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The Variation of Meteorological Elements at St. Helena

and at some other places in the Atlantic Region

By C. E. P. BROOKS, D.Sc.

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THE VARIATION OF THE METEOROLOGICAL ELEMENTS AT ST. HELENA AND AT SOME OTHER PLACES IN THE ATLANTIC REGION

ABSTRACT

It is shown that since 1892 pressure, wind velocity and temperature (mean daily maximum and minimum) at St. Helena have been subject to marked secular variations, pressure and maximum temperature rising, while since 1903 wind velocity has decreased. These variations are inter-related in such a way that they are probably real and not instrumental, and it is shown that the most likely explanation is the gradual northward movement of the South Atlantic anticyclone. The variations are further examined by the calculation of "partial" correlation coefficients. The investigation is then extended to the North Atlantic; in Sierra Leone pressure has increased slowly while temperature has decreased slowly and rainfall has decreased by an average of 2·4 inches a year. These variations also are investigated by "partial" correlation. In the Azores and Madeira pressure has increased more rapidly than in Sierra Leone, and it is shown that the variations are probably accounted for by an increase in the intensity of the North Atlantic anticyclone and in the strength of the north-east trade wind. Various meteorological changes in Europe, North America and the Arctic, which may be related to the above variations, are also discussed.

§ I Secular Changes of the Meteorological Elements at St. Helena.

The meteorological station at St. Helena lies in the heart of the south-east trade wind near an important centre of action, and is far distant from any other station. The present station was founded in 1892 and continued until 1924 without change of observer. The observations up to the year 1908 were discussed by J. S. Dines in 1910 (*) ; in preparing the tables for the collection of "long series" of data called for by the International Meteorological Committee the whole set of observations was re-investigated. The station has never been inspected nor the instruments compared with standards since observations were first started in February, 1892, and it was therefore necessary to examine the records very closely in order to discover and allow for the gradual development of instrumental or other errors. The examination showed that the observations appeared to be trustworthy, and that certain changes which appeared at first sight to be due to errors were real and formed part of a remarkable progressive change in the climate of St. Helena since 1892. In the course of the investigation data for other stations in the Atlantic region were examined for purposes of comparison, and helped to throw some light on the nature of the change.

At St. Helena the elements considered include barometric pressure, mean daily maximum, and mean daily minimum temperature, and wind velocity; the mean values of these elements for each year from 1892 to 1923 are given in Table I. The

(*) London, Meteorological Office, M.O. 203. "The Trade Winds of the Atlantic Ocean," London, 1910.

TABLE I—ANNUAL VALUES AT ST. HELENA

—	Wind Velocity in m/s.	Pressure 32° F. lat. 45° Station Level in mb.	Mean Max. Temp. °F.	Mean Min. Temp. °F.	Rainfall in.
1892	—	945·2	65·3	56·7	36·64
1893	—	944·9	65·3	57·1	40·34
1894	—	945·1	66·1	57·3	39·09
1895	7·0	945·1	67·1	57·8	32·31
1896	7·2	945·4	65·7	57·2	40·52
1897	7·4	945·5	65·8	57·1	35·20
1898	8·0	944·9	65·1	55·7	33·95
1899	7·8	944·8	66·3	56·9	47·31
1900	7·5	945·5	67·4	56·8	30·97
1901	8·0	945·6	67·9	57·0	38·88
1902	—	945·6	67·7	56·5	35·00
1903	8·5	945·4	65·2	55·8	43·35
1904	—	945·8	65·3	55·7	45·69
1905	—	945·1	67·1	56·9	35·60
1906	7·3	945·8	65·8	55·8	49·77
1907	7·5	945·8	65·7	56·2	43·81
1908	8·1	945·7	64·8	55·6	39·36
1909	7·6	945·2	65·8	56·3	42·37
1910	7·5	945·3	66·1	56·5	44·39
1911	7·1	946·7	67·1	56·3	31·64
1912	7·2	946·6	67·5	57·1	44·25
1913	6·5	946·1	69·6	57·0	43·64
1914	6·7	946·5	69·0	56·2	49·22
1915	6·6	946·0	69·7	56·3	40·93
1916	6·4	945·7	70·1	56·1	30·99
1917	6·7	945·9	69·5	56·6	49·39
1918	—	946·4	69·7	56·1	40·06
1919	—	946·5	69·9	56·2	41·76
1920	6·9	946·8	71·8	56·7	37·44
1921	6·5	947·5	71·0	57·1	42·00
1922	7·0	946·7	70·1	55·7	41·76
1923	5·6	946·6	69·2	54·9	49·50

