World Weather.[1]

By Sir GILBERT WALKER, C.S.I., F.R.S.

THE data recognised as necessary for the forecasting of weather come from a region that is ever widening. Before telegraphic charts were prepared the local observatory had to suffice; but the daily maps now used in predicting the weather of a single country of Europe may cover several thousand miles from west to east. Further, the desirability of warnings of the famines that have devastated semi-tropical and tropical countries has led to thinking in terms of seasons rather than days, and it soon became clear that seasonal variations over much of the earth are related to a surprising extent.

The first fact emerged in 1878 when Hoffmeyer pointed out the association between pressure in the North Atlantic and weather in Europe; and he was shortly followed by Blanford in India and by a group of continental meteorologists, including Teisserenc de Bort, Hann, Meinardus, and Pettersson. The far-reaching character of the subject was first visualised by Hildebrandsson, who in 1897 published the pressure data for ten years of 68 stations scattered over the world, and directed attention to certain relations between them as indicated by plotted curves. But in this and in his later papers the graphic methods used, and the shortness of the series of data available, generally prevented him from reaching final conclusions. In 1902 the Lockyers confirmed his discovery of the 'see-saw' of pressure in the Argentine and in India or Australia, and, still using purely graphical methods, they made it the basis of a classification of pressures over the world according as they oscillated with India or with Cordoba.

Since then, work on the Continent has been chiefly occupied with conditions in northern latitudes, and the more general problem has been mainly studied in connexion with Indian monsoon forecasting. For this purpose it was necessary to have quantitative information as to relationships, not merely visual impressions from plotted curves, and to work with seasonal, not annual, values. Also there was no hope of unravelling the tangled threads of causes and effects unless help was got by finding cases in which the conditions in one place were related with those in another in a subsequent season. Statistical methods were therefore indicated, and these efforts have culminated in the production of tables of relationships between conditions of pressure, temperature, rain, or river-flood at 32 centres scattered over the world. For each of these the correlation coefficient has been worked out for each quarter with those of contemporary quarters of the other stations, and also with those of one quarter before and after, and with those of two quarters before and after.

The total number of coefficients worked out is considerable, but simplification of the process has reduced the time spent on each to one or two minutes; also, by confining attention to those figures which are larger than the biggest that chance can be expected to produce, the number of significant figures is reduced to 396, and these fall very consistently into the scheme of oscillations indicated below.

The main conclusion reached is that there are three big swayings or surgings:

(*a*) The North Atlantic oscillation of pressure between the Azores or Vienna on one hand and Iceland or Greenland on the other;

(*b*) The North Pacific oscillation between the high-pressure belt and the winter depression near the Aleutian Islands; and

(*c*) The southern oscillation mainly between the South Pacific and the land areas round the Indian Ocean.

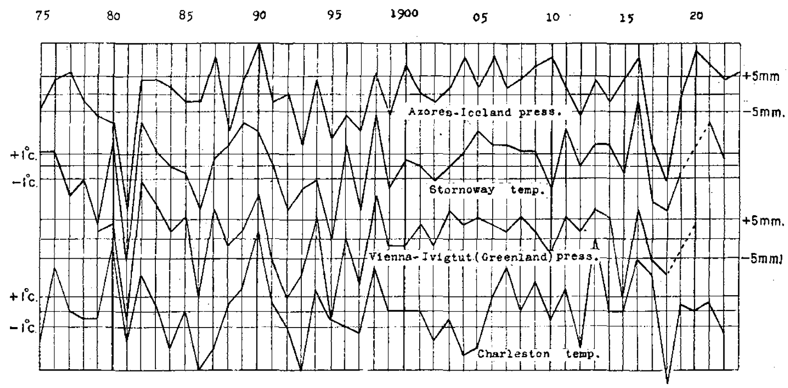

FIG. 1.—The North Atlantic oscillation.

