The Simultaneous Oscillation of Barometers along and near the Equator

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Abstract

Oscillations of surface pressure which, within the observational error, occur at the same time over very large oceanic regions, have been described by Frolow in the tropical Indian Ocean and the Caribbean. Similar oscillations in the equatoral Pacific are reported and the widespread, presumably planetary, extension of the pressure variations emphasized. Statistical investigation suggests that simultaneous falls of pressure along the equator are associated with solar disturbances.

Introduction

The success of weather forecasts based upon the analysis of moving patterns in the surface pressure field and the explanation of the diurnal and semi-diurnal pressure waves by the resonance theory incline most meteorologists to the view that any short-term variation of the surface pressure at a given place can be entirely accounted for by the movement and development of "pressure systems" of various scales, including the diurnal and semi-diurnal waves and orographic perturbations. However, most experienced synoptic workers in the tropics (and, on rare occasions, in high latitudes) have noticed curious pressure oscillations at the surface which are not explicable in advective terms; over very wide regions the pattern may remain the same for several days but the absolute value of the pressure may rise and fall several millibars during this time. The most extensive investigations of these pressure changes seem to be attributable to FROLOW (1942, 1951); he described some remarkable and wide-spread stationary oscillations in the Caribbean and the western Indian Ocean. Recently, PYLE (1954) described a similar change in surface pressure over the Pacific; during his study of the diurnal pressure variation over Oahu, he had occasion to refer to the synoptic trend of pressure at four stations on the island. He says, "All four synoptic trend graphs show the pronounced fall of pressure on the 15th and 16th" (of June 1953) "which seems not to have been associated with any specific feature on the synoptic maps up to 500 mb. The sea level isobars retreated northward on these days apparently uniformly along the entire southern edge of the Pacific high, and then moved back southward again on the 17th". He mentions that the surface pressures fell not only at the Hawaiian stations but also at Midway and Johnston Islands. These stations are sufficiently far removed from one another and from Hawaii to make it improbable that the oscillation was due to a moving pressure system.

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In Frolow's investigations, more particularly those devoted to stationary oscillations in the Caribbean (FROLOW, 1942), a rather complicated smoothing of the data was undertaken in an attempt to eliminate the effect of moving perturbations in the pressure field. In the Caribbean these can produce pressure variations at a station as large as, or larger, than the stationary oscillations which he wished to study. It is possible that the smoothing process introduced a fictitious wave, having a period of about 6 days, into the pressure curves for all his stations. At all events his early researches emphasize the periodic character of the variations, a feature not obvious in the Pacific. Since Pyle described an *aperiodic* stationary pressure variation and since it was revealed by a method of analysis quite different from Frolow's, we thought it desirable to investigate the variations in the tropical Pacific on a scale much greater than any previously attempted. This appeared all the more necessary, because Frolow's work had not attracted the attention its importance warranted.

The enquiry, then, was planned to fall into two parts: first, the investigation of the reality of stationary pressure waves in the tropical Pacific; secondly, if the reality of the oscillations was established in the first phase, the exploration of possible explanations of the phenomenon.

The Data and the Method of Analysis

Selection of the material for study was based on the following reasoning: if widespread stationary perturbations like those suggested by Frolow exist in the Pacific, they can best be discovered by eliminating, or reducing to a minimum, all moving and local disturbances of the surface pressure field. At the same time, *treatment* of the raw data, e.g. by reduction to sea level or smoothing by running means, ought to be avoided as far as possible, since fictitious standing waves or the magnification of effects due to orography might be introduced by such handling. The following principles of selection were then derived:

(a) Only stations on atolls, where the islands themselves are quite tiny and not above a few metres in height above mean sea level, were selected. This eliminated orographical effects and reduction errors.

(b) Only atolls far from any continent or large mountainous island were selected. Two stations (Tarawa and Funafuti) were about 2000 nautical miles away from the continent of Australia. All others were more than 2000 miles distant from any large land mass. Thus, possible "monsoon" effects, such as might be advanced to explain Frolow's results in the western Indian Ocean and the Caribbean, were automatically eliminated.

