slighter. This seems to be well in harmony with the development of a sharp front from originally diffuse conditions.

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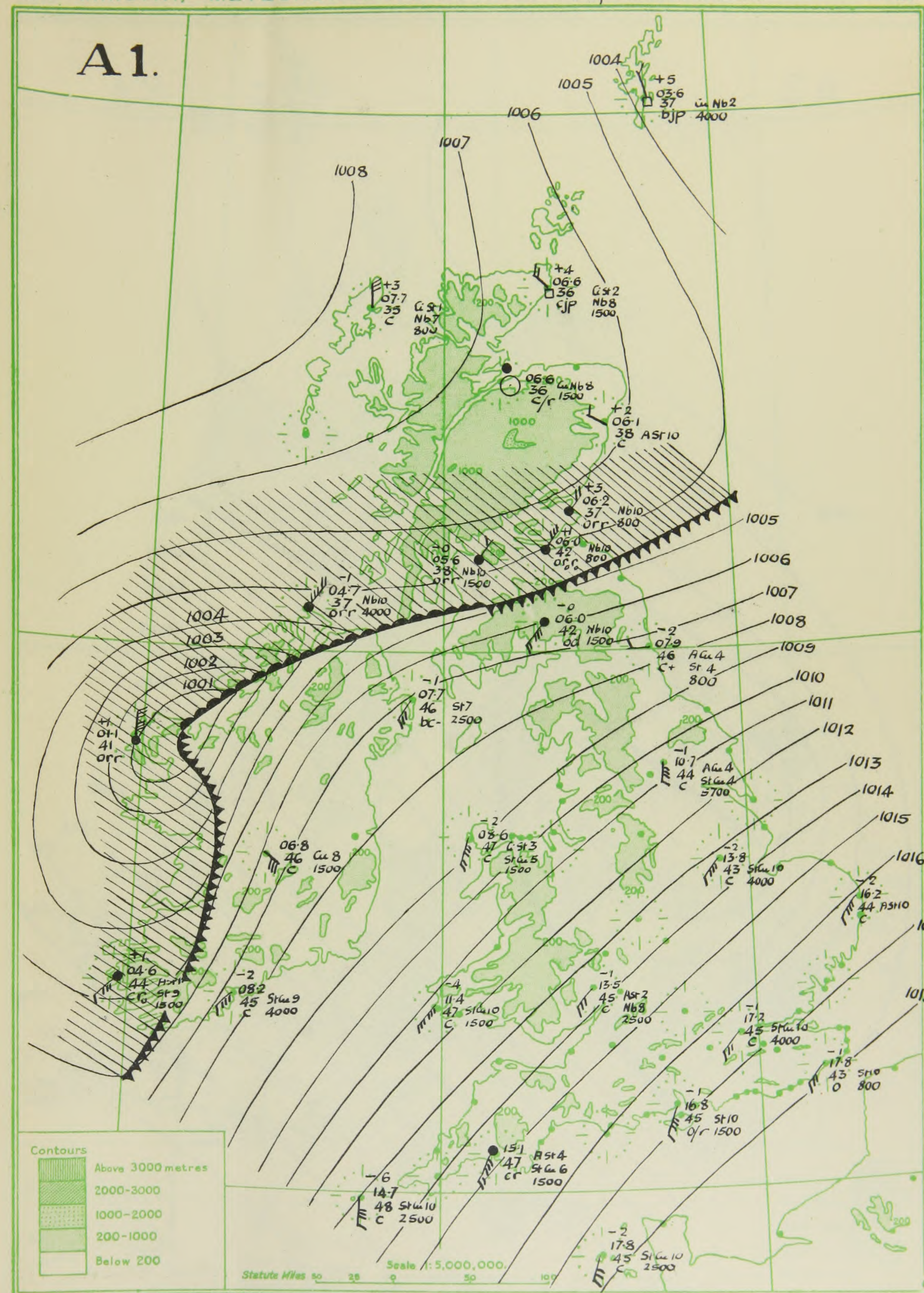
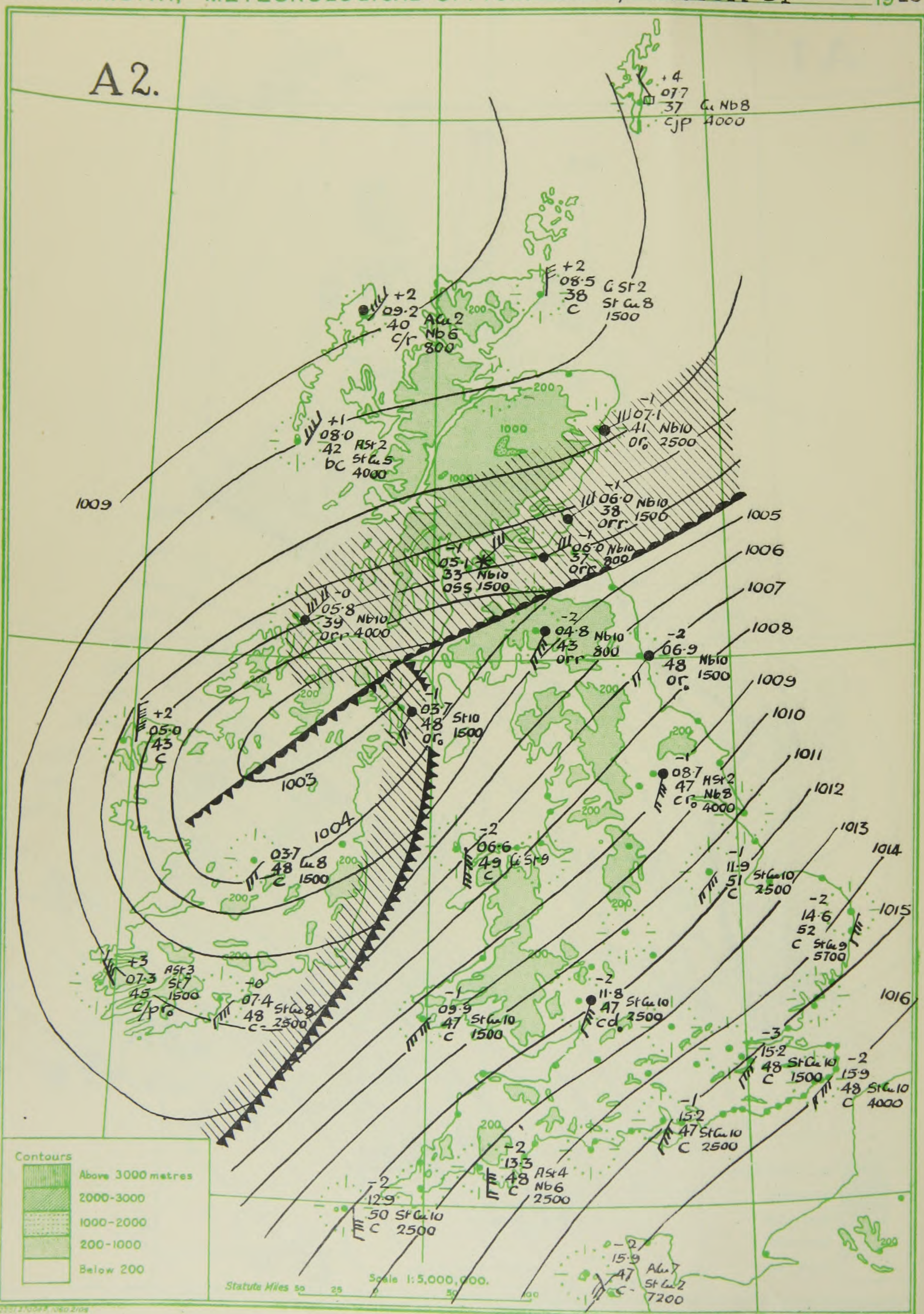
AIR MINISTRY, METEOROLOGICAL OFFICE. 7h., March 31 1925

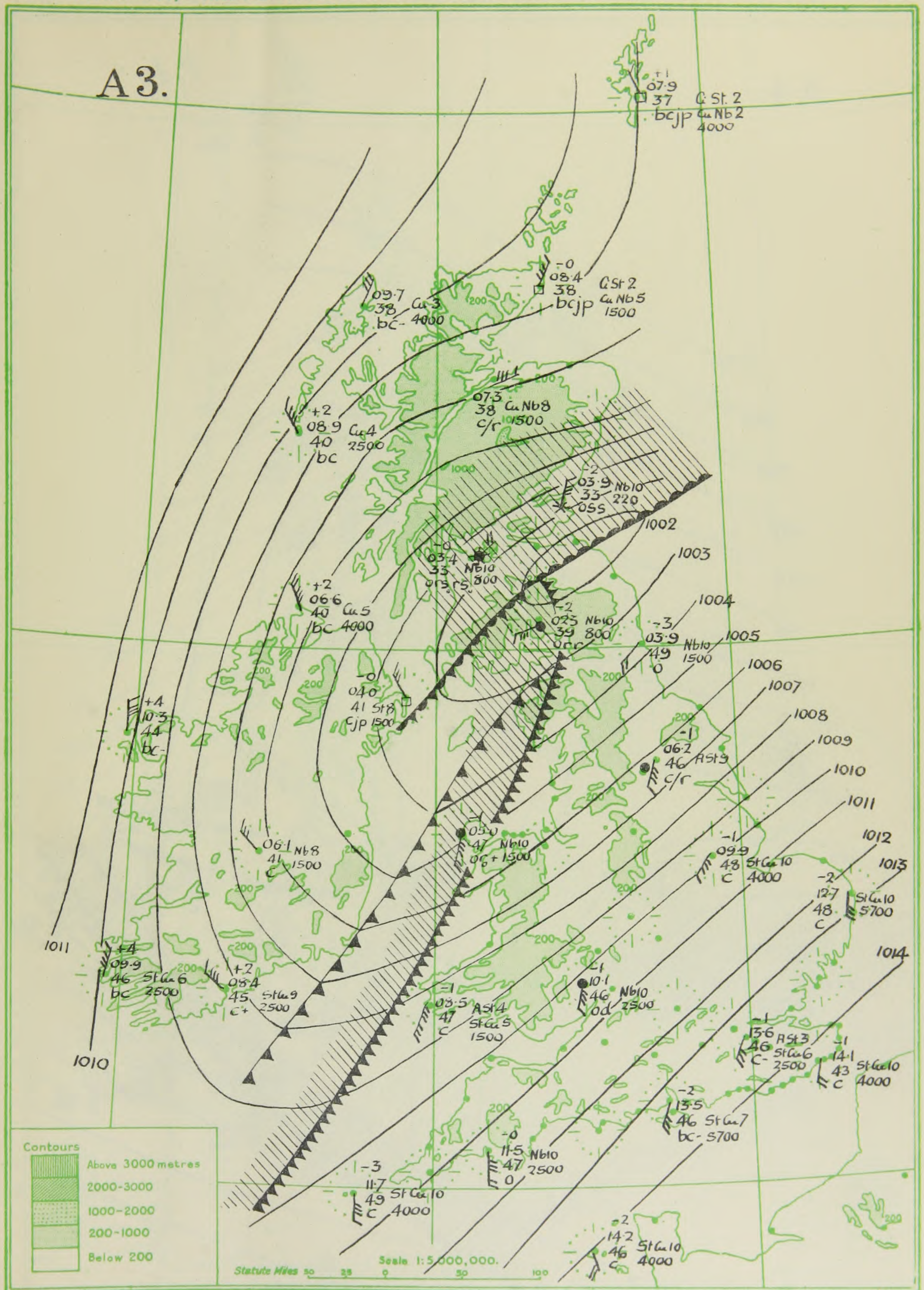


AIR MINISTRY, METEOROLOGICAL OFFICE. 13h, March 31 1925

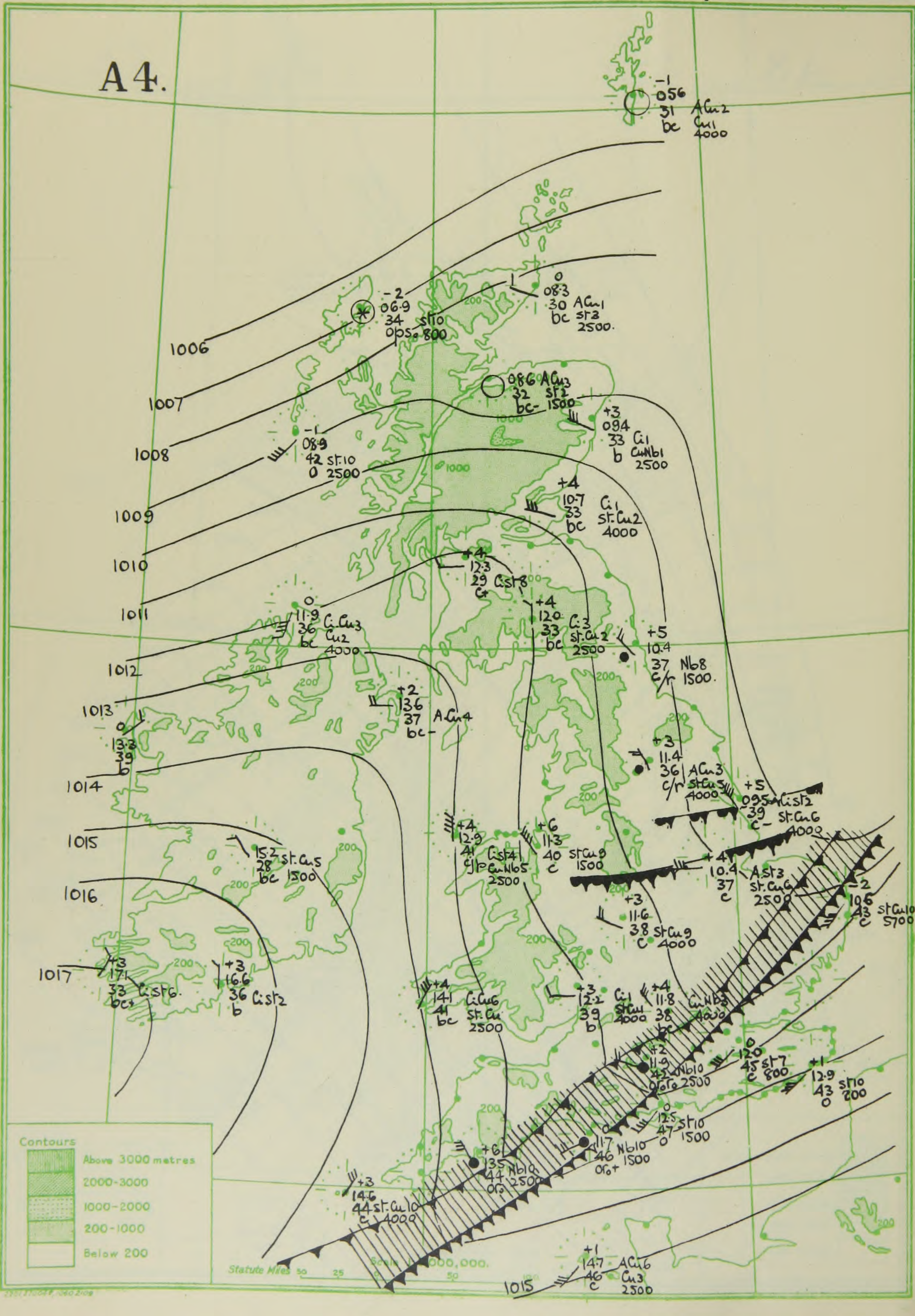


AIR MINISTRY, METEOROLOGICAL OFFICE. 18h., March 31 1925

A3.