figures for 1892 were completed by inserting the average January values over the period 1893 to 1923. The pressure values have been corrected to the 1923 height above mean sea level, but some uncertainty exists as to what this height actually is. According to Mr. A. L. C. Hands, the observer from 1892 until 1923, the height of the barometer cistern was 1,905 feet from the beginning of observations in 1892 until November 19th, 1910. No information is available as to how this height was arrived at, and it was probably estimated from a rough survey of the island. On November 19th, 1910, the barometer was removed to a new site which was stated to be at a height of 2,070 feet, a difference of 165 feet, but a few years' observations sufficed to show that the difference could not be anything like this amount. Finally, in 1925, a survey of the country between the old and new sites, carried out by Major H. E. W. Iremonger, gave the difference of elevation between them as 75 feet, and this figure has been adopted. A rough survey by Captain Mainwaring, the present observer, gave the height of the present site as 1,900 feet, but a comparison with some earlier observations at a low-level station and with isobaric charts of the South Atlantic based on observations taken on board ships suggests that this determination is about 100 feet too low. The mean annual values of pressure reduced to the present height, at 32°F and lat. 45°, are given in Table I, and are also shown graphically in Figure 1.

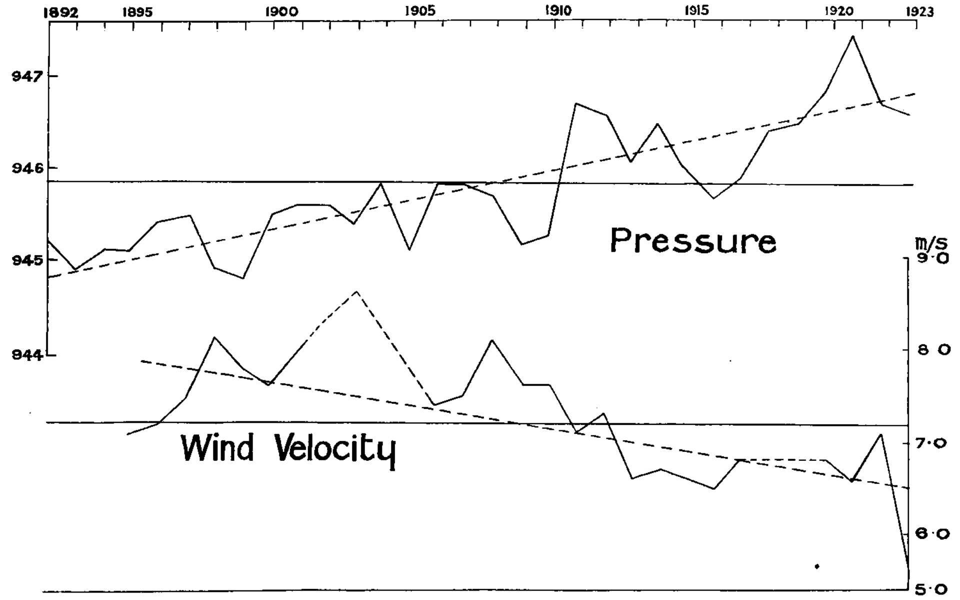

Fig. 1—Pressure and Wind Velocity at St. Helena.

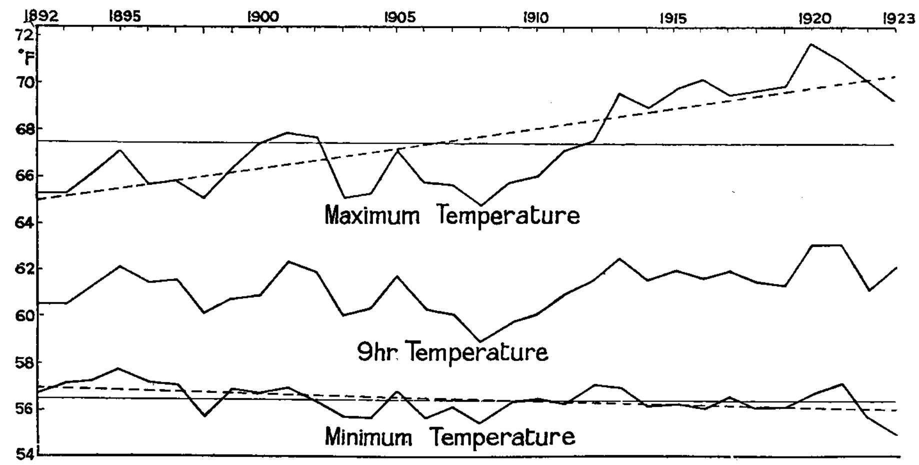

Fig. 2—Temperatures at St. Helena.