(c) The diurnal and semidiurnal pressure waves were eliminated by using as the primary datum the departure of the surface pressure at each synoptic epoch from its mean for the month. For example, the observed pressure at Tarawa at 00.00 G.C.T. on each day of March 1953 had subtracted from it the mean 00.00 G.C.T. pressure for March 1953; similarly the 06.00, 12.00, and 18.00 G. C. T. mean pressures for the month were subtracted from the individual observations at the relevant times. The result is what we call here the "pressure departure" which could be plotted against time throughout the month, giving, in the ideal graph, 124 sequential observations in a 31 day month. Some stations reported less frequently than four times a day and there were, of course, gaps in the record at individual stations. Nevertheless, the method of treatment eliminated the diurnal and semidiurnal waves from the final plot even in an incomplete record and at the same time left the stationary (if any) and moving pressure perturbations completely unaffected.

(d) The moving perturbations were eliminated, or reduced, by natural means. This resulted from selecting only stations within a belt lying between the parallels (approximately) 10° N and 10° S and east of 165° E. It had been shown some time ago that the moving vortices and atmospheric waves of the Marshall Islands produce surface pressure waves of approximately 1/10 of the amplitude of the semidiurnal pressure wave. One of us (OHMSTEDE 1955) had also shown that simultaneous pressure oscillations affecting the entire Marshall archipelago occurred during the fall of 1952 and that these were of an amplitude 10 to 20 times greater that those associated with passing vortices. When it is remembered that the period studied by Ohmstede was one of exceptional typhoon activity and that many of the vortices passing the Marshall Islands were, without

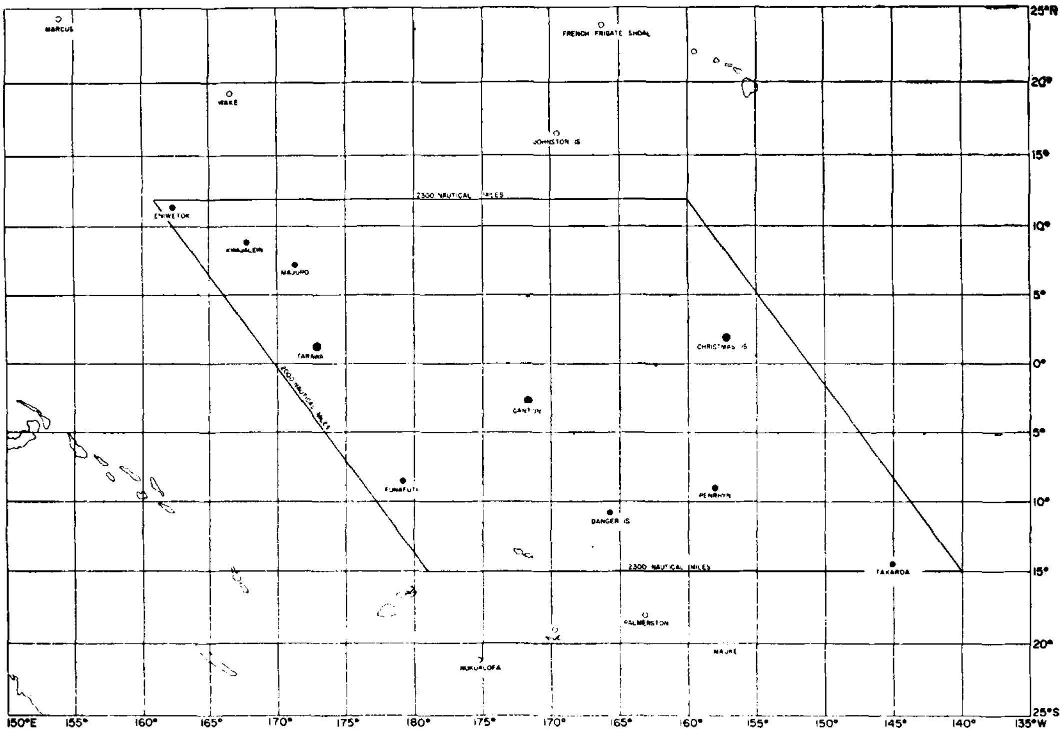

Fig. 1. The atoll stations of the Central Pacific. Blackened circles indicate "parallelogram" stations. The three surrounded by an additional circle were used in the study of 1955 data. Open circles indicate "fringe" stations.

any doubt whatever, the early stages of typhoons, the advantage of restricting the present study to atolls in and east of the Marshall Islands can readily be seen. No smoothing of the pressure departures was therefore undertaken and the effect of moving disturbances, such as they were, have not been eliminated from the graphs for 1953 and 1954.