AIR MINISTRY, METEOROLOGICAL OFFICE. 7h., April 1 1925



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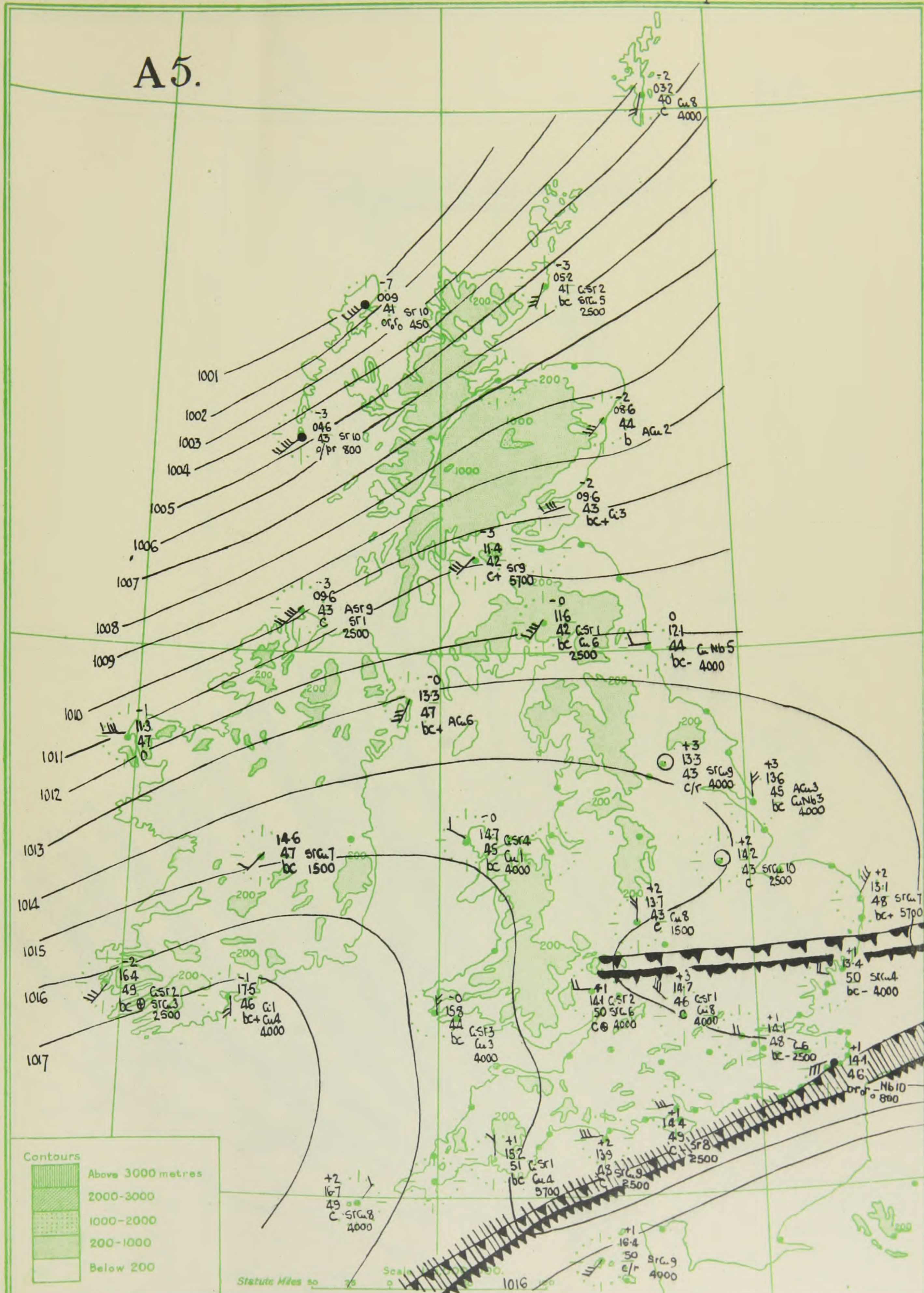
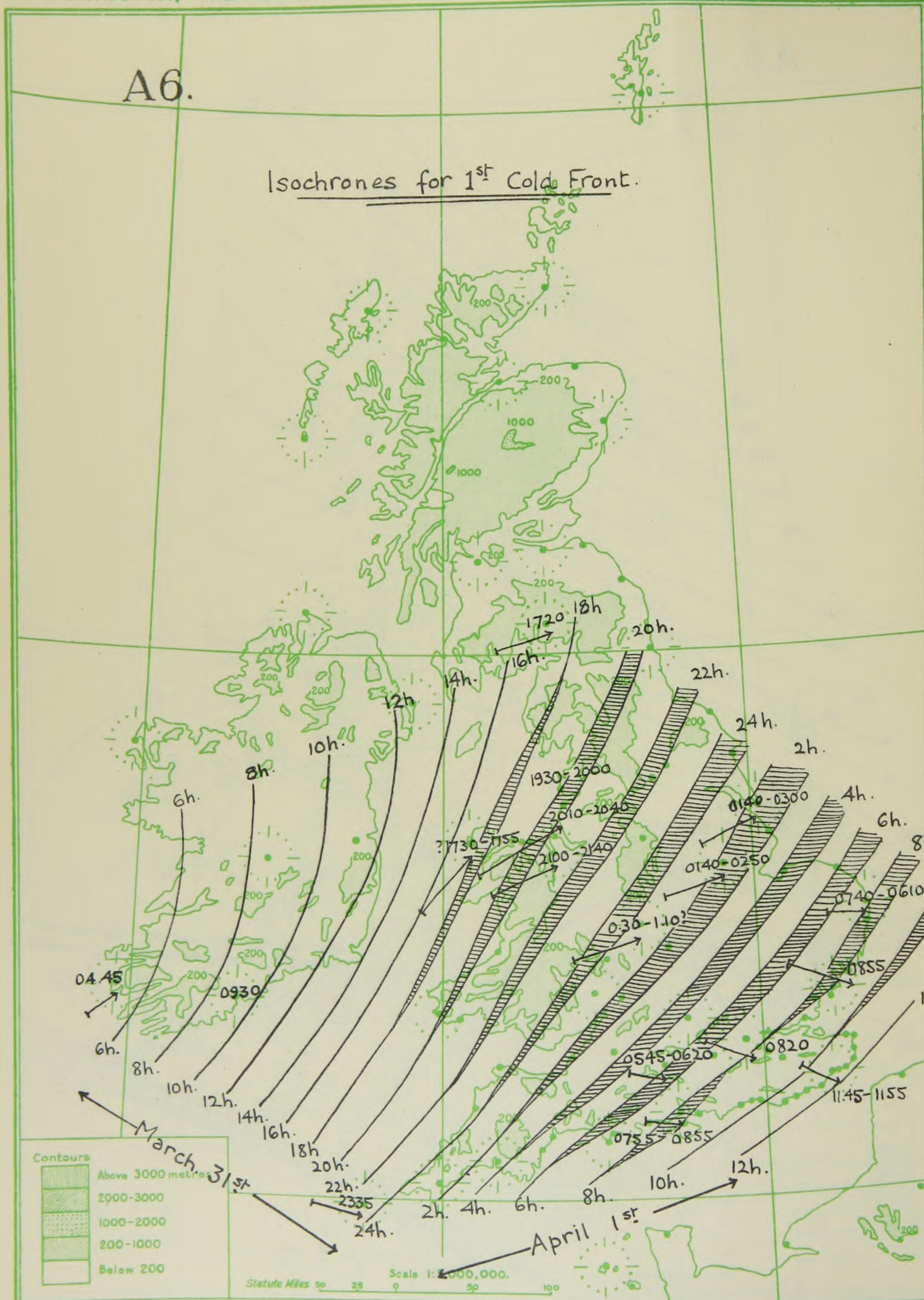
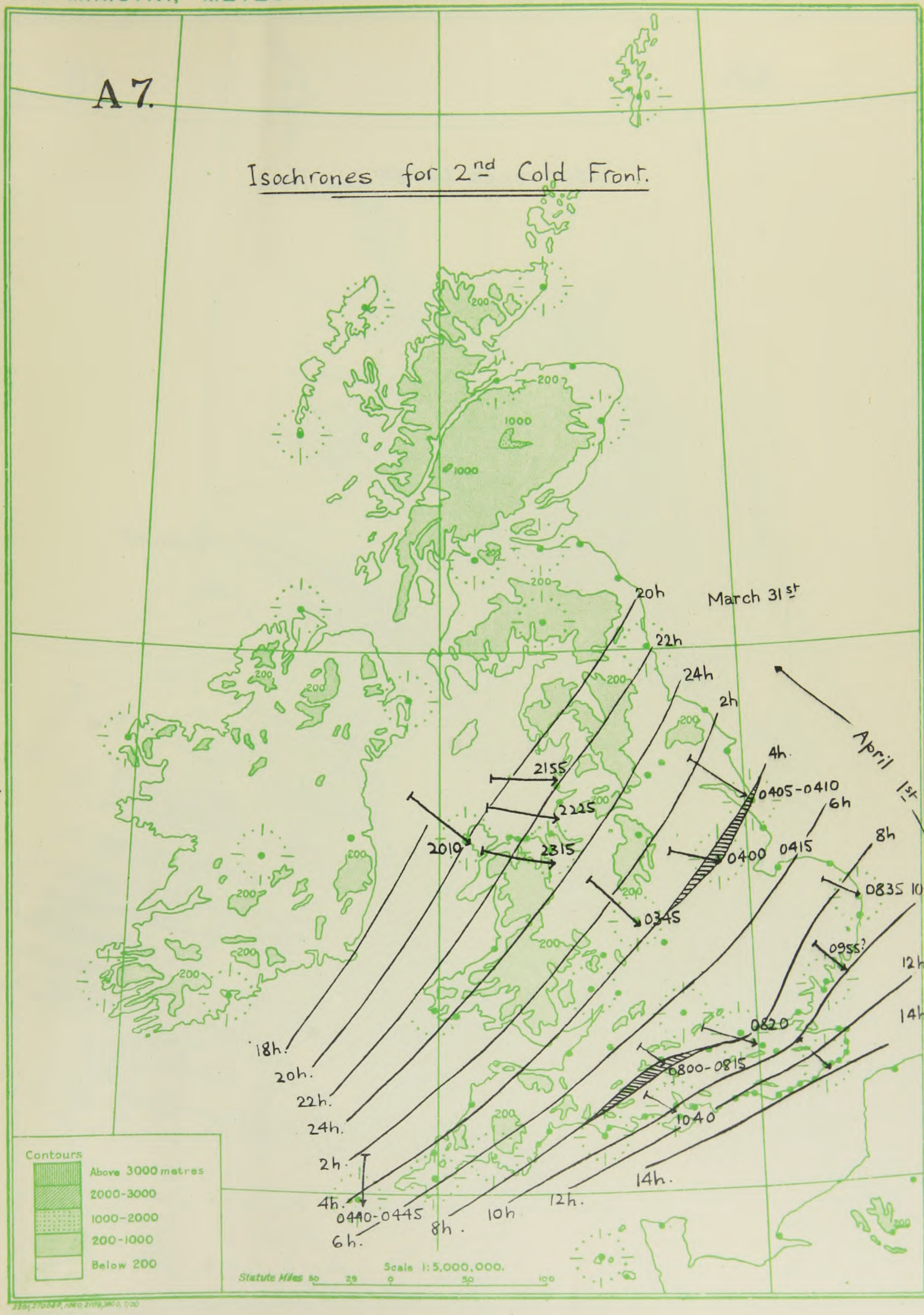
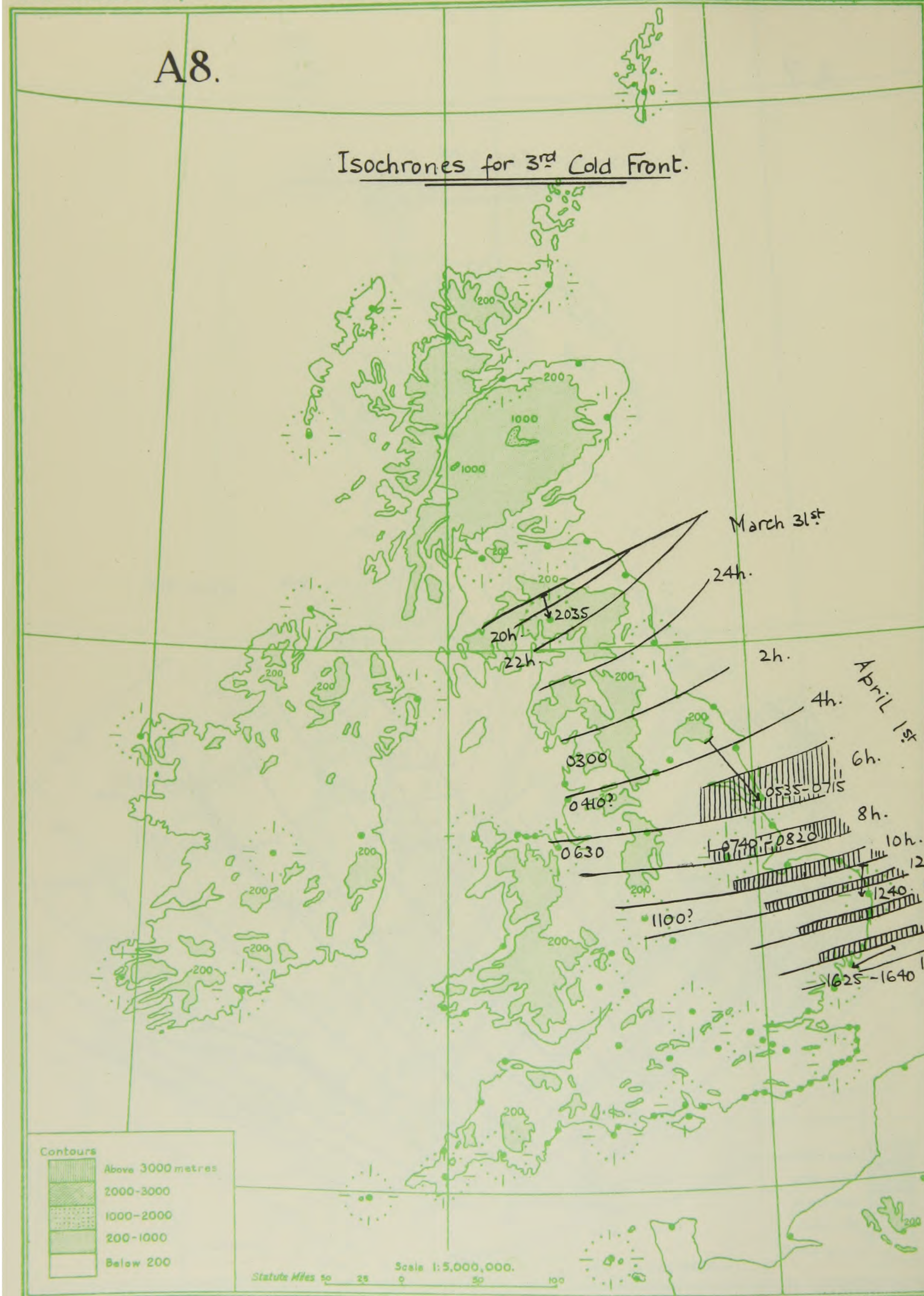


A6.