Regarding (*a*), it is well established that a strengthening of the pressure gradients and of the ocean winds (indicated in Fig. 1 by the pressure differences Azores—Iceland and Vienna—Greenland) is associated with a strengthening of the Gulf Stream and higher temperatures in northern Europe (*e.g.* Stornoway in Fig. 1) and along the east coast of the United States (*e.g.* Charleston). The diagram shows the variations of these quantities in successive Januaries from 1875 for nearly fifty years, and the relationships are closer than is generally realised, the correlation coefficient (or degree of association) between the second and third curves being 0·88. Increased circulation goes also with higher temperature in Siberia and Java and less monsoon rainfall in India.

The North Pacific oscillation is rather like that of the North Atlantic, strengthening of the winter pressure differences and winds being associated with higher winter temperatures in central and

[1] This article contains the substance of a recent presidential address to the Royal Meteorological Society.

western Canada, and increased rain in the North Pacific coast states.

The southern oscillation is more far-reaching than the two oscillations just described, and as the effect of an abnormal season is propagated slowly, it may not appear at the other side of the earth until after an interval of six months or more. In illustration we may see in Fig. 2 in the topmost curve the variations of the Nile floods of July to October in successive years from 1889 to 1925; they are, however, reversed, so that a dip below the normal line like that of 1916 means a high Nile. The next curve shows the variations of temperature at Samoa in the following summer, December to February, and the correspondence is obvious, the coefficient between the departures being 0·72. The third curve is that of Samoa temperature during the succeeding autumn, March to May, which brings out the great persistence of the ocean temperatures. Following this we have the pressure at Port Darwin in North Australia for September to November, six months before the third curve, yet with so close a correspondence that the coefficient between them is 0·80. Lastly, we have the pressure at Zanzibar of December to February three months later, and so three months after the third curve, with which its coefficient is 0·72.

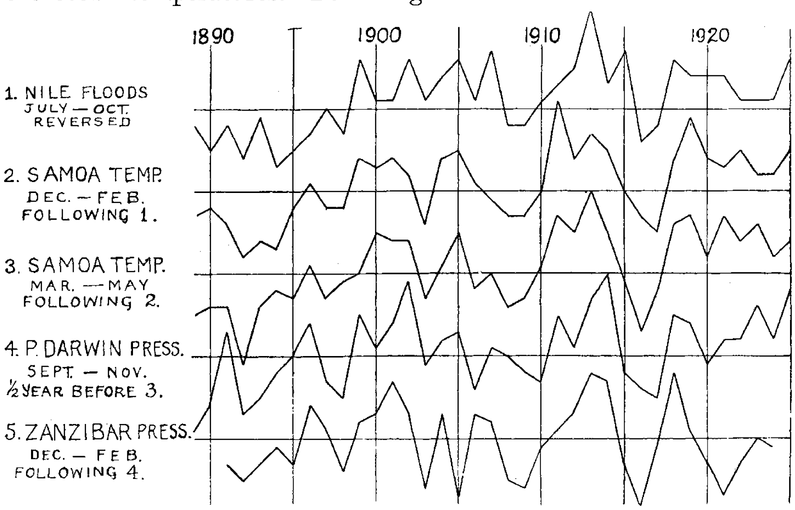

FIG. 2.—The southern oscillation.

The general character of the southern oscillation may be inferred from the statement that in the season June to August the first group of stations, *i.e.* that oscillating with pressure in the Pacific, is most clearly represented by pressure at Honolulu, Samoa, the Argentine, and Chile, by India monsoon rainfall and by the Nile floods; and the second group, tending to have departures of the sign opposite to those of the first, is represented by Port Darwin pressure, and by temperature at Batavia and Samoa. During the season December to February the most representative stations are materially different. In the first group there are only Samoa pressure and rainfall at Java; and in the second, pressure at Honolulu, Zanzibar, North-West India, Port Darwin, and the Cape, with the temperatures of central North America, Batavia, and Samoa.