The use of these principles of selection gave the network of observing stations within the parallelogram on Figure 1. A latitude belt of 17° was covered and the greatest distance between any two stations was that between Eniwetok and Takaroa (approximately 4000 nautical miles). In order to study possible interference effects of moving pressure systems in higher latitudes, as a contrast to the changes within the parallelogram, additional fringe stations were selected north and south of the parallelogram; these also are shown on Fig. 1. The treatment of the data for these stations was exactly the same as for stations within the parallelogram.

The majority of the stations shown on the map possessed mercurial barometers and the standard corrections were applied. Whenever possible, our data were taken from the published Daily Weather Bulletin—Pacific Island Section (DIRECTOR, NEW ZEALAND METEOROLOGICAL SERVICE: 1953, 1954, 1955). These Bulletins lacked the observations for certain synoptic epochs, the deficiencies differing in the different years—some of these deficiencies, together with the complete observations for the Marshall Islands and the fringe stations north of the parallelogram, were supplied from our teletype record, as received in Hawaii. We estimated that the pressure departure graphs were accurate to 1/10 millibar and that the transcription and transmission errors were less than 2 %.

In this account of the investigation we are concerned mainly with establishing the chief properties of the oscillations and with exploring in a very preliminary way, means to explain them. A total of eighteen months' data was

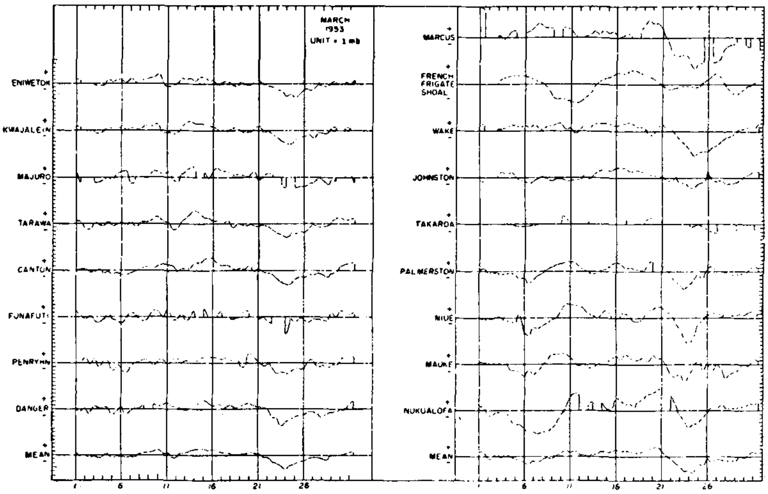

Fig. 2. Daily pressure departures. March 1953.

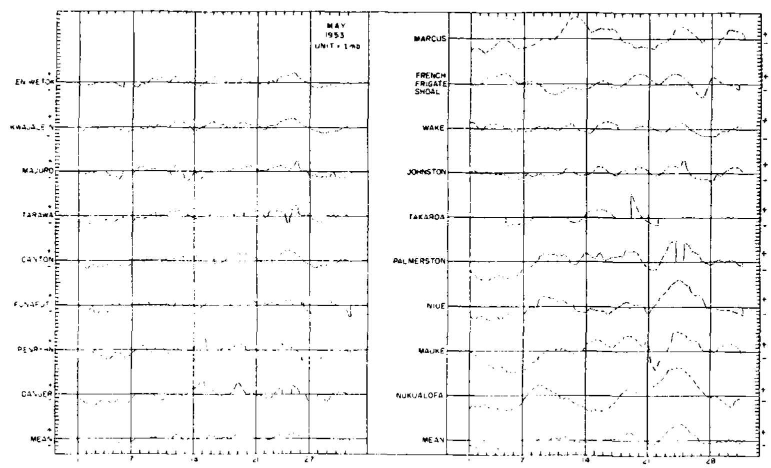

Fig. 3. Daily pressure departures. May 1953.

chosen for this pilot project; six months were chosen by lot from 1953 and the early part of 1954—these months sufficed to establish the reality of the oscillations and the data for 1955 were then examined for clues leading to explanatory hypotheses.