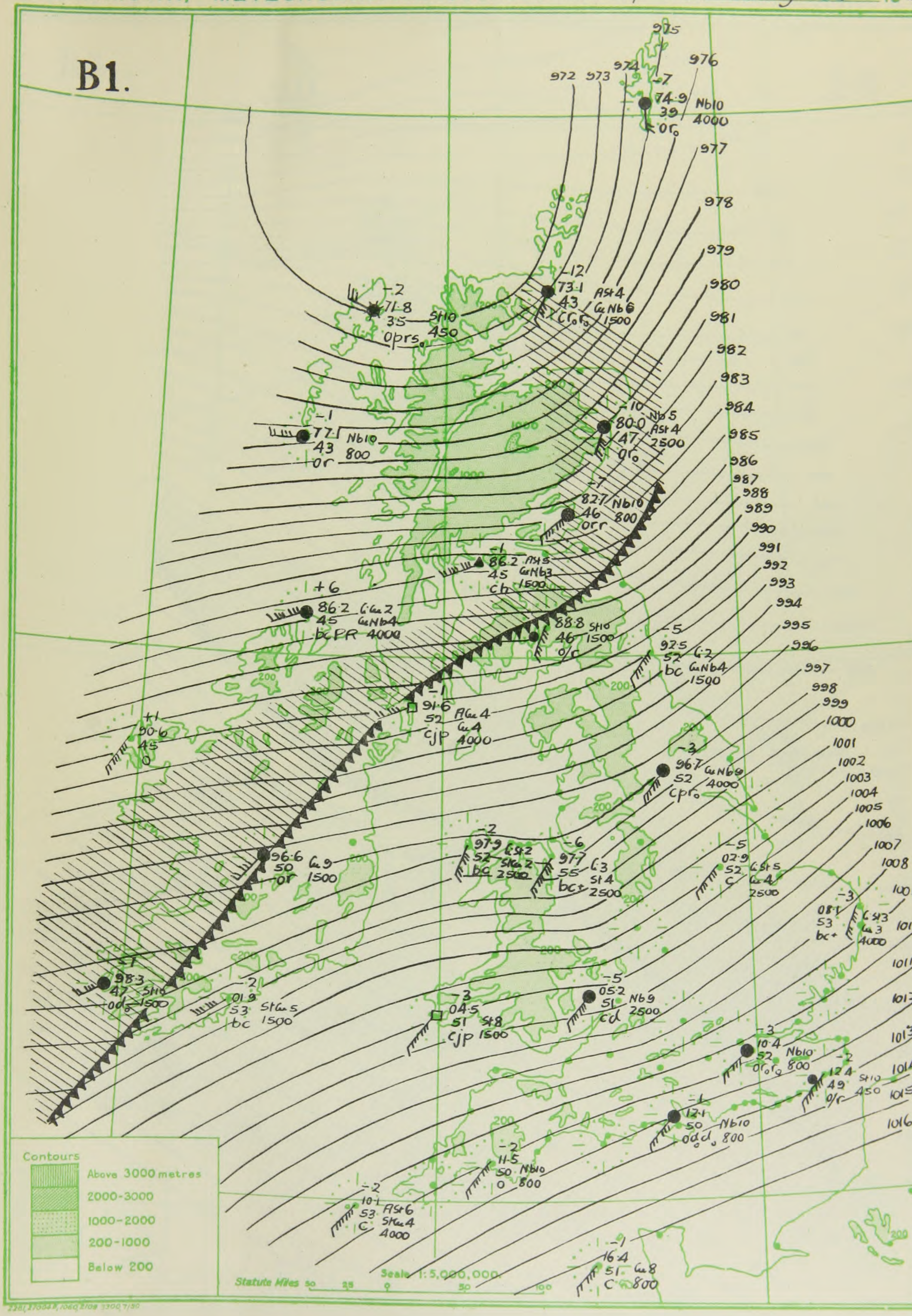
Isochrones for 1st Cold Front.




A7.
Isochrones for 2nd Cold Front.
March 31st
April 1st
20h
22h
24h
2h
4h.
6h
8h
10h
12h
14h
18h.
20h.
22h.
24h.
2h.
4h.
6h.
8h.
10h
12h.
14h.
2155
2225
2010
2315
0405-0410
0400
0415
0345
0835
0955?
0820
0800-0815
1040
0440-0445
Contours
Above 3000 metres
2000-3000
1000-2000
200-1000
Below 200
Statute Miles 50 25 0 50 100
Scale 1:5,000,000.


A8.
Isochrones for 3rd Cold Front.
March 31st
24h.
20h.
22h.
2035
2h.
April 1st
4h.
6h.
0300
0410?
0535-0715
8h.
0630
0740-0820
10h.
12h.
1240
14h.
1100?
16h.
18h.
1625-1640
200
1000
Contours
Above 3000 metres
2000-3000
1000-2000
200-1000
Below 200
Scale 1:5,000,000.
Statute Miles 50 25 0 50 100

AIR MINISTRY, METEOROLOGICAL OFFICE. 13h., February 10 1925



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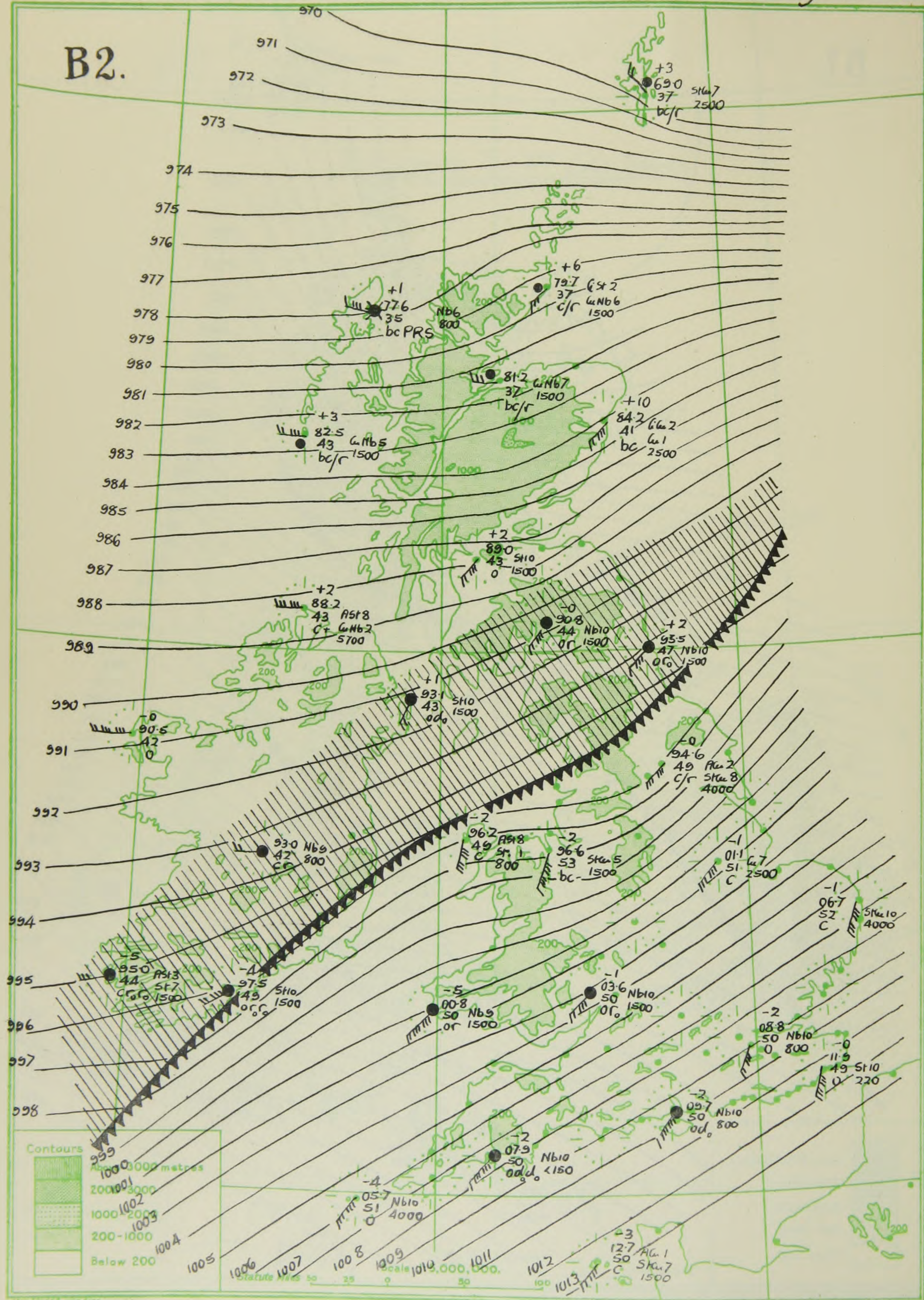

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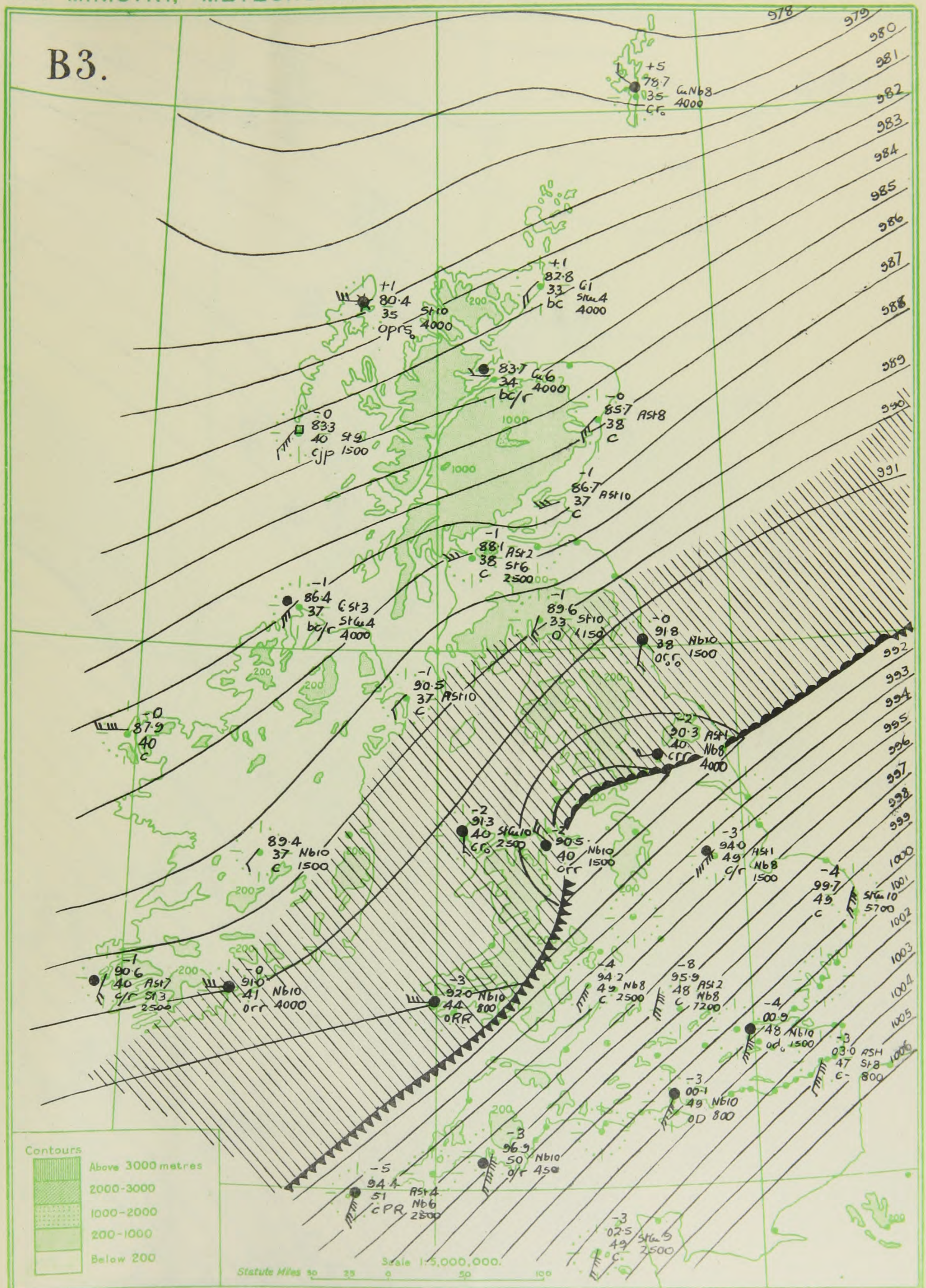