The first question that arises is that of the mechanism that binds together the southern oscillation; we have seen that the North Atlantic and North Pacific oscillations implied variations in the strength of the air circulation in those areas, and there is a presumption that a similar interpretation is applicable here. Now where there are areas of low pressure and areas of high pressure in the same latitude, the former are in general relatively warm and the latter relatively cool; so that in winter, seas have low pressure and in summer high; and for land the opposite obtains. Thus the low pressures of Iceland and the Aleutian Islands are much more developed in winter than in summer, and the high-pressure belts in the Atlantic and Pacific in summer than in winter. Accordingly, in the southern oscillation the first group consists of those areas the pressure of which will increase with increased temperature contrasts or increased circulation; thus, in the Pacific, Honolulu is in the first group in summer when the high-pressure area is more marked, and in the second group in winter when the reverse obtains; similarly, the Argentine and Chile as land areas are only in the high-pressure group in winter. Also Samoa as a high-pressure centre at times of increased circulation is much more marked in summer than in winter; and the Cape is only in the second group in its summer when pressure is relatively low.

This explanation is not complete, however, for Northern Australia is almost as strong in the second group in its winter as in its summer. Further, at times of increased circulation, when we should expect solar radiations to be stronger, temperatures are markedly lower except in higher latitudes. But here we are reminded of the old paradox, that at times of sunspot maxima, when there is a definite though small general increase of rainfall owing presumably to increased circulation, temperature is decidedly lower in the tropics and generally lower in the middle latitudes; and, going further, if we compare the relationships of sunspots with pressure, temperature, and rainfall, we find a remarkably close resemblance with those of the southern oscillation, extending in many cases into the detail. Thus if we consider our description of the southern oscillation in terms of representative centres, there were, in the season June to August, 5 centres in the first group and 3 in the second, while from December to February the numbers were 2 and 8; and without an exception we find the variations of centres of the first group associated positively with those of sunspots and those of the second group negatively, even when the members of the group change between summer and winter.

This correspondence would be explained if the southern oscillation were an effect of sunspots; but this hypothesis is untenable as the relationships between factors in the southern oscillation are much closer than those between the factors and sunspots. It seems too speculative to postulate some solar influence which should closely control terrestrial conditions and yet have but a small influence on the sunspot numbers. So we are led to the view that the southern oscillation merely expresses a natural oscillation or system of surges in the general circulation, and that, for example, the fall of temperature in the tropics is, on physical grounds, associated with an accentuation of low pressure in the Indian Ocean. If this is granted, we suppose that an increase in the number of sunspots or of solar radiation will increase slightly the general circulation and so bring about the observed relationships with sunspot numbers.

The belief held by Hildebrandsson in 1910 was that, in the tropical and temperate regions, circumstances were too regular to afford an explanation, and it must lie in the ice conditions of the polar seas; he believed also that in the southern hemisphere types of season were propagated eastwards like waves, the character of the pressure at the Cape during its summer appearing at Mauritius in the next winter, in Java and Australia the succeeding summer, and finally in South America six months later, or eighteen months after its original appearance at the Cape. This generalisation was founded on inadequate materials, and the feature which stood out most prominently in the first set of relations worked out in India was that while winter pressures in the Argentine and Chile were not controlled by any centre in the southern oscillation six months before, they controlled conditions six months later round the Indian Ocean, appearing as a reversed pressure wave which took six months to reach the Cape. It seemed therefore as if South America was the origin of the variations.