The stationary oscillations

The pressure departure graphs for March, May, July and December 1953 and for January and February 1954, the six months chosen by lot, are displayed in Fig. 2, 3, 4, 5, 6, and 7 respectively. Christmas Island is missing from these graphs, as the station was not furnished with a barometer until later. The record for Takaroa is very broken; it is therefore omitted from the mean for the parallelogram, shown at the bottom left of each figure.

Examination of these graphs shows that stationary oscillations of the type described by Frolow undoubtedly occur in the equatorial Pacific. Note, for example, the variation of the barometers between 21 March 1953 and the end of that month (Fig. 2). Taking the mean of the departures within the parallelogram smooths out the very slight moving disturbances affect-

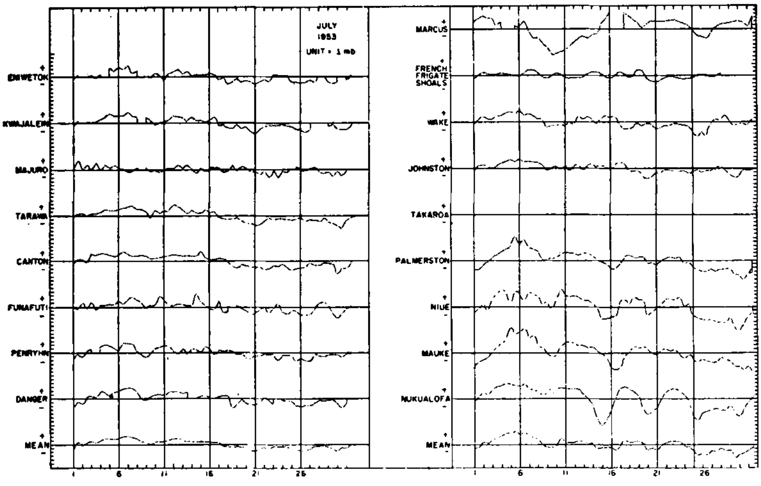

Fig. 4. Daily pressure departures. July 1953.

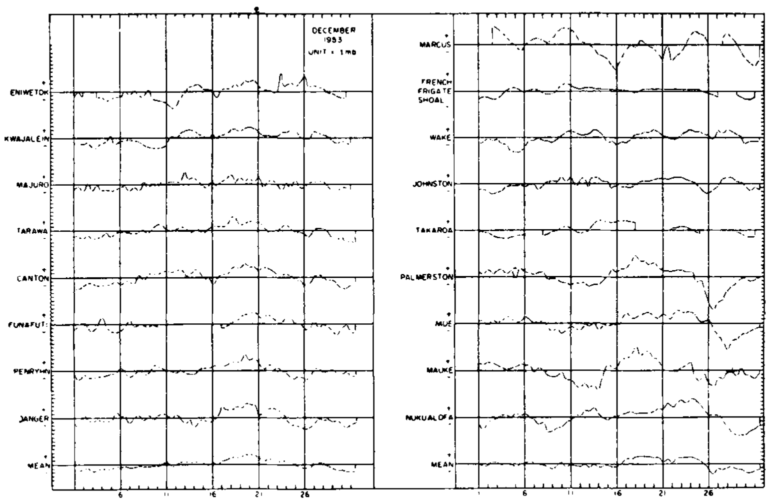

Fig. 5. Daily pressure departures. December 1953.

ing the stations during this period and facilitates the study of the details of the oscillation. It is surprising how many of these details are repeated at each station. Even Takaroa, with its fragmentary record, confirms the existence of the disturbance. The fringe stations also confirm its existence. However, more intense moving disturbances also affect those stations, so that the details of the stationary variation only appear in the their mean (bottom right).