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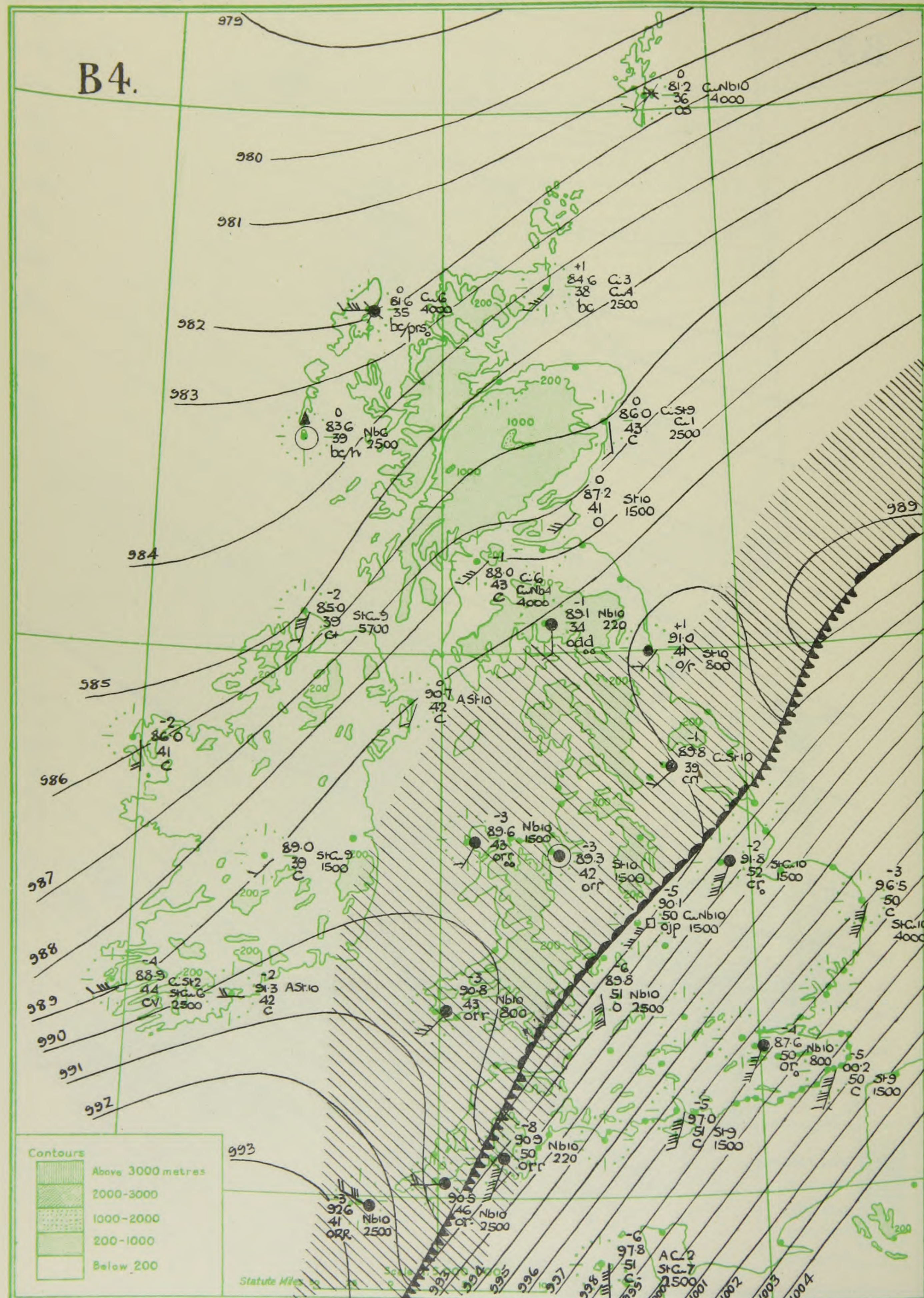
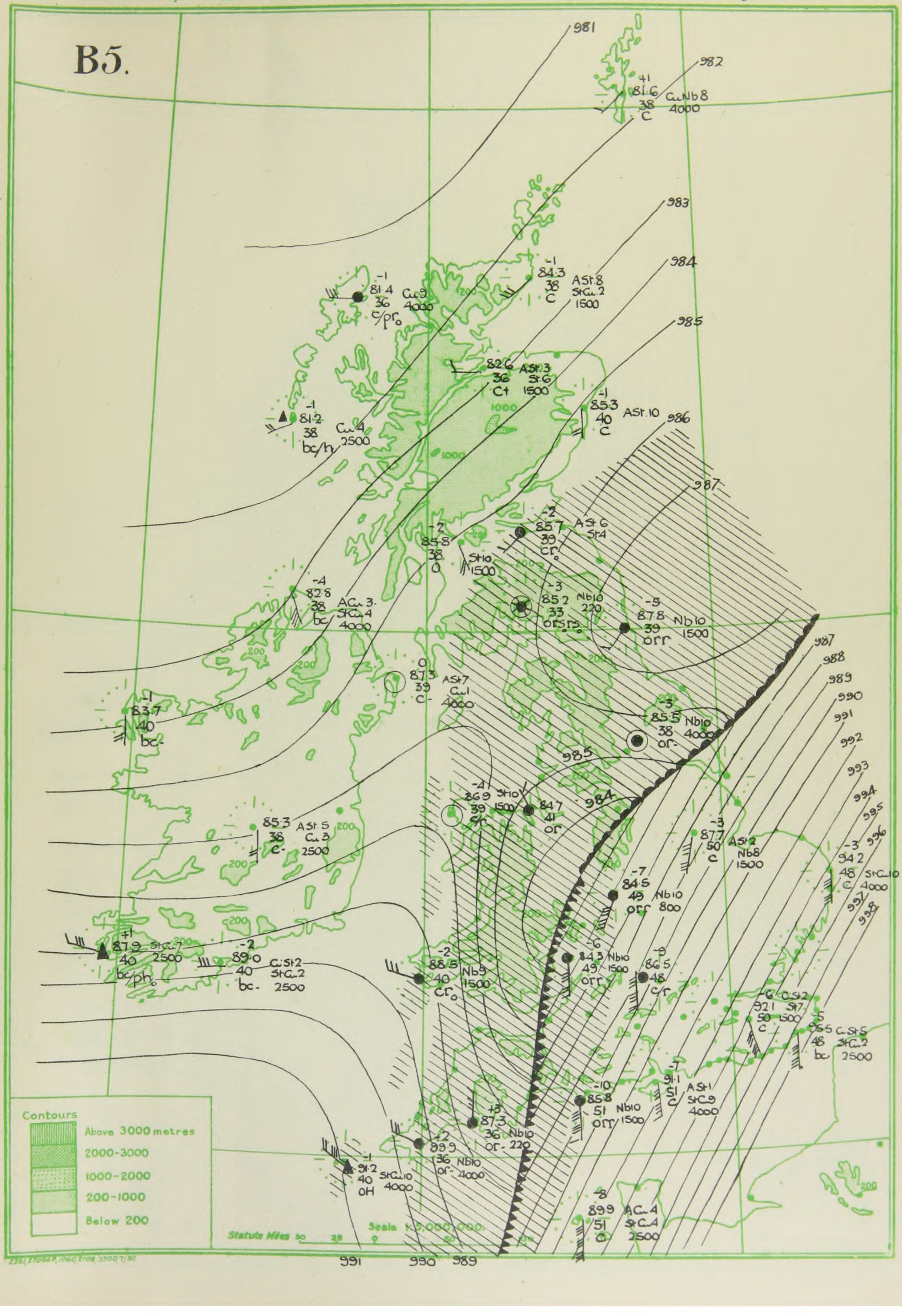


AIR MINISTRY, METEOROLOGICAL OFFICE. 18h., February 11 1925

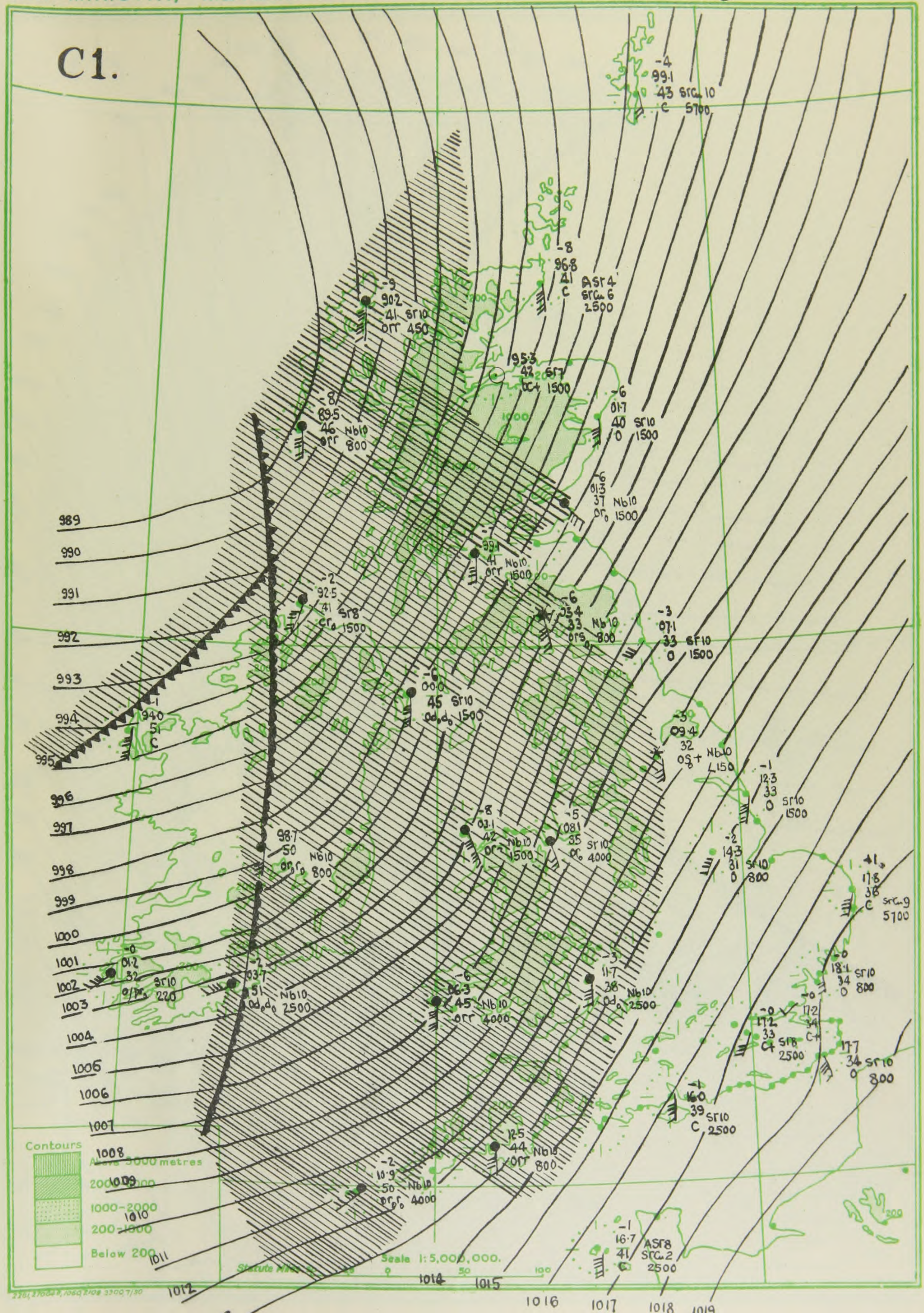
B5.

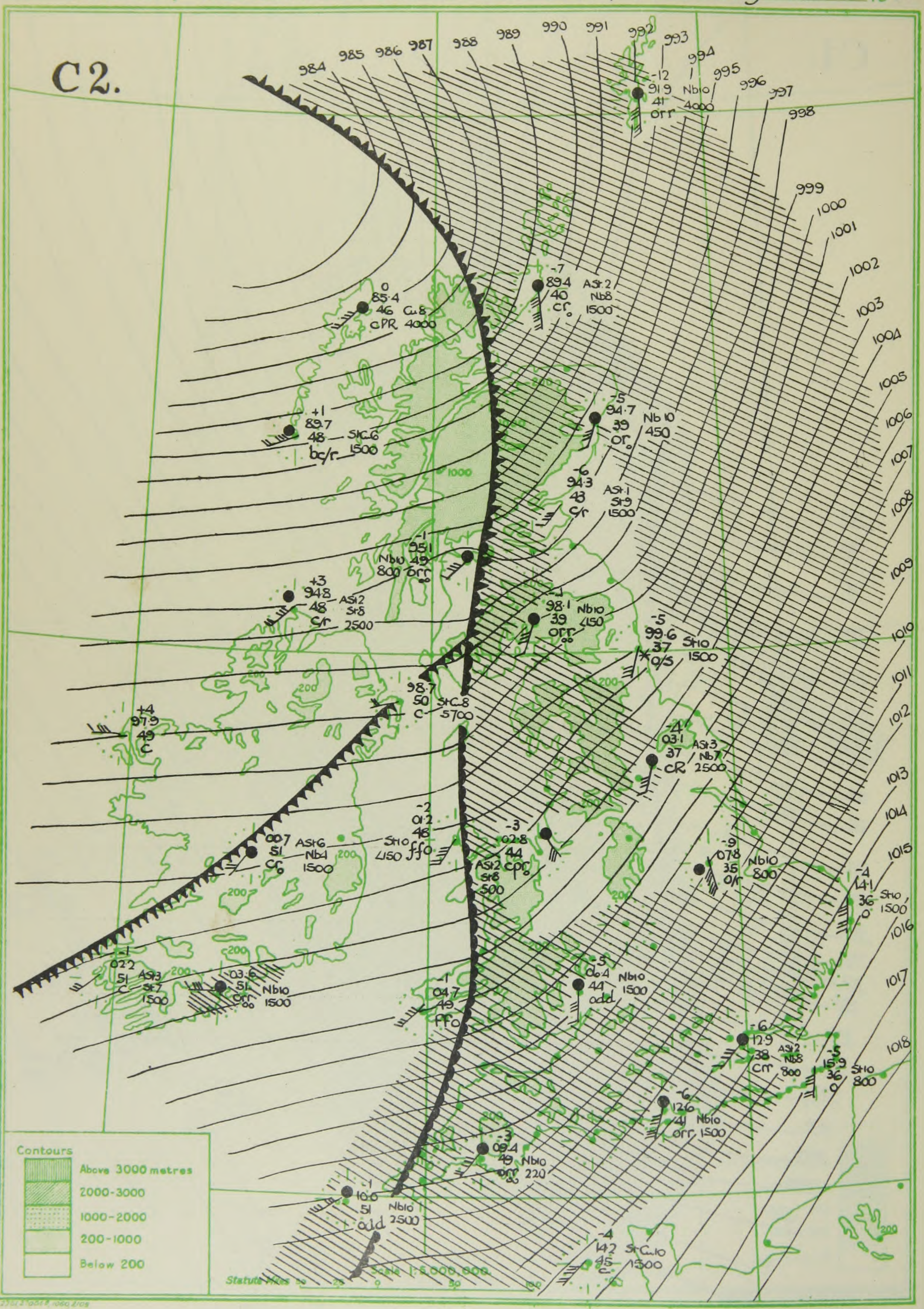


226(2708) 8,106C 2109 3300 7/30

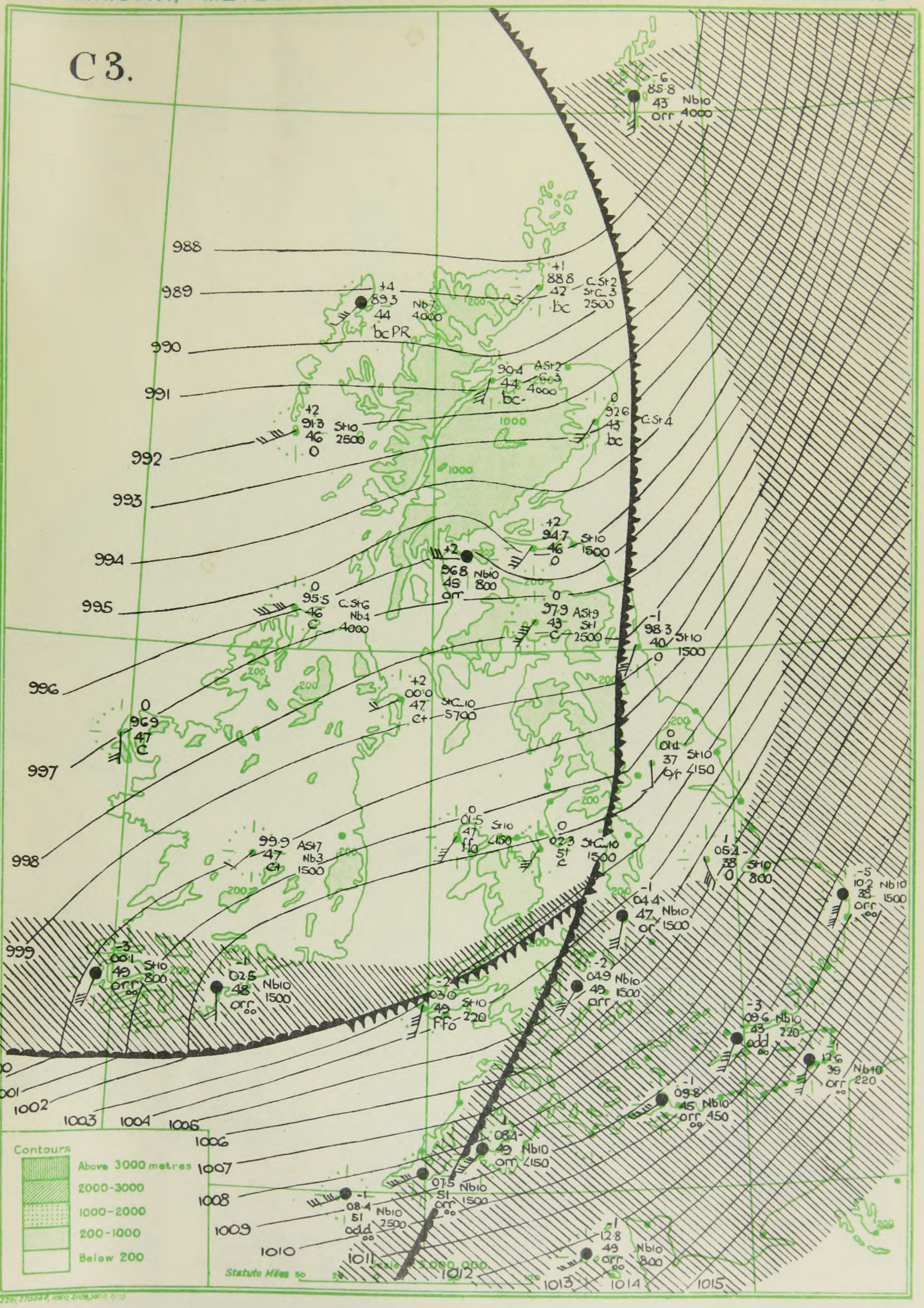

Contours
Above 3000 metres
2000-3000
1000-2000
200-1000
Below 200
Statute Miles 50 25 0 50 100
Scale 1:5,000,000.
200
1000