The wind velocity has been obtained from the records of a Robinson anemometer. The same instrument has been in use throughout the period, but in 1904 it was sent to England for a thorough overhaul, and for this reason there is a gap in the records from January, 1904, to May, 1905. There are other shorter gaps, especially in the records for the earlier years, so that only 24 years could be regarded as sufficiently complete (Table I). The data for these years indicate a gradual rise in the average wind velocity from 1895 to 1903, in which year the average velocity was 8·6 metres per second, followed by a gradual fall during the remainder of the period, the average velocity for 1923 being 5·6 metres per second. When this variation of the wind velocity was first noticed, it appeared to be slightly greater than it actually is, owing to an error in the table on pages 18 and 19 of "The Trade Winds of the Atlantic Ocean," in which the wind velocities for the period December, 1901, to November, 1902, were corrected by using the factor 3 instead of 2·8, thus introducing an excess of 7 per cent. The mean annual velocities are shown graphically in Figure 1, and the fall from 1903 to 1923 is very striking. We have to suppose either that there has actually been a great falling off in the wind velocity or that the anemometer has been deteriorating gradually, with the result that it has worked more and more stiffly. The latter is an unlikely assumption as at these velocities any resistance to the motion of the cups must be very great if it is to affect the records appreciably.

The series of mean values of temperature at St. Helena is very striking. There is no record of any change of site or other discontinuity in the St. Helena temperature records, but between January and February, 1913, there was an extraordinary rise in the mean daily maximum temperature. From 1892 to 1912 the *highest* of the annual means of the mean daily maximum was 67·9°F., whereas from 1913 to 1923 the *lowest* annual value was 69·0°F. This remarkable rise suggests the development of an instrumental error in the maximum thermometer, but intrinsic evidence, as will be seen, shows that the figures are probably correct. Figure 2 shows that the rise actually began in 1908 and continued with remarkable steadiness until 1920, the difference between the annual means of the daily maxima in these two extreme years being as much as 7·0°F. Out of the twelve pairs of successive years there were only two in which there was a decrease of the mean daily maximum from one year to the next. Since 1920, however, there has been a steady fall. The annual averages of the mean daily minimum do not share in the rise of the mean daily maximum, but remain almost constant. Intermediate between the maximum and minimum, but nearer the latter than the former, is the dry-bulb reading at 9h. ; if the rise in the mean daily maximum is real and not instrumental, we should expect the 9h. dry bulb readings to show a rise during the same period, which is rather less than half the rise of the mean daily maximum. The means obtained before and after the apparent break early in 1913 are as follows :—

	1892-1912	1913-1923	Change
A. Mean daily maximum, °F	66·2	70·0	+3·8
B. Dry bulb, 9h.,°F.	60·8	62·0	+1·2
C. Mean daily minimum, °F.	56·6	56·3	—0·3
Ratio, (A-B)/(B-C)	1·29	1·40	

If we suppose that the 9h. dry bulb and the mean daily minimum are correct, and there is no reason to doubt them, and that the mean daily maximum is correct for the period 1892-1912, then we can apply the value of 1·29 for the ratio (A-B)/(B-C) to the period 1913-1923 also. From this ratio and the values of B and C, the value of the mean daily maximum during the latter period comes out as 68·8°F., and the difference of 1·2°F. between this value and the observed mean of 70·0°F. is only just over a third of the increase in the mean daily maximum from 66·2°F. to 70·0°F. Further, the comparison of the diurnal variation of temperature at a number of different stations shows that a large daily range is usually due mainly to an accentuation of the maximum during the hottest part of the day, and not to an exaggeration of the scale in all parts of the curve. Thus, if the mean daily range at St. Helena increased, the ratio (A-B)/(B-C) should also increase. From this consideration it seems probable that the rise in the mean daily maximum is a real phenomenon, and not due to instrumental error.

§ 2. Secular Change of South Atlantic Anticyclone.