The question of the horizontal extent of stationary oscillations now arises: are such changes restricted to the parallelogram and its fringes, or are they more widespread? The answer to this question is illustrated by considering the oscillation 25—27 May, 1953 (Fig. 3). The surface synoptic map for 00.00 G.C.T. 25 May 1953 is shown on Fig. 8, that for the corresponding hour on the 27th on Fig. 9. Both these maps were derived with the minimum analysis on our part. The North Pacific analysis was copied, with kind permission, from the routine forecast maps of the United States Weather Bureau, Honolulu, the South Pacific being derived from the published surface analysis of the Commonwealth Weather Bureau,

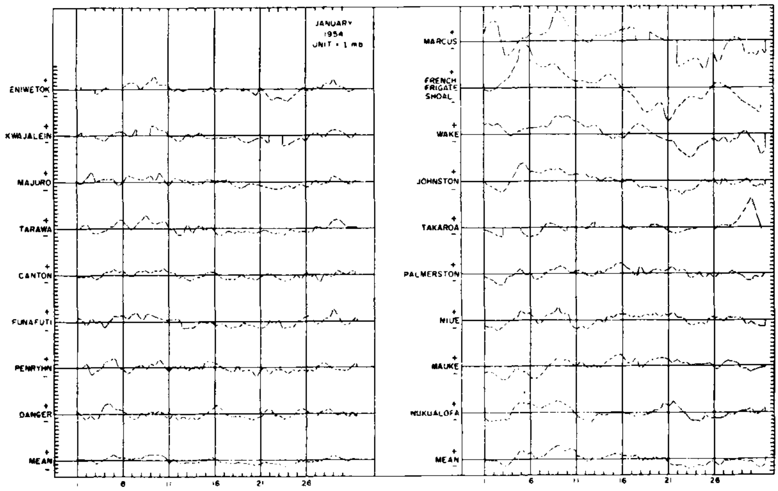

Fig. 6. Daily pressure departures. January 1954.

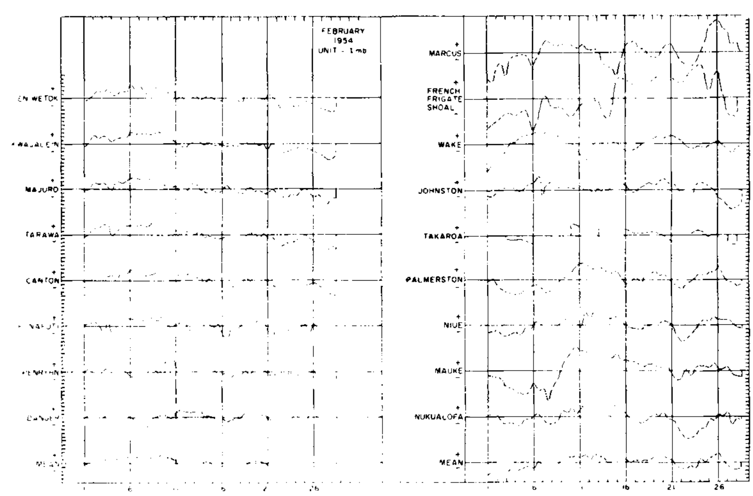

Fig. 7. Daily pressure departures. February 1954.

Australia. The two analyses fitted remarkably well in the equatorial regions, but some analytic splicing was necessary here and there, for which we take responsibility.

48-hour isallobars for the region between the parallels 35° N and 35° S were derived by graphical subtraction on the light table. The results are shown on Fig. 10, which reveals that the stationary oscillation was much more extensive than the observations from the parallelogram could indicate. We have not investigated the full extent of any of the oscillations on our graphs. It is possible that they are more widespread than the Pacific stations alone can show—unfortunately the equatorial and sub-equatorial data in the Indian and Atlantic Oceans, which would illuminate this problem, are not available to us.

From the study of the months chosen by lot, alone, one can conclude that:

(a) stationary pressure oscillations, like those described by Frolow, occur in the Pacific.

(b) the oscillations are not large, by high latitude standards, the isallobaric change being usually 1 to 3 mb per day, and the total change amounting to 10 mb.