AIR MINISTRY, METEOROLOGICAL OFFICE. 7h., January 22 1926




C2.
Contours
Above 3000 metres
2000-3000
1000-2000
200-1000
Below 200
Scale 1:5,000,000
Statute Miles

AIR MINISTRY, METEOROLOGICAL OFFICE. 18h., January 22 1926



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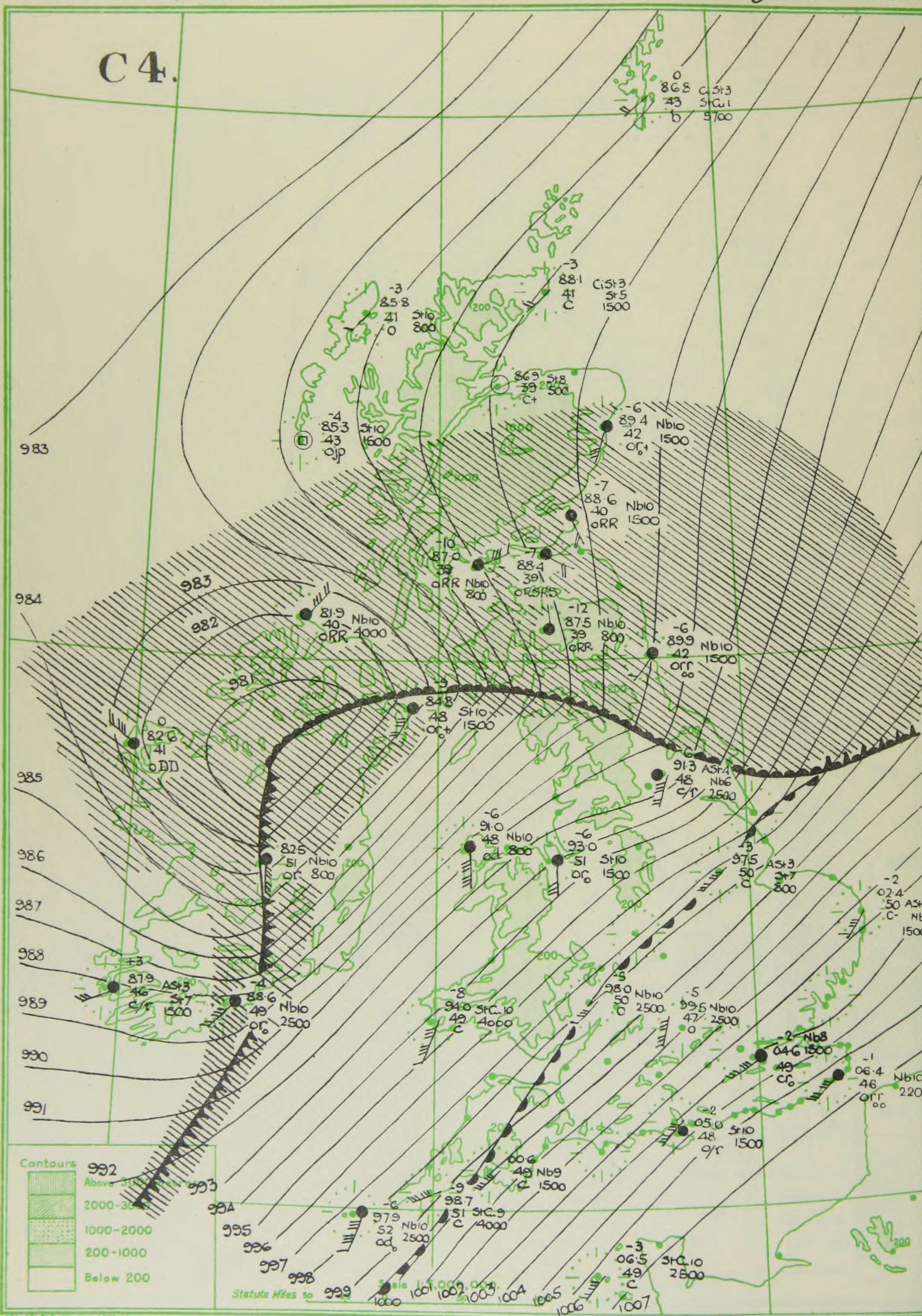

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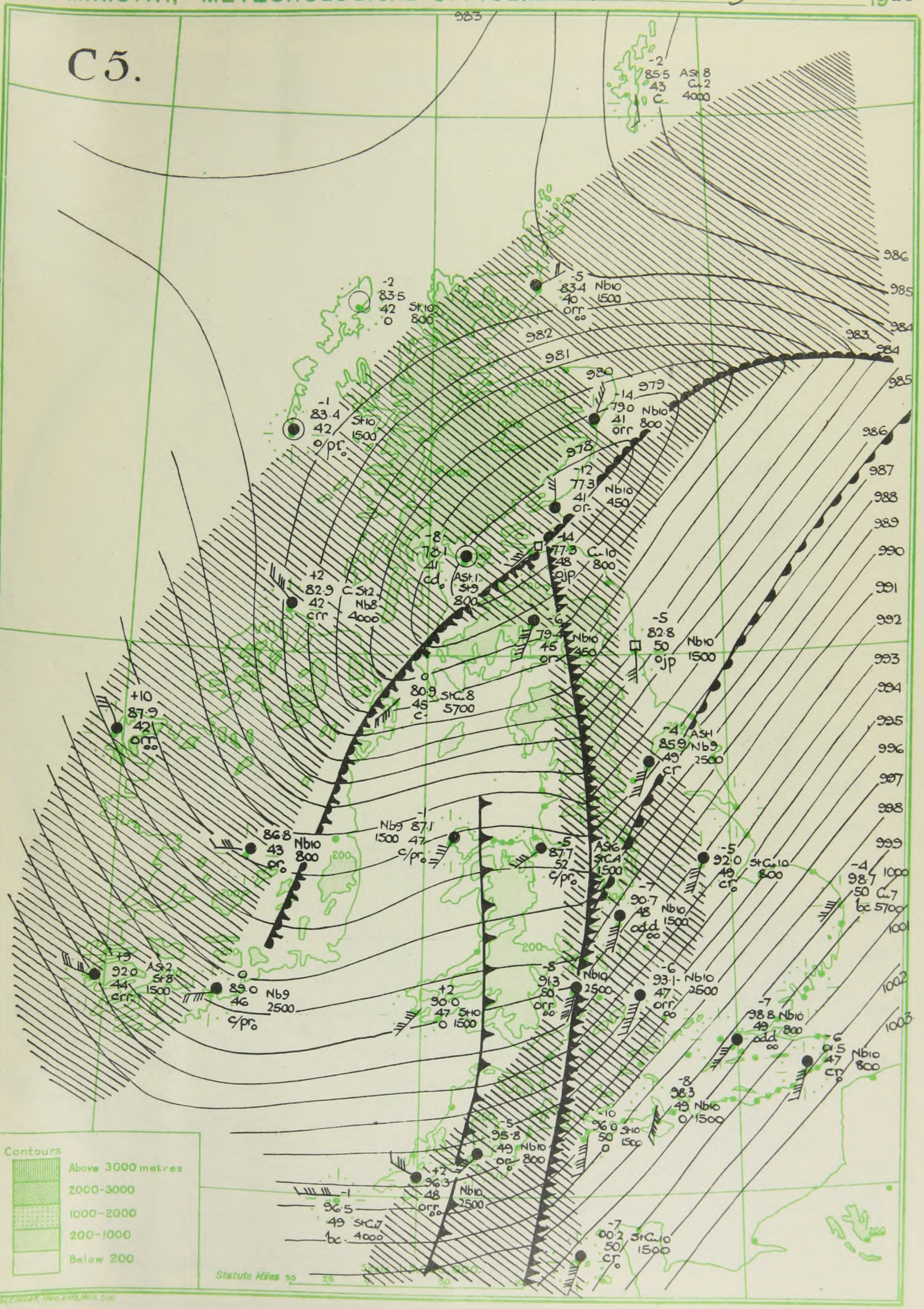

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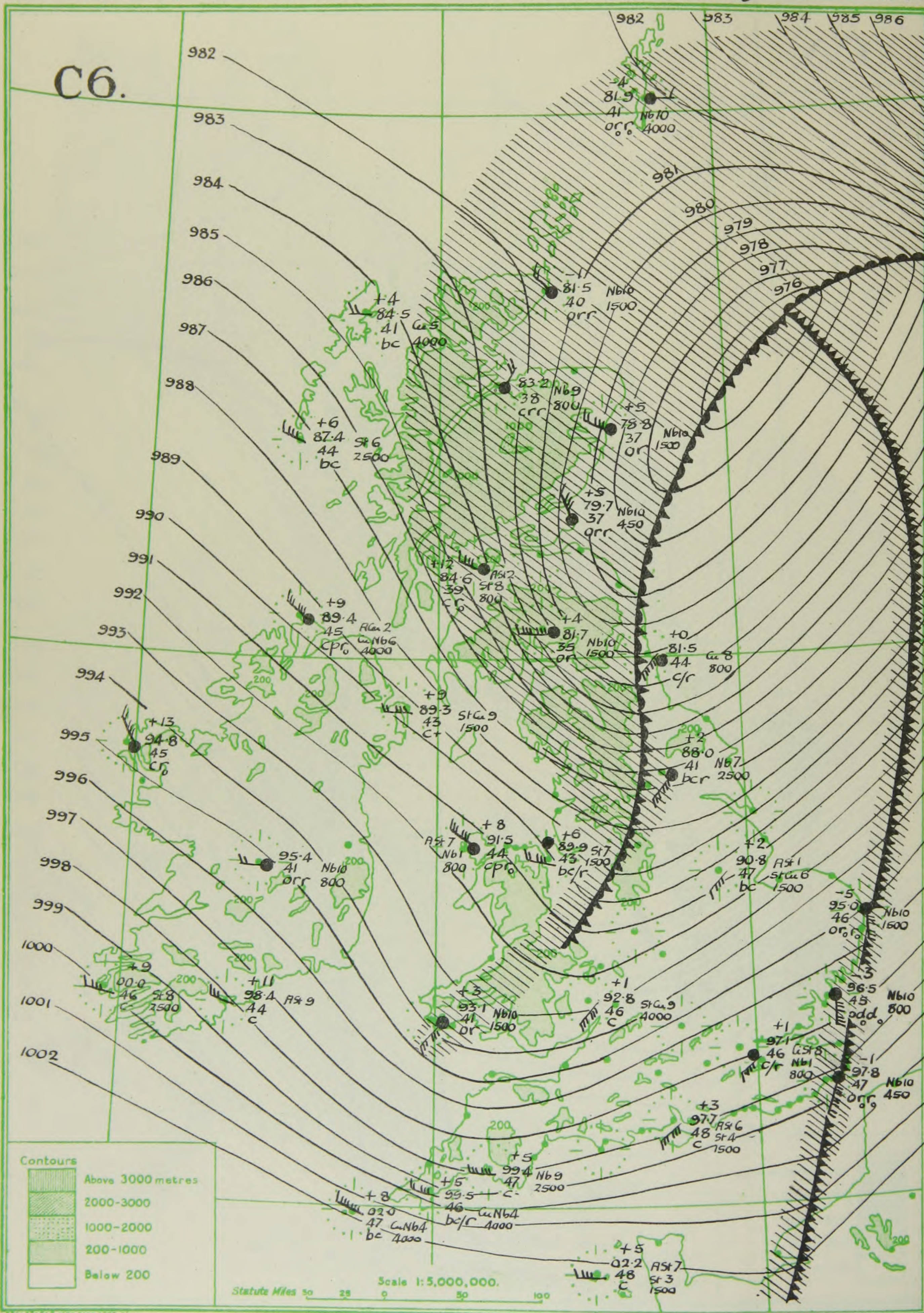
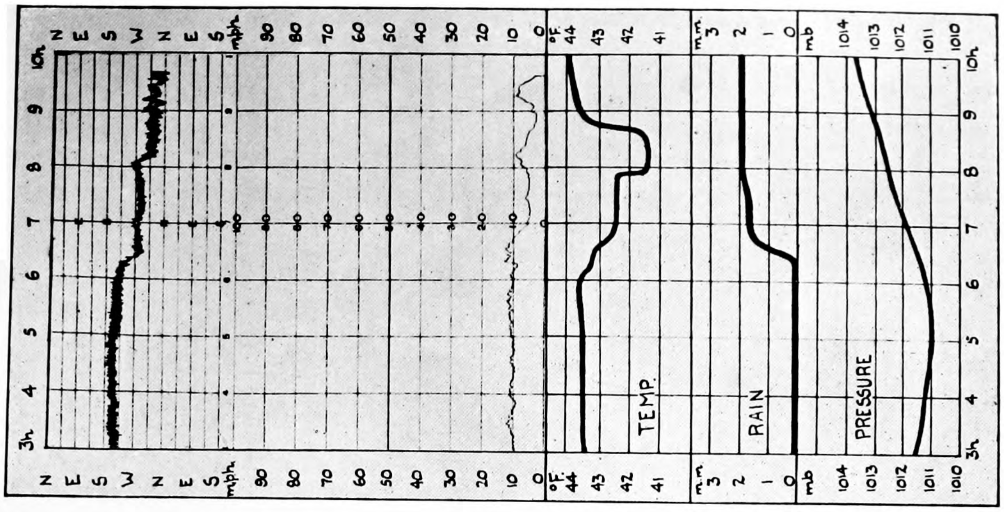
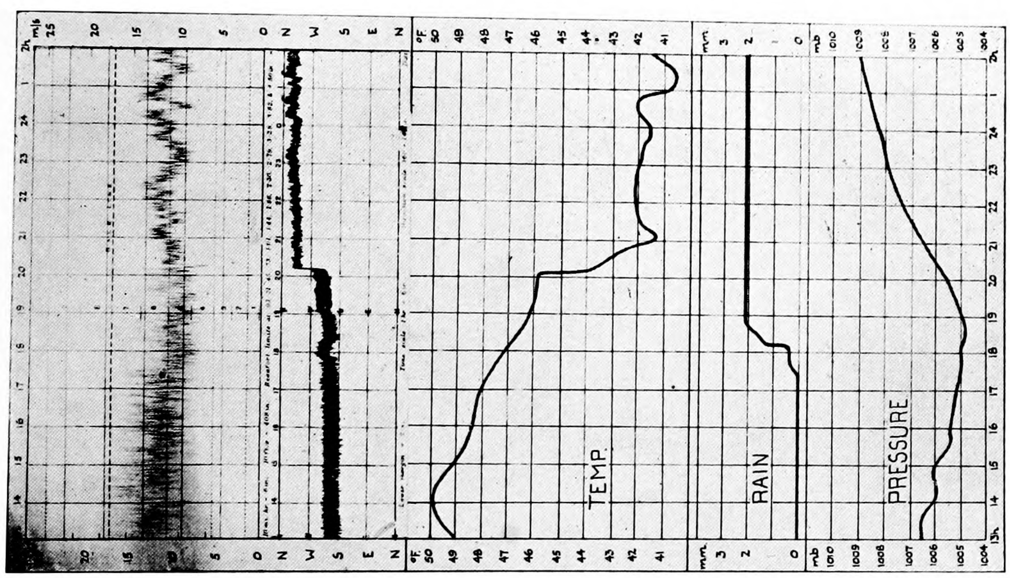
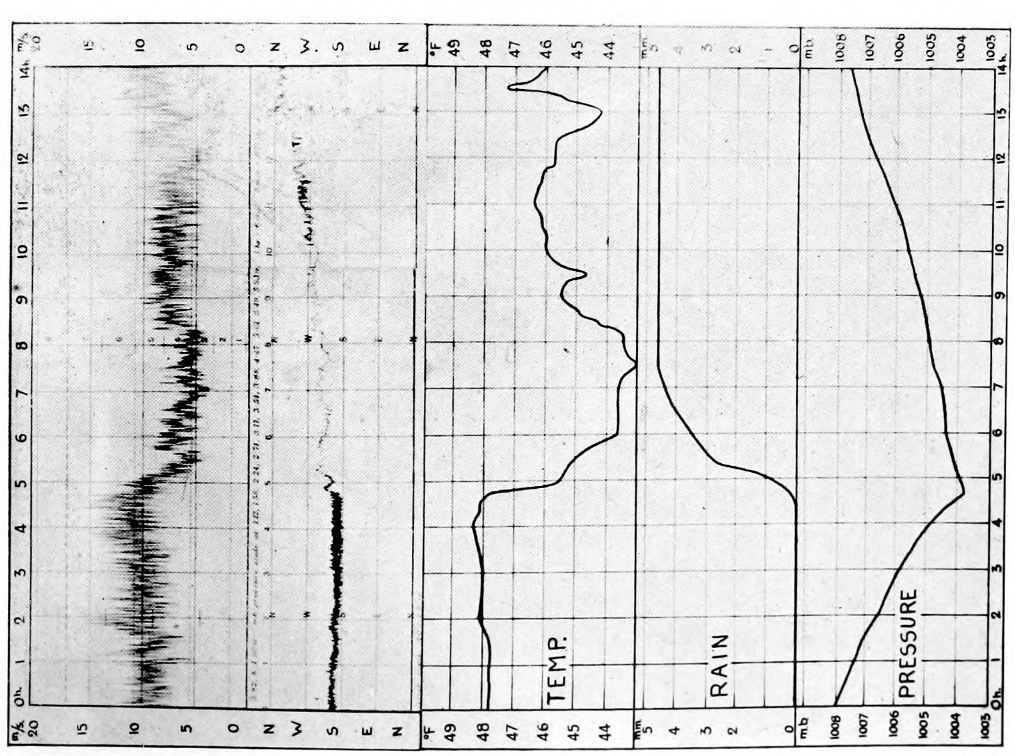