These secular changes of pressure, wind velocity and temperature are obviously related in some way, and they suggest that an important change in the meteorology of the South Atlantic has been in progress. The normal position of the centre of the South Atlantic anticyclone is in about latitude 26°S. longitude 5°E. to 15°W. St. Helena, in latitude 16°S. longitude 6°W lies between this anticyclonic centre and the equatorial low pressure belt, and a rise of the barometer at St. Helena means either that the high pressure system has become intensified or that it has moved northward. Of these alternatives, the second appears to be the more probable. An intensification of the whole system should result in an increase of the wind velocity at St. Helena, whereas Figure 1 shows a slight increase from 1892 to 1903, and a very marked decrease from 1903 to 1923. The rise of pressure has, however, been almost continuous, and two explanations of the curve of variation of wind velocity are possible. The anticyclonic centre may have increased in intensity from 1892 to 1903 and only commenced to move northward in the latter year, or, if the northward movement has been continuous, the steepest barometric gradient between the anticyclonic centre and the belt of equatorial calms is in such a position relative to the centre that it passed over St. Helena about 1903. The second alternative is illustrated

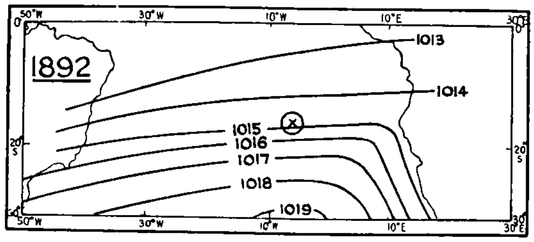

Fig. 3.

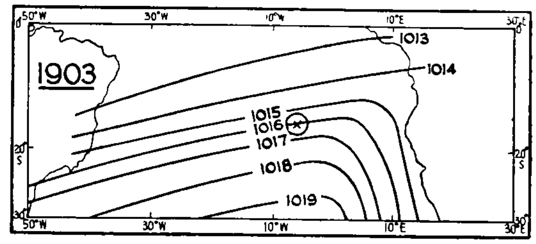

Fig. 4.

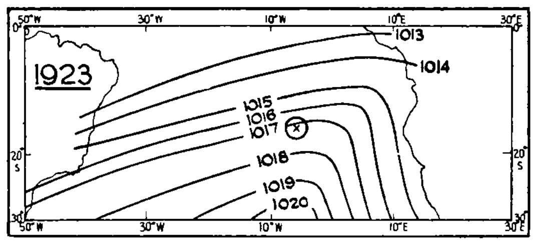

Fig. 5.

in Figures 3-5, which show the distribution of pressure over the South Atlantic between the equator and 30°S. The normal distribution of barometric pressure in this area shows that it can be divided into three parts : (1) an area near the equator in which pressure falls rather slowly towards the north and the wind velocity is moderate ; (2) an area in the neighbourhood of St. Helena in which pressure falls rapidly towards the north and the wind velocity is high ; (3) an area near the anticyclonic centre in which pressure again falls slowly towards the north and the wind velocity is low. It is suggested that the conditions in 1892, when the wind velocity was moderate, were as shown in Figure 3, in which St. Helena (marked by a cross) lies to the north of the area of steepest pressure gradient. The northward motion of the anticyclone resulted also in a northward shift of the area of steepest gradient, and by 1903 (Figure 4) the latter had come to be directly over St. Helena. The isobars may also have been crowded together somewhat. After 1903 the further northward movement of the anticyclone carried the area of steepest pressure gradient still further north, and the wind velocity again decreased (Figure 5).

This northward movement of the anticyclone would bring in its train other phenomena, such as :—

(1) higher pressure,

(2) higher day temperature,

(3) A greater daily range of temperature, and therefore little change in the night temperature.

The rise in the day temperature did not begin until 1909, when the wind velocity had already fallen considerably; probably the high wind velocities about 1903 prevented the increase in the maximum temperatures which would otherwise have resulted from the approach of the anticyclonic centre. It might also be supposed that the rainfall would decrease, but the observations actually show a slight increase. It is probable that the rainfall of St. Helena is made up of two types, orographic rainfall due to the forced ascent of air where the wind strikes the high ground, and convectional rainfall due to the heating of the surface. A small wind velocity would decrease the amount of the orographic rainfall but would increase the amount of convectional rainfall, and the latter tendency seems to have predominated. This supposition could be tested by an examination of the frequency of thunderstorms in St. Helena, but unfortunately no records of these phenomena are available.

§ 3. Decrease of Rainfall at Sierra Leone.