At first it appeared that a modification of Hildebrandsson's hypothesis would solve the problem. For, owing to the shape of the Antarctic continent, it would seem inevitable that the ice which flows in a westerly direction along the coast would be thrown off northwards into the Drake Strait by the projection of Graham Land, so that it would then flow north-eastward and eastward in the currents of the 'roaring forties.' The few data forthcoming from that neighbourhood indicated that a winter of low pressure in Chile was a winter of much ice at the South Orkneys, and as this would take some months to produce an area of chilled ocean and therefore of high pressure at the Cape, it seemed as if we might hope to understand how a period of low winter pressure in South America could produce a period of high summer pressure at the Cape. But subsequent examination showed that although low winter temperature at the South Orkneys produced low temperature at the Cape a year later, the coefficient between the two temperatures being $+0{\cdot}56$, the effect six months later was small; and, apart from this, the explanation would break down because the effect of Cape temperature on Cape pressure proves on calculation to be negligible.

Unfortunately, it is easier to reject this hypothesis than to replace it. If we count in the tables the number of significant relationships, we find that pressure at Port Darwin has no less than 76 with other places, of which 32 are with subsequent seasons; next in importance come temperatures at Batavia and Samoa, each with about 60 relationships, of which only 13 are with subsequent seasons; and then come the pressures of North-West India and Samoa with smaller numbers. So pressure in the neighbourhood of Port Darwin seems to exercise more control over other regions than any other world factor, and its influence seems to be increased by Batavia temperature, which varies in close sympathy. Temperature at Samoa, the oscillations of which closely resemble those of Batavia temperature, is an equally important world centre, but belongs to the second group, while Samoa pressure belongs to the first group and has not more than half its influence. On the whole, then, although certain pressures appear to come earlier than any temperatures in the sequence of cause and effect, it is clear that ocean temperatures play a most important part in world weather. Their effectiveness may be due in part to their extreme persistence, so that successive seasons produce cumulative instead of antagonistic results.

Although it may be some time before we learn the processes by which Nature effects these enormous oscillations, and the relationships found must in general be regarded as empirical, there is no reason why they should not be utilised when possible for administrative or commercial purposes such as seasonal forecasting. Thus methods of predicting the general character of the winter and spring temperatures of a large part of northern Europe have been known for twenty years, and much additional knowledge has been won in recent researches by Brooks, Exner, Wiese, and others. The facts of the southern oscillation have been systematically utilised in predicting the rice crops of Japan, and the Java rainfall; and the recent tables have been shown by Bliss to have an immediate application to the Nile, the final relationship for forecasting being $0{\cdot}72$. The latest purpose to which they have been directed is in connexion with Ceara, a state in north-east Brazil liable to terrible droughts, and, as rainfall there belongs to the second group in the southern oscillation, a formula with a coefficient of $0{\cdot}82$ follows at once, the effect being shown in Fig. 3.

It must be admitted that a certain amount of scepticism over these matters is of great value as an antidote to rashness; for it is obvious that if we examine short series of data of pressure, temperature, and rainfall of hundreds of stations chosen at random, and look for similarities of conditions separated by all intervals of time up to five years, the laws of chance will provide one or two promising results. But, on the other hand, it is impossible to deny the validity of conclusions based on close relations over an adequate number of years, such as forty or fifty, and this view is confirmed by actual experience. For in 1908, in my early years in India, I published an admittedly imperfect formula for predicting the monsoon based on about 34 years of data; and its reliability can be definitely estimated by comparing the indications that would have been given by it if employed during the past 19 years with the actual rainfall. Now the coefficient expressing the closeness of fit between the results of the formula and past data in 1908 was 0·58, and I should have been satisfied under the conditions if the indications of the past 19 years had a closeness of fit of 0·48 instead of 0·58; actually, however, as will be seen from Fig. 4, the foundations of the relationship have proved sound and the coefficient has worked out as 0·56; so it may be claimed that our present improved formulæ based on 50 or 55 years instead of 35 years are worthy of confidence if used with due caution. It is in my view essential that forecasts should only be issued when the indications are well marked, and if during the past 19 years a prediction had only been made in the 11 years when an excess or deficit of one inch or more had been indicated, the character of the season's rainfall, expressed merely as 'in excess' or 'in defect,' would have been correctly given 9 times (Fig. 4).