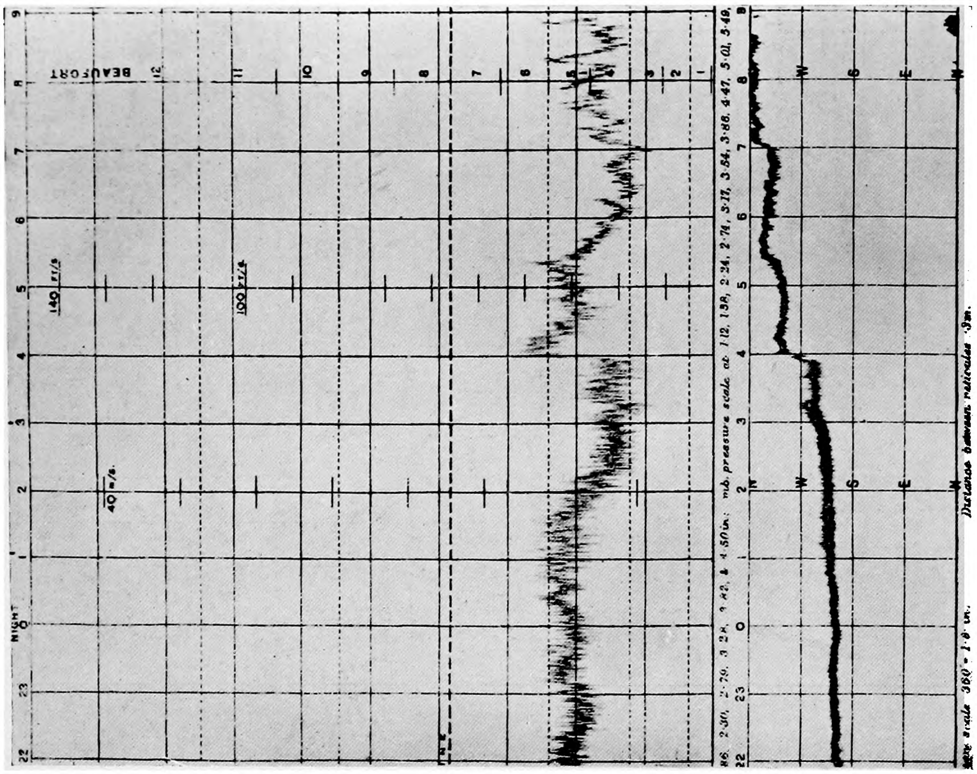
Record A3.—Andover, April 1, 1925.



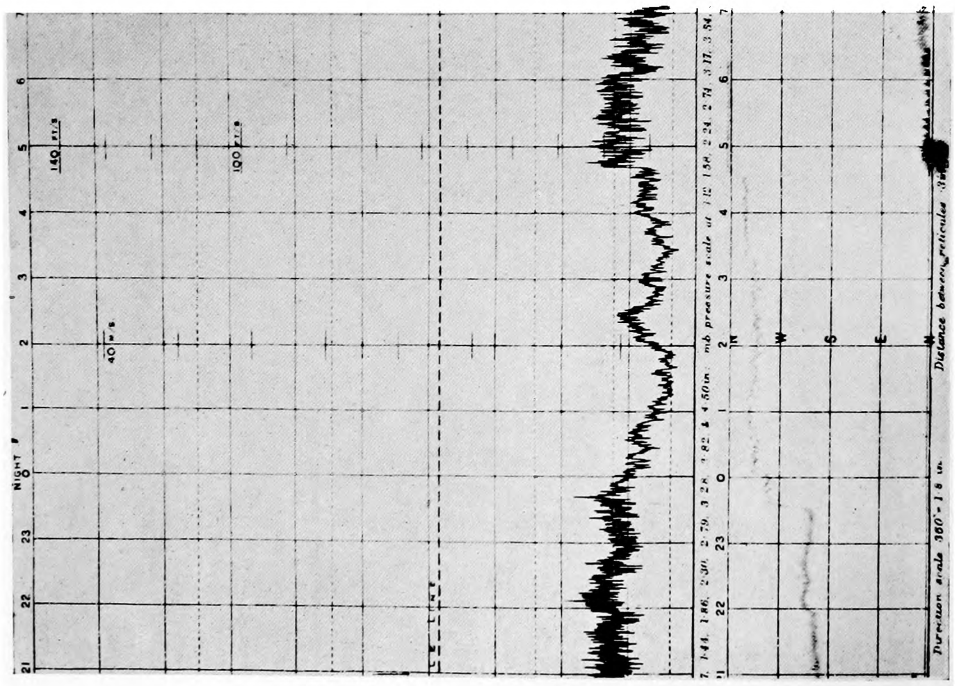
Record A2.—Holyhead, March 31 to April 1, 1925.



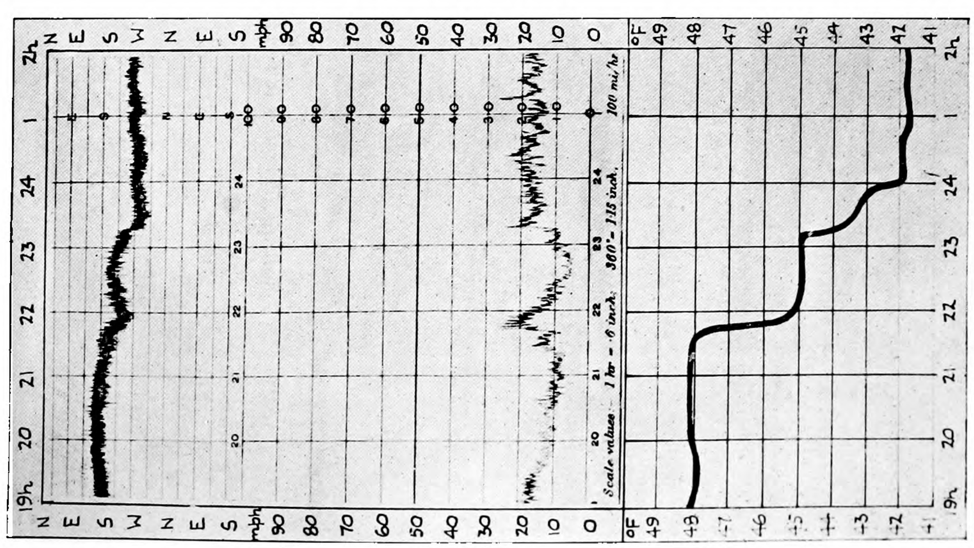
Record A1.—Valentia, March 31, 1925.



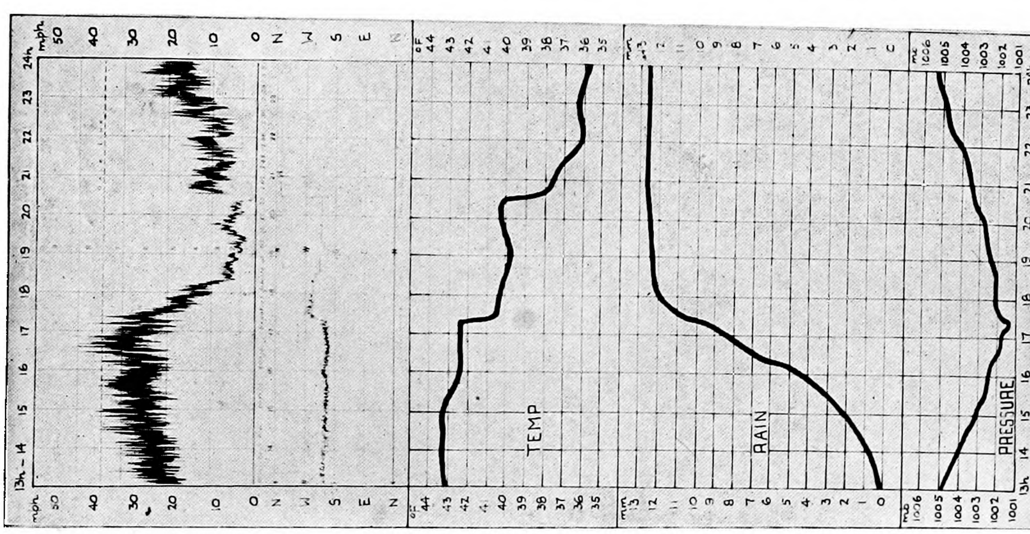
Record A6.—Spurn Head, March 31 to April 1, 1925.



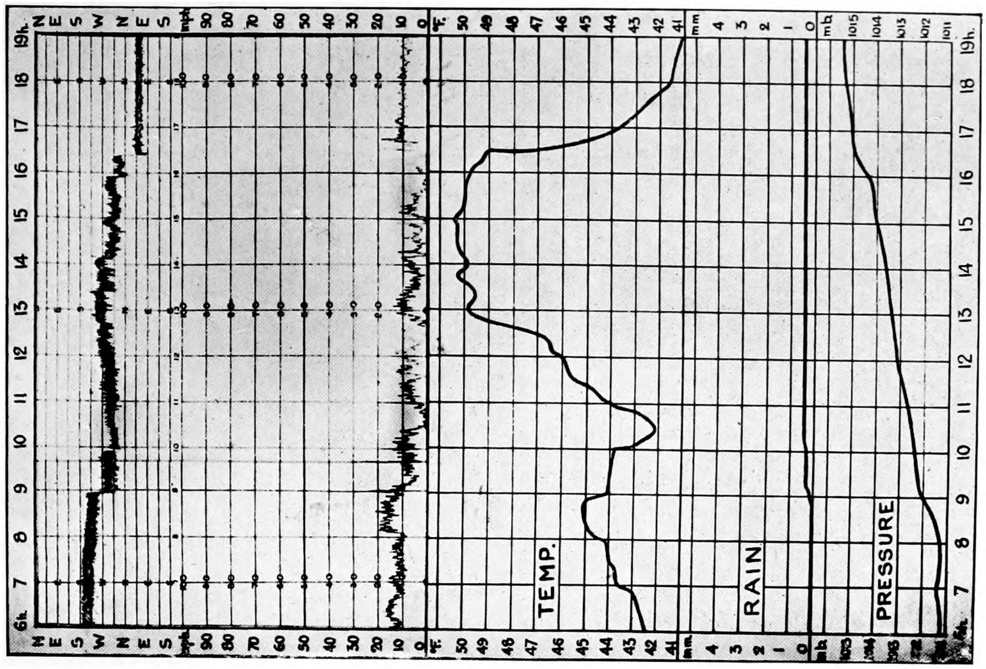
Record A4.—Scilly, March 31 to April 1, 1925.