There is one other remarkable example of secular variation of climate within the Atlantic area with which the phenomena at St. Helena may have some point of contact, namely, the remarkable decrease of rainfall on the west coast of Africa, and especially at Sierra Leone. There is no anemometer at Sierra Leone, so the discussion

Table II—Annual Values at Sierra Leone

—	Pressure 32° F. lat. 45° Station Level	Mean Max. Temp.	Mean Min. Temp.	Rainfall
	29+ in.	°F.	°F.	in.
1896	·644	88·4	74·0	203·55
1897	·624	88·5	73·1	164·31
1898	·625	87·8	73·3	144·64
1899	·627	88·8	73·9	146·63
1900	·645	88·4	73·7	175·43
1901	·645	88·5	74·0	198·84
1902	·651	87·8	73·8	183·41
1903	·644	88·4	73·5	173·31
1904	·666	87·5	72·7	158·16
1905	·682	88·4	73·6	176·94
1906	·663	88·4	73·7	170·92
1907	·650	88·3	73·1	153·13
1908	·629	87·9	72·9	142·85
1909	·640	88·4	72·8	140·97
1910	·621	88·7	73·3	133·44
1911	·630	88·4	72·9	136·59
1912	—	88·9	73·6	130·07
1913	·652	88·7	72·3	124·48
1914	·681	88·4	72·8	102·46
1915	·651	88·1	74·5	127·40
1916	·646	87·7	74·2	149·21
1917	·656	87·4	73·7	130·81
1918	·677	87·2	73·0	102·48
1919	·684	87·2	72·1	117·98
1920	·670	87·1	72·8	106·85
1921	·647	87·4	72·1	134·17
1922	·667	86·6	73·7	153·89
1923	·652	87·1	73·9	125·28

was limited to the values of mean pressure, mean daily maximum and mean daily minimum temperature, and total rainfall. The annual values are given in Table II,

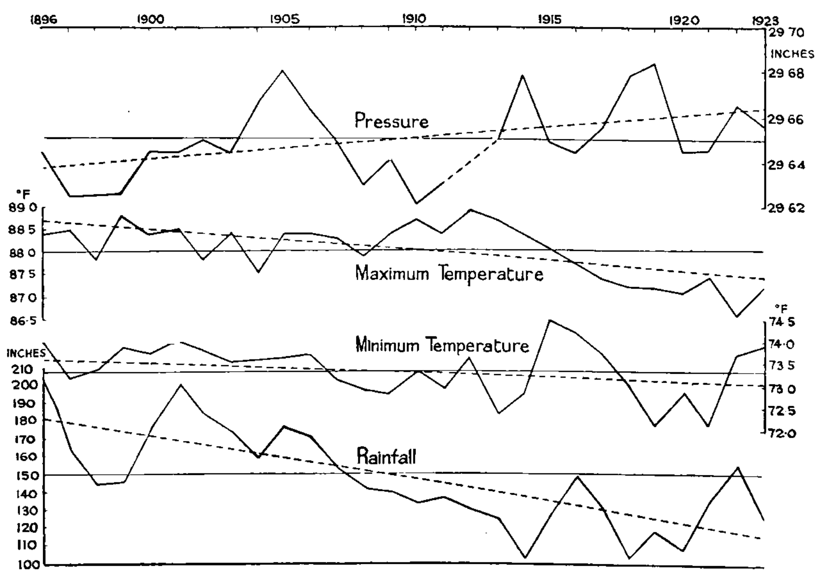

Fig. 6.—Pressure, Temperature and Rainfall at Sierra Leone, 1896-1923.

and are shown graphically in Figure 6, from which it will be seen that the decrease of rainfall has been associated with a slight rise of pressure but with a fall of the mean daily maximum temperature.

§ 4. Correlation Coefficients.

In order to investigate these relationships more closely, the various elements, both at St. Helena and at Sierra Leone, were correlated with each other and with "time." The latter variable was taken as the number of years before or after the middle year of the series, the early years being considered as negative and the later years as positive. This method of dealing with secular variations is convenient, though not entirely free from technical objections. The mean values and standard

Table III—Mean Values and Standard Deviations

	St. Helena		Sierra Leone	
	Mean Values	Standard Deviations	Mean Values	Standard Deviations
Pressure at Station Level	945·9 mb.	0·67mb.	29·651 in.	0·019 in.
Wind Velocity (m/s.)	7·2	0·64	—	—
Mean Maximum Temperature (°F.)	67·6	2·04	88·0	0·59
Mean Minimum Temperature (°F.)	56·4	0·65	73·3	0·62
Rainfall (in.)	40·96	5·86	147·34	26·67

deviations are shown in Table III, where the most interesting point to notice is the large standard deviation of the mean daily maximum temperature at St. Helena, which is mainly due to the secular variation.