Since 1908 many new relationships have been ascertained, and the present formulæ for North-West India and for the Peninsula have coefficients of 0·76 instead of 0·58. Also, there is no reason whatever for thinking that finality has been reached; for with the seasonal changes in India are associated very big changes in the strength of the upper currents; and it is an obvious hypothesis that when the change in the upper currents takes place with unusual vigour the seasonal rainfall will be abundant. The pilot-balloon observations hitherto made strongly support this hypothesis, and what appears to hold in India very probably holds over a far wider region. Moreover, the idea that upper-air conditions are vital to the study of world weather derives support from the table of relationships with the Nile. The significant relationships with other stations for its single season number 31, while the greatest number for a single season at any other centre is 24; and as the corresponding number for pressure at Cairo is only 8, it seems likely that this effect of the Abyssinian rainfall is brought about by the agency of the upper air, not by surface conditions. Similarly, the monsoon rainfall of India has eight significant relationships elsewhere, but June to August pressure in North-West India only one.

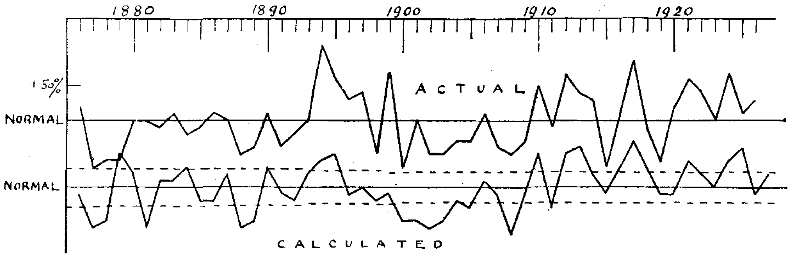

FIG. 3.—Forecast on Dec. 1 of Ceara rainfall, January–June.

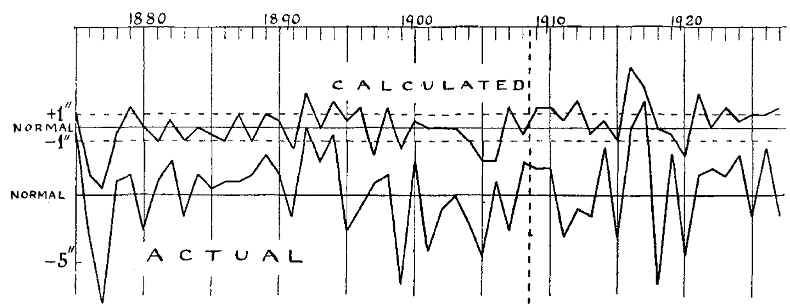

FIG. 4.—Forecast on June 1 of Indian monsoon, June–September. (1908 Formula, R = 0·58.)

It is to be hoped, therefore, that the tables of the *Réseau Mondial*, to which statistical workers have been enormously indebted in the past, will in future contain monthly means of air motion at fixed heights above such observatories as can provide the data.

Recent Earthquakes in Bulgaria and Greece.

By DR. CHARLES DAVISON.

WITHIN the last year, destructive earthquakes have occurred in Palestine, the Crimea, Smyrna, and Asia Minor, and, so lately as Mar. 27, in north-eastern Italy. They have been followed, during the latter half of April, by a series of equally violent shocks in the south-east of Europe. Indeed, the close succession of earthquakes—and, since April 15, scarcely a day has passed without news of fresh shocks—has given rise to the impression that earthquakes have of late been more frequent than usual. There is nothing to support the impression beyond the clustering of shocks within a limited area. Assigning roughly the intensity according to Milne's scale for destructive shocks, it would seem that, in the first four months of this year, there have been one earthquake of intensity III (strong enough to destroy towns and devastate wide regions), perhaps two of intensity II (capable of shattering many buildings and overthrowing some), and two of intermediate strength. In each of ten years during the latter half of the nineteenth century there