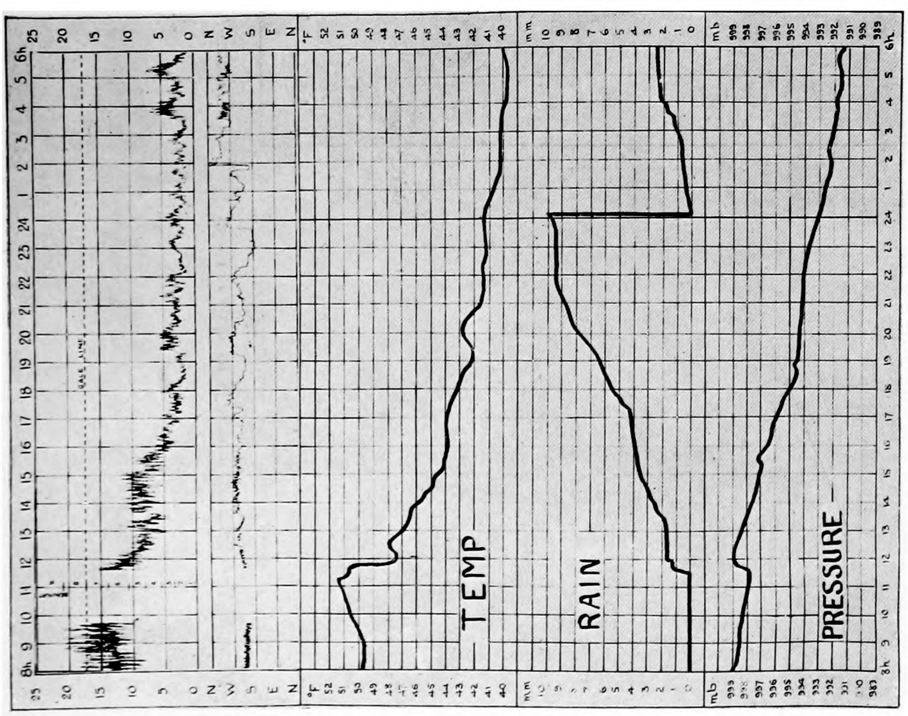
RECORD A5.—Sealand, March 31 to April 1, 1925.



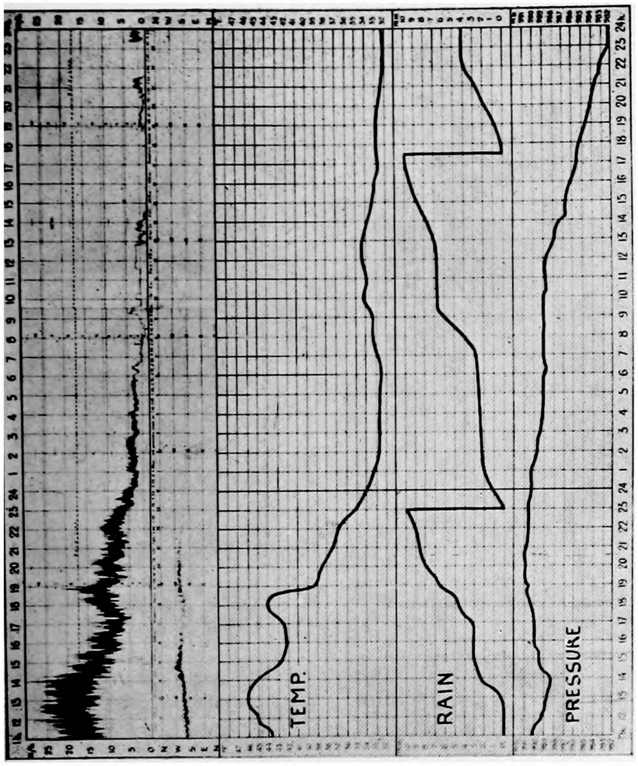
RECORD A7.—Eskdalemuir, March 31, 1925.



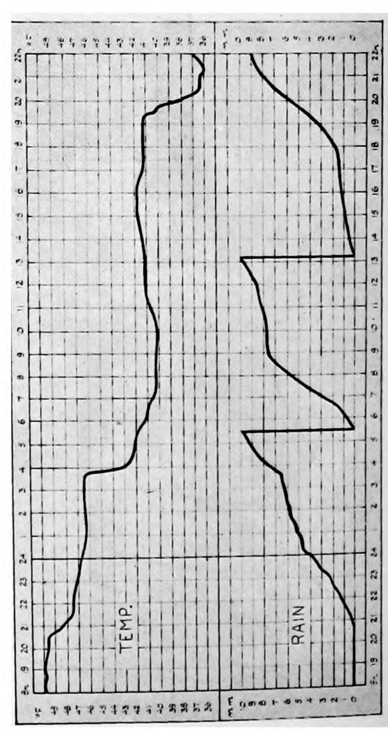
RECORD A8.—Felixstowe, April 1, 1925.



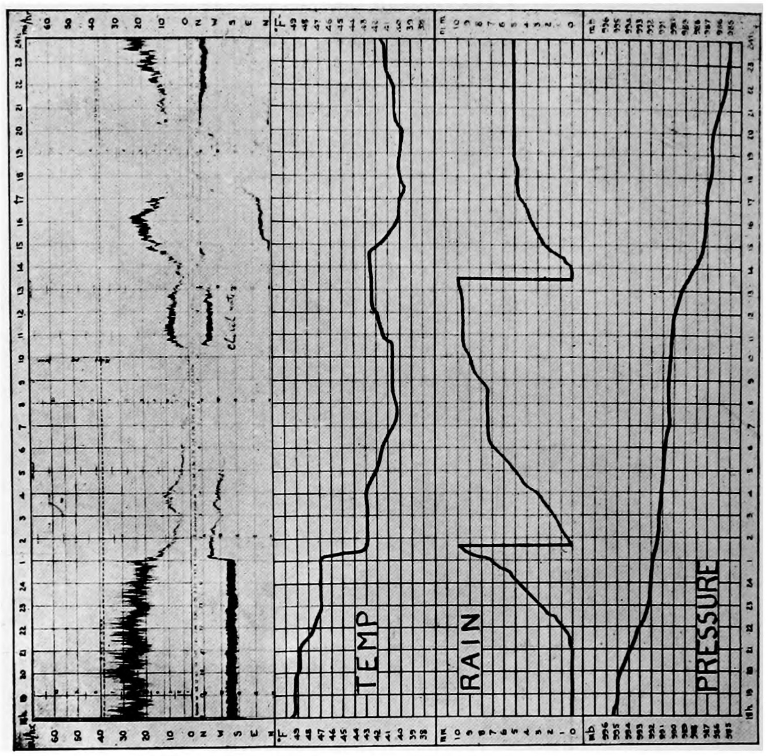
Record B1.—Valentia, February 10 to 11, 1925.



Record B2.—Eskdalemuir, February 10 to 11, 1925.



Record B4.—Southport, February 10 to 11, 1925.



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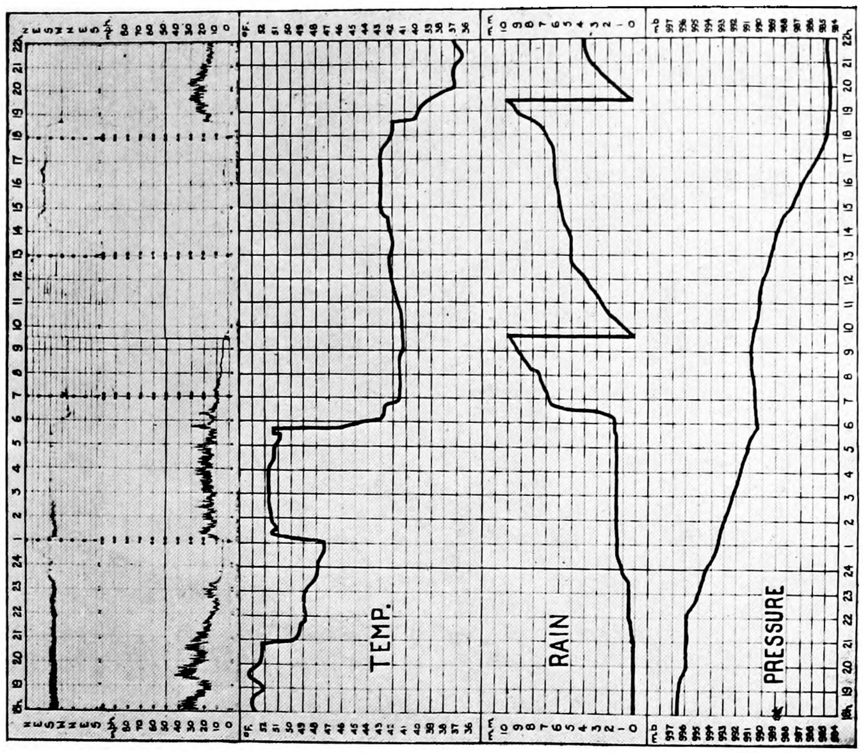
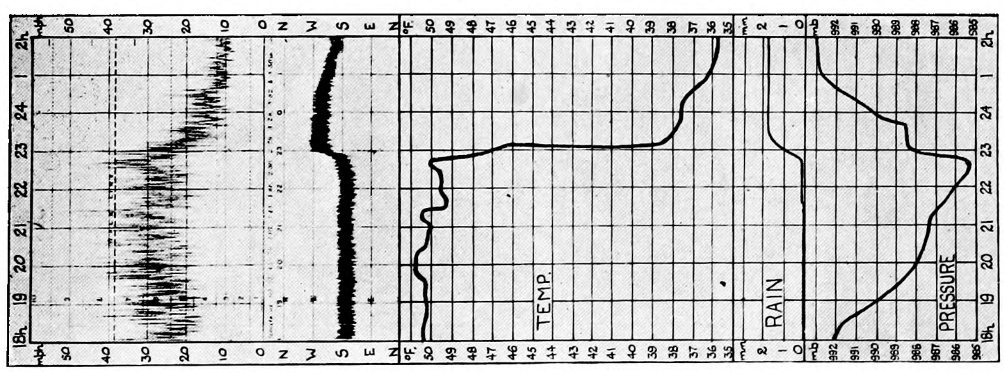
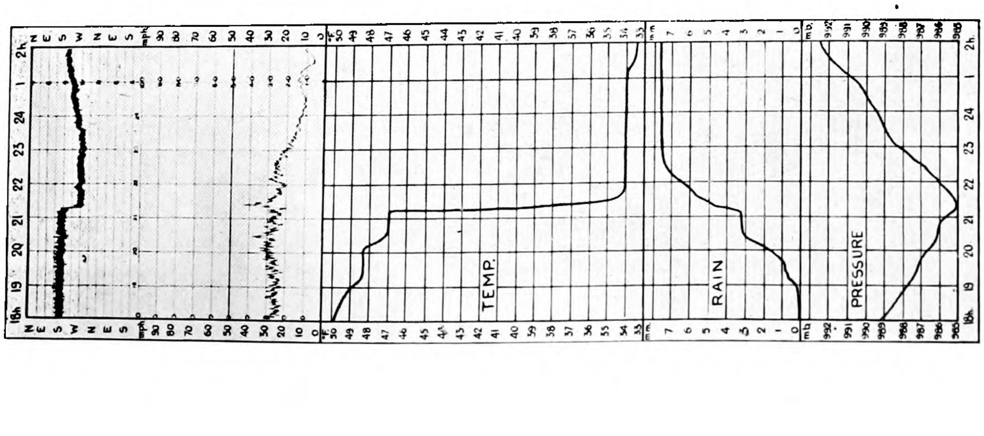


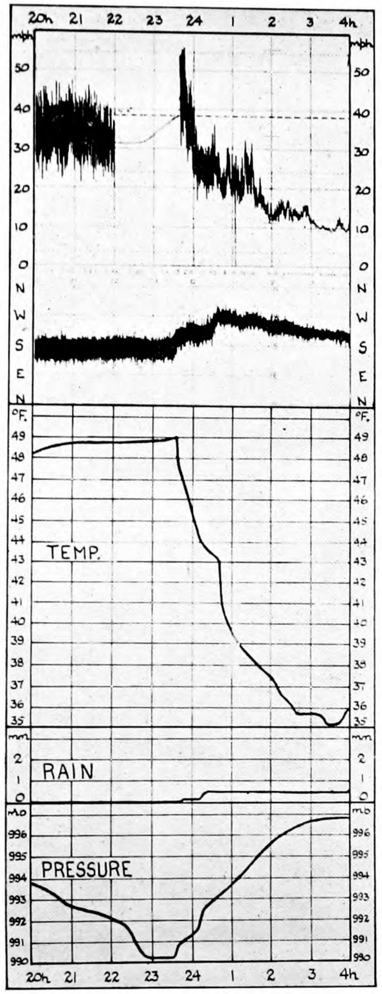
RECORD B7.—Sealand, February 10 to 11, 1925.



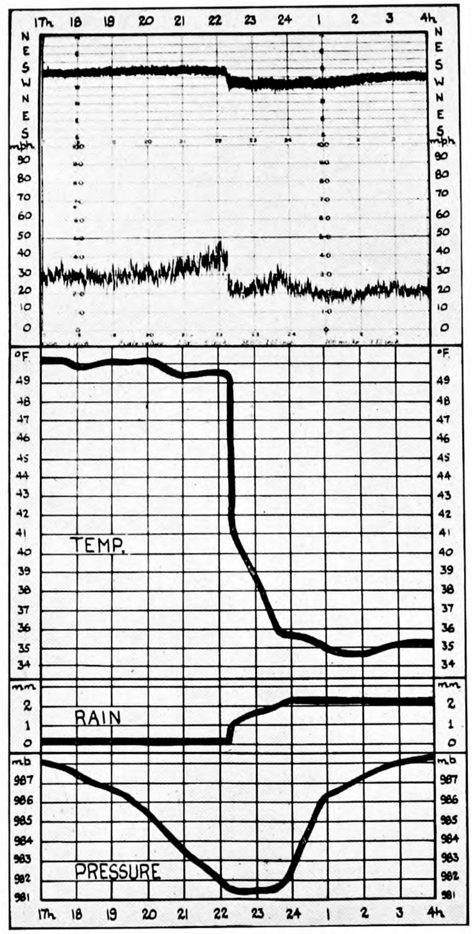
RECORD B6.—
Croydon, February 11 to 12, 1925.