St. Helena.—Table IV contains the correlation coefficients of zero order at St. Helena for the 24 years for which the wind velocity is available. Six of the ten coefficients exceed a value of 0·5; the largest being pressure with "time" and mean daily maximum temperature with "time" and with wind velocity. It is interesting to note that though the mean daily maximum has a large positive correlation with "time" and the mean daily minimum has a negative correlation with "time," the two temperature series have a small positive correlation. In Table IVa the correlation

Table IV—St. Helena Coefficients of Zero Order, 24 years

1 = Wind Velocity.
2 = Pressure.
3 = Mean daily maximum temperature.
4 = Mean daily minimum temperature.
5 = "Time."

12	—·60	—	—	—	—	—	—
13	—·75	23	+·71	—	—	—	—
14	+·04	24	—·10	34	+·09	—	—
15	—·67	25	+·80	35	+·76	45	—·40

Table IVa—St. Helena, Coefficients of Zero Order, 32 years

23	+·73	—	—	—	—
24	—·25	34	—·01	—	—
25	+·83	35	+·79	45	—·46

coefficients between pressure, mean daily maximum and mean daily minimum temperature, and "time," are given for the whole series of 32 years. The coefficients are generally slightly larger than those in Table IV, that between pressure and "time" reaching the value of +·83.

Table V gives the coefficients of the regression equations connecting the different elements directly with "time." These give the average amount of progressive change of the element in a year, and are shown by the straight lines of Figures 1 and 2.*

TABLE V—ST. HELENA—CORRELATION WITH "TIME" (ALL YEARS)

Correlation with "Time"	Wind Velocity	Pressure	Temperature Mean Max.	Temperature Mean Min.
	m/s.	mb.	°F.	°F.
Correlation coefficient	—·67	+·83	+·79	—·46
Regression coefficient	—·05	+·06	+·17	—·03

Tables VI, VII and VIII give the "partial" correlation coefficients at St. Helena. The calculations were carried out to four places of decimals, but the third and fourth places, though necessary to secure accuracy in the final results, have no intrinsic interest, and have been omitted from the tables. Table VIII shows the direct relationships between the different variables, when all the others are supposed to remain constant.

TABLE VI—ST. HELENA PARTIAL COEFFICIENTS OF 1ST ORDER

12·3	—·15	14·2	—·03	23·1	+·49	25·1	+·67	35·1	+·53
12·4	—·60	14·3	+·16	23·4	+·72	25·3	+·57	35·2	+·47
12·5	—·14	14·5	—·35	23·5	+·25	25·4	+·83	35·4	+·88
13·2	—·57	15·2	—·40	24·1	—·10	34·1	+·18	45·1	—·51
13·4	—·75	15·3	—·23	24·3	—·24	34·2	+·24	45·2	—·53
13·5	—·49	15·4	—·72	24·5	+·39	34·5	+·68	45·3	—·74

TABLE VII—ST. HELENA PARTIAL COEFFICIENTS OF 2ND ORDER

12·34	—·12	14·23	+·13	23·14	+·52	25·13	+·55	35·12	+·32
12·35	—·02	14·25	—·32	23·15	+·21	25·14	+·72	35·14	+·74
12·45	—·01	14·35	—·02	23·45	—·02	25·34	+·59	35·24	+·72
13·24	—·58	15·23	—·18	24·13	—·22	34·12	+·27	45·12	—·60
13·25	—·47	15·24	—·49	24·15	+·37	34·15	+·62	45·13	—·73
13·45	—·37	15·34	—·17	24·35	+·32	34·25	+·65	45·23	—·75

TABLE VIII—ST. HELENA PARTIAL COEFFICIENTS OF 3RD ORDER

12·345	—·02	—	—	—	—	—	—
13·245	—·37	23·145	—·03	—	—	—	—
14·235	—·01	24·135	+·32	34·125	+·60	—	—
15·234	—·13	25·134	+·59	35·124	+·62	45·123	—·75

In Table VIII wind velocity shows itself most closely related to mean daily maximum temperature. A high wind velocity keeps down the maximum temperature, but it was thought possible that the inverse relationship might also hold. The anemometer is at a height of 632 metres—nearly 2,000 feet—and at this height the normal diurnal variation of wind velocity near sea level is reversed. The mean hourly velocity for the period 1892 to 1907 ranges from 7·7 metres per second at 7h. to 6·6 metres per second at 14h. The decrease of wind velocity during the day is due to the interchange of air by convection between the low ground and the free air at the level of the anemometer. An increase in the day temperature, by increasing convection, would lower the mean wind velocity during the afternoon. In order to check this supposition the data for 1913 (the last year for which the velocities had

* The curve of wind velocity is represented best by the expression

$$V\ (m/s.) = 7{\cdot}63 + {\cdot}0102\ (t - 1900) - {\cdot}0035\ (t - 1900)^2$$

where t is the date in years. The correlation coefficient between the annual values calculated by this formula and the observed values is + ·75.

been tabulated hour by hour) were examined. The mean velocity for the year was found to range from 7·0 metres per second at 7h. to 6·0 metres per second at 15h. Compared with the average for the period 1892 to 1907 the year 1913 showed a decrease of 0·7 metres per second in the early morning and 0·6 metres per second in the afternoon. This seems to show that no part of the decrease of wind velocity is due to the increase in the maximum temperature, the whole being due to a change in the barometric gradient.