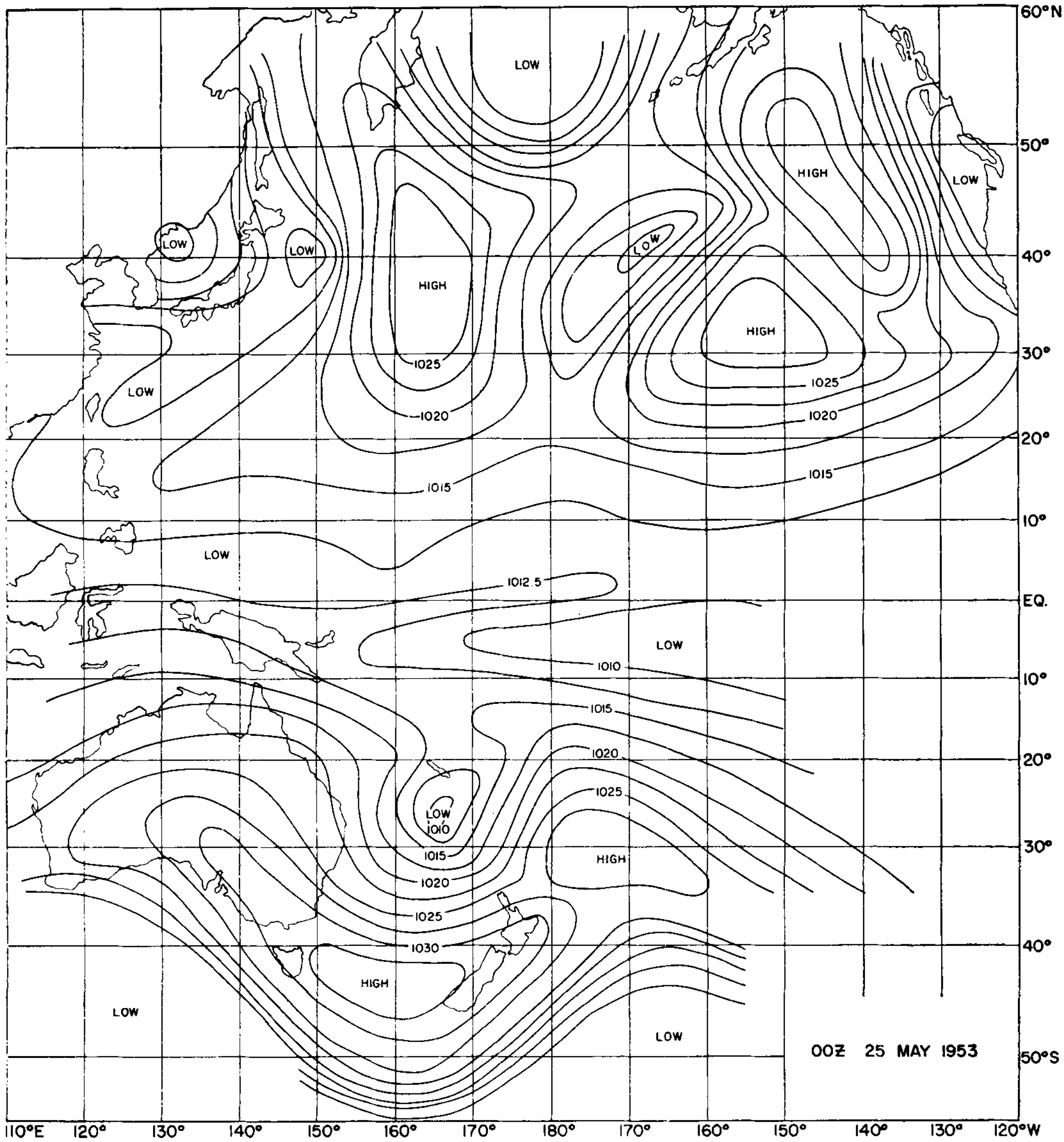

Fig. 8. Sea-level pressure analysis. 00 G.C.T. 25 May 1953.

(c) although the changes are not large, they are, along the equator, larger than any other pressure variations except those due to the semi-diurnal pressure wave.

(d) Pressure data from the equatorial atolls, Tarawa, Canton Island and Christmas Island probably constitute the best material yet available for the study of the stationary pressure variations.

Explanatory hypotheses

In considering stationary oscillations in the Caribbean, Frolow (1942) says, "We have two basic possibilities: either these disturbances are produced by a terrestrial cause or they result from cosmic activity. In considering extra-terrestrial influences it is natural to contemplate the sun's activity. We know that variations in its activity show in numerous phenomena."