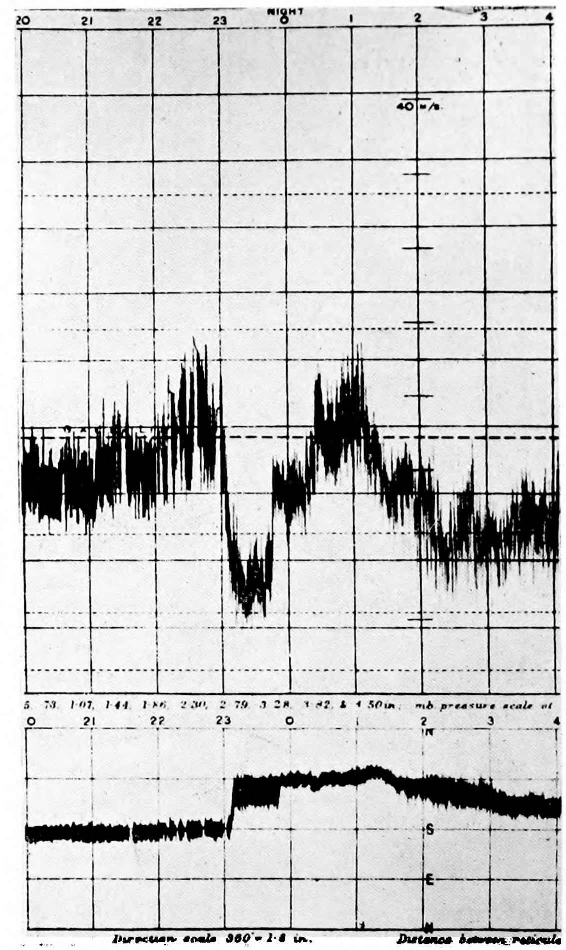
RECORD B5.—
Andover, February 11 to 12, 1925.



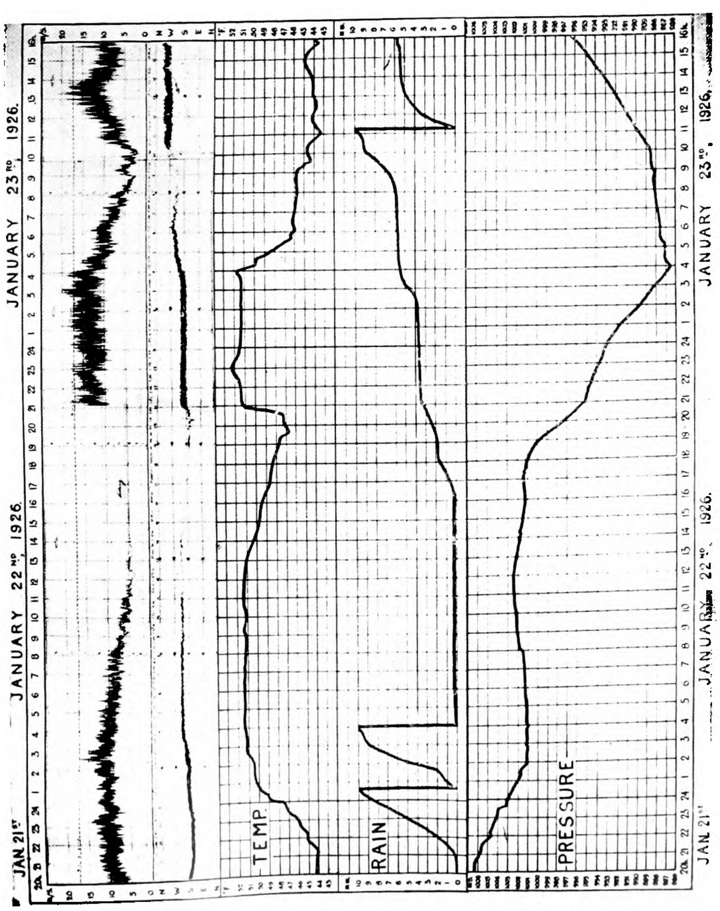
Record B8.—
Lympne, February 11 to 12, 1925.



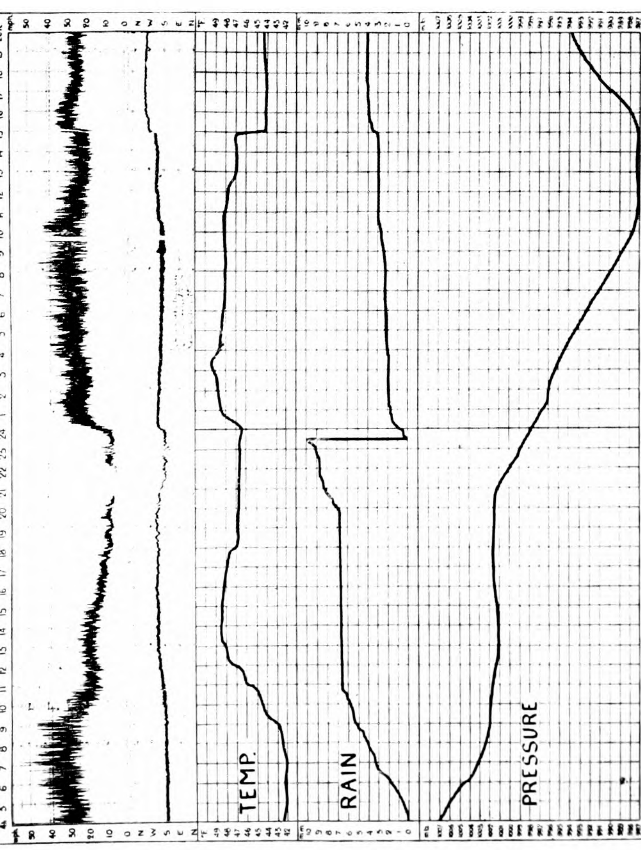
Record B9.—Cranwell, February 11 to 12, 1925.



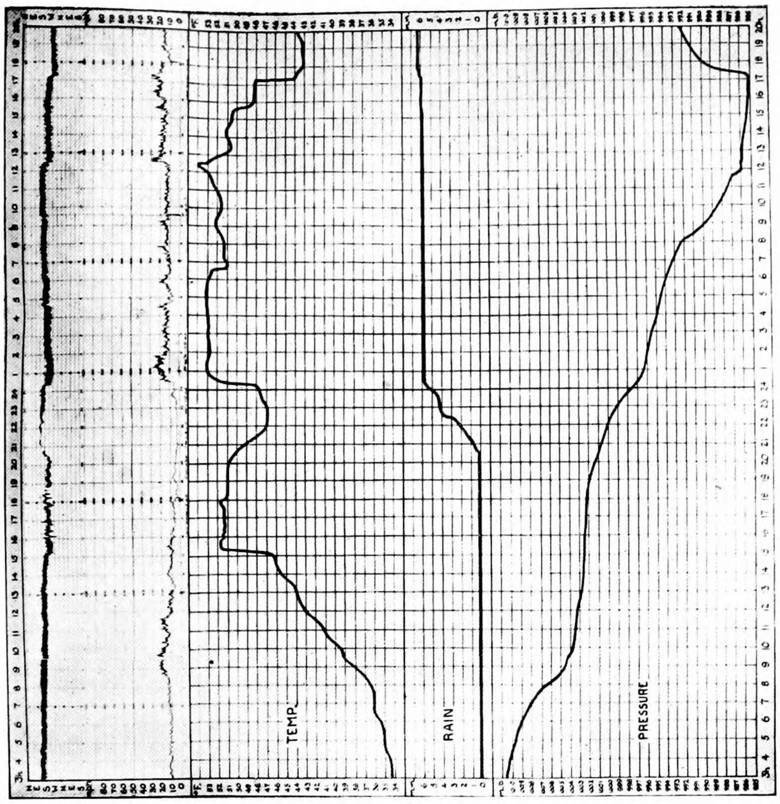
Record B10.—Spurn Head, February 11 to 12, 1925.



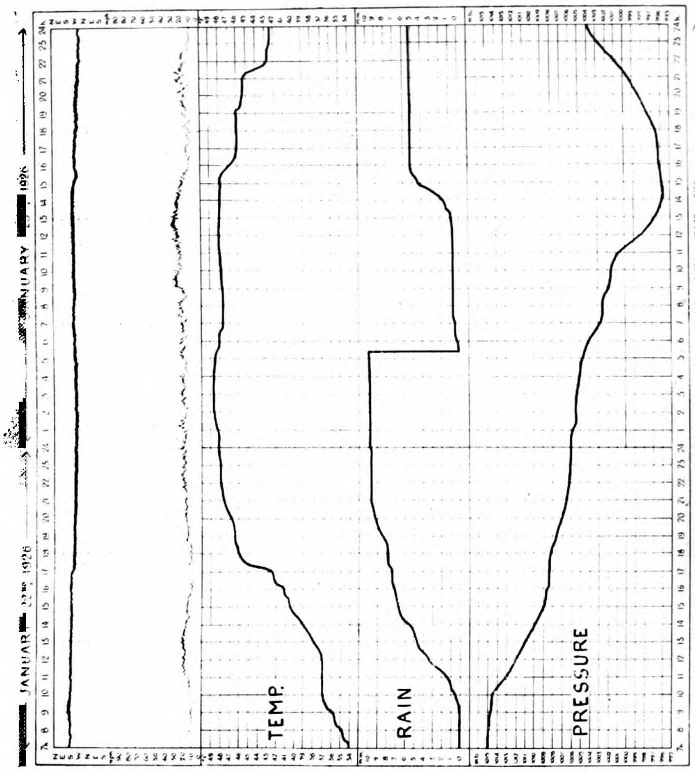
RECORD C1.—Valentia, January 22 to 23, 1926.



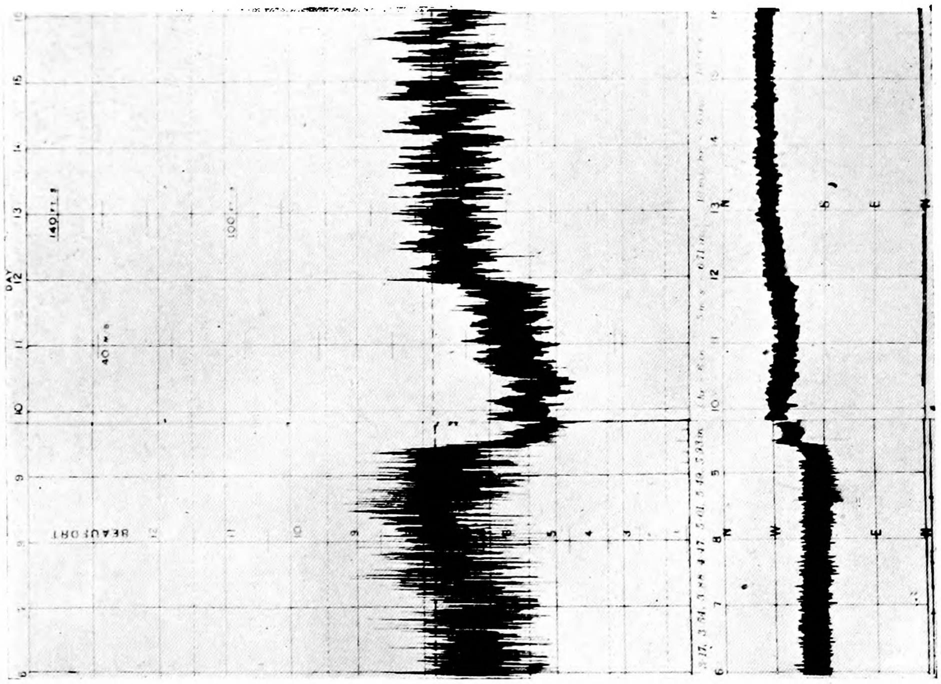
RECORD C2.—Holyhead, January 22 to 23, 1926.



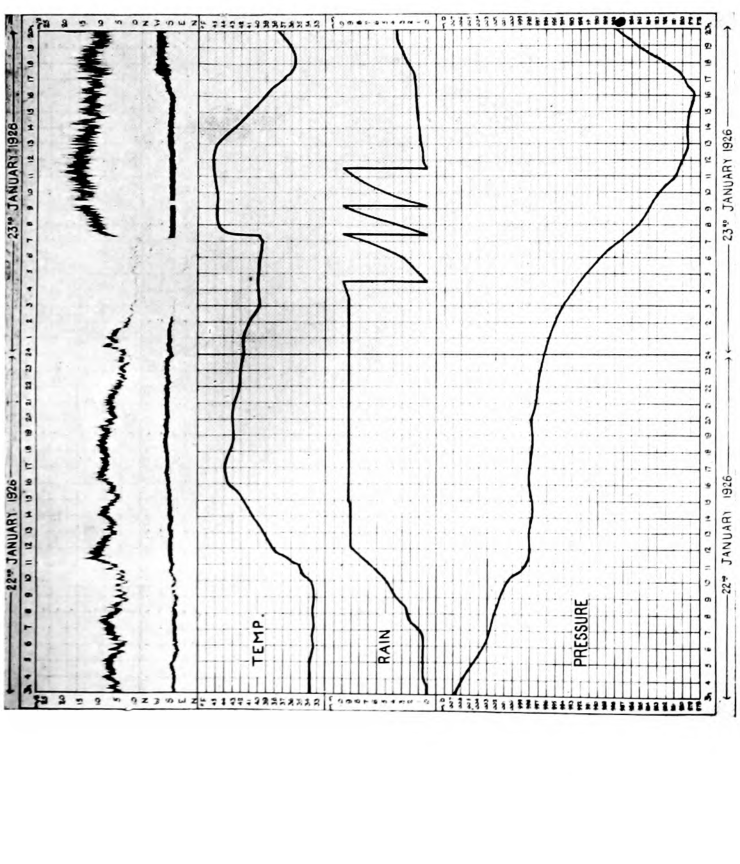
RECORD C3.—Sealand, January 22 to 23, 1926.



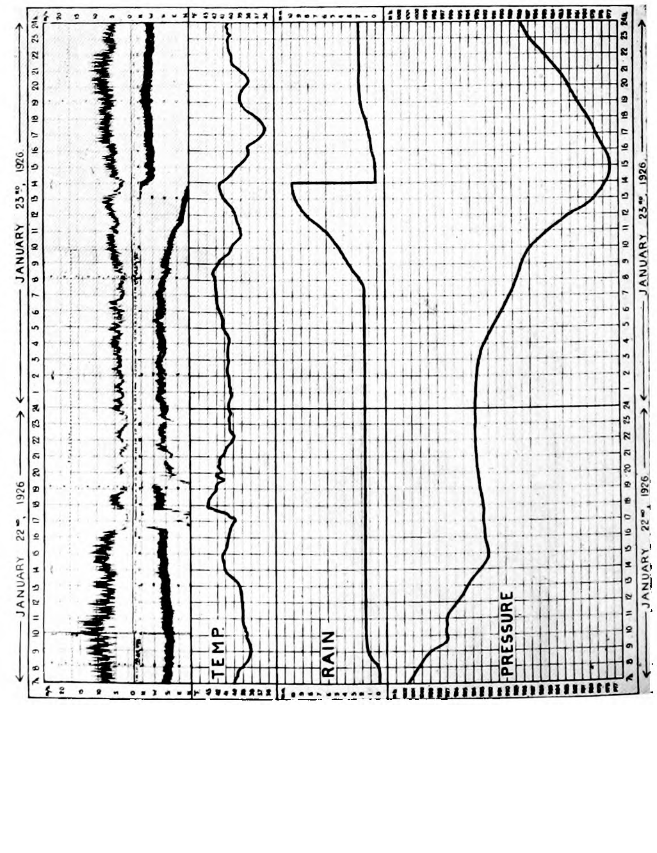
RECORD C4.—Andover, January 22 to 23, 1926.



Record C7.—Scilly, January 23, 1926.



Record C5.—Eskdalemuir, January 22 to 23, 1926.



Record C6.—Aberdeen, January 22 to 23, 1926.