The small " partial " coefficients between wind velocity and pressure and between wind velocity and " time " are due mainly to the fact previously explained that the relationships are not linear, the highest wind velocity occurring at an intermediate stage between the highest and the lowest pressures.

The apparent relationship between pressure and mean daily maximum temperature is found to be due to the fact that both these variables have a high correlation with " time." The temperature relationships are of great interest. The coefficients of zero order in Tables IV and IVA, show a large positive correlation between maximum temperature and " time," a moderate negative correlation between minimum temperature and " time," and a negligible correlation between maximum and minimum temperatures. The partial coefficients of Table VIII show large positive correlations between maximum temperature and minimum temperature and between maximum temperature and " time," and a large negative correlation between minimum temperature and " time." Evidently the minor fluctuations of the mean daily maximum and minimum temperatures agree, but are superposed on a gradual divergence of the curves, the mean daily maximum rising while the mean daily minimum falls slowly. This can be seen also from the curves in Figure 2.

From the partial coefficients in Table VIII the following regression equation has been deduced for calculating missing values of the wind velocity —

$$W = 10{\cdot}4 - {\cdot}02\,(P - 940) - {\cdot}16\,(M - 50) - {\cdot}01\,(m - 50) - {\cdot}025\,(t - 1900)$$

where W is the wind velocity in metres per second, P is the mean pressure in millibars at the station level of 1923, M is the mean daily maximum temperature and m the mean daily minimum temperature, both in Fahrenheit degrees, and t is the date in years.

Sierra Leone.—Table IX gives the correlation coefficients of zero order. Only two exceed 0·5, mean daily maximum with " time " and rainfall with " time," but five coefficients exceed 0·4. In contrast with St. Helena, Sierra Leone shows a progressive decrease of maximum temperature, the fall being continuous from 1912 to 1920. The decrease of rainfall has averaged as much as 2·4 inches a year. The partial coefficients given in Tables XI, XII and XIII, do not show much change

TABLE IX—SIERRA LEONE, COEFFICIENTS OF ZERO ORDER

1 = Pressure.
2 = Mean daily maximum temperature.
3 = Mean daily minimum temperature.
4 = Rainfall.
5 = " Time."

12	−·43	—	—	—	—	—	—
13	−·15	23	+·15	—	—	—	—
14	−·22	24	+·32	34	+·45	—	—
15	+·44	25	−·63	35	−·26	45	−·74

TABLE X—SIERRA LEONE, REGRESSION COEFFICIENTS WITH " TIME "

(AVERAGE CHANGE IN ONE YEAR)

Pressure + ·0010 in.	Maximum Temperature — ·05°F.
Rainfall — 2·40 in.	Minimum Temperature — ·02°F.

TABLE XI—SIERRA LEONE PARTIAL COEFFICIENTS OF 1ST ORDER

12·3	—·41	14·2	—·10	23·1	+·10	25·1	—·55	35·1	—·22
12·4	—·39	14·3	—·18	23·4	+·01	25·3	—·62	35·2	—·21
12·5	—·22	14·5	+·16	23·5	—·01	25·4	—·62	35·4	+·12
13·2	—·09	15·2	+·24	24·1	+·25	34·1	+·43	45·1	—·73
13·4	—·06	15·3	+·42	24·3	+·28	34·2	+·42	45·2	—·73
13·5	—·04	15·4	+·41	24·5	—·28	34·5	+·39	45·3	—·72

TABLE XII—SIERRA LEONE PARTIAL COEFFICIENTS OF 2ND ORDER

12·34	—·39	14·23	—·07	23·14	—·01	25·13	—·54	35·12	—·19
12·35	—·22	14·25	+·01	23·15	—·02	25·14	—·55	35·14	+·16
12·45	—·19	14·35	+·19	23·45	+·11	25·34	—·63	35·24	+·16
13·24	—·05	15·23	+·22	24·13	+·23	34·12	+·42	45·12	—·73
13·25	—·04	15·24	+·24	24·15	—·26	34·15	+·41	45·13	—·72
13·45	—·12	15·34	+·42	24·35	—·30	34·25	+·41	45·23	—·72

TABLE XIII—SIERRA LEONE, PARTIAL COEFFICIENTS OF 3RD ORDER

12·345	—·18	—	—	—	—	—	—
13·245	—·10	23·145	+·09	—	—	—	—
14·235	+·14	24·135	—·27	34·125	+·41	—	—
15·234	+·25	25·134	—·55	35·124	+·18	45·123	—·73

from the co-efficients of zero order, except that the correlation between mean daily maximum temperature and rainfall has changed from + ·32 to — ·27. The positive correlation was due to the fact that both elements have a high negative correlation with " time " ; when " time " is eliminated it is seen that, as would be expected, high maximum temperature is associated with low rainfall and *vice versa*. The correlation of mean daily minimum with " time," — ·26 in Table IX, has become + ·18 in Table XIII. The general temperature-" time " relationships at Sierra Leone are the reverse of those at St. Helena ; the maximum temperature has decreased, the minimum temperature has increased and the two curves, while remaining similar in their minor details, have converged. A high minimum temperature goes with a high rainfall, but the most striking of all the Sierra Leone relationships is that between rainfall and " time," the coefficient of — ·74 in Table IX remaining almost unchanged in Table XIII. This suggests that the secular decrease of rainfall is due to some cause not connected with the local values of pressure and temperature, and, in fact, there has been a similar decrease of rainfall at Bathurst in Gambia, and in the Cape Verde Islands. Table XIV shows the average change of pressure in a year at various stations in or on the borders of the Atlantic Ocean.

§ 5. SECULAR CHANGE OF NORTH ATLANTIC ANTICYCLONE.

The prevailing wind at Sierra Leone is from ENE. in the morning, but from WSW. during the afternoon ; the former is the ordinary north-east trade wind strengthened to some extent by a land breeze, the latter is the sea-breeze. This afternoon sea-breeze brings in the moisture which gives Sierra Leone its heavy rainfall. Now it appears from Table XIV that while pressure has increased slightly at Sierra Leone during the period in question, further to the north-east, at Ponta Delgada, the increase has been more than twice as great. This points to an increase in the strength of the north-east trade wind, and such an increase would tend to keep down the sea-breeze and therefore decrease the rainfall.

TABLE XIV—CORRELATION AND REGRESSION COEFFICIENTS OF PRESSURE WITH "TIME"

	Correlation Coefficient	Regression Coefficient
		mb.
St. Helena	+·83	+·06
Sierra Leone	+·44	+·03
Ponta Delgada	+·45	+·07
Cape Town	+·04	—
Rio de Janeiro	+·04	—

Sierra Leone is on the south-eastern side of the North Atlantic sub-tropical anticyclone, whereas Ponta Delgada is nearer the centre but on the northern side. The secular increase of pressure at both these stations therefore implies a general increase in the intensity of that anticyclone. There has been a similar gradual increase of pressure at Madeira.

§ 6. RELATED EXAMPLES OF SECULAR CHANGE.

The cause of the variations of wind velocity, temperature and rainfall at St. Helena and Sierra Leone, thus appears to be a northward movement and perhaps an intensification of the South Atlantic sub-tropical anticyclone, and an intensification *in situ* of the North Atlantic sub-tropical anticyclone. The ultimate cause is still obscure ; it is hardly likely to be local temperature, because the variations of temperature at Sierra Leone are opposite to those at St. Helena. More probably the phenomena form part of some world-wide change, which may also include in its scope such phenomena as the period of mild winters in central Europe, which began about 1911.* There has, however, been a decrease of temperature at Gibraltar, which would naturally result from an increase in the strength of the north-east trade wind. In the central part of the United States the annual means of pressure have been above normal since 1910.

The amount of ice in the Arctic Sea also appears to have become greater about 1911. Off Iceland the average number of days per year on which ice was observed was 20 from 1904 to 1910, but during the years 1911 to 1917 the average number rose to 69. The area of ice in the Barents Sea and the Greenland Sea shows a similar change. In the Barents Sea, during the years 1904 to 1910 the average area covered by ice was 64,000 square kilometres below normal, while for the period 1911 to 1917 it was 148,000 square kilometres above normal. In the Greenland Sea there was also an increase in the ice-covered area ; in the years 1904 to 1910 the average area was slightly above normal, in the years 1911 to 1917 markedly above normal. In contrast with the conditions in the tropical Atlantic, however, the ice-conditions appear to have returned to a more normal state in 1918.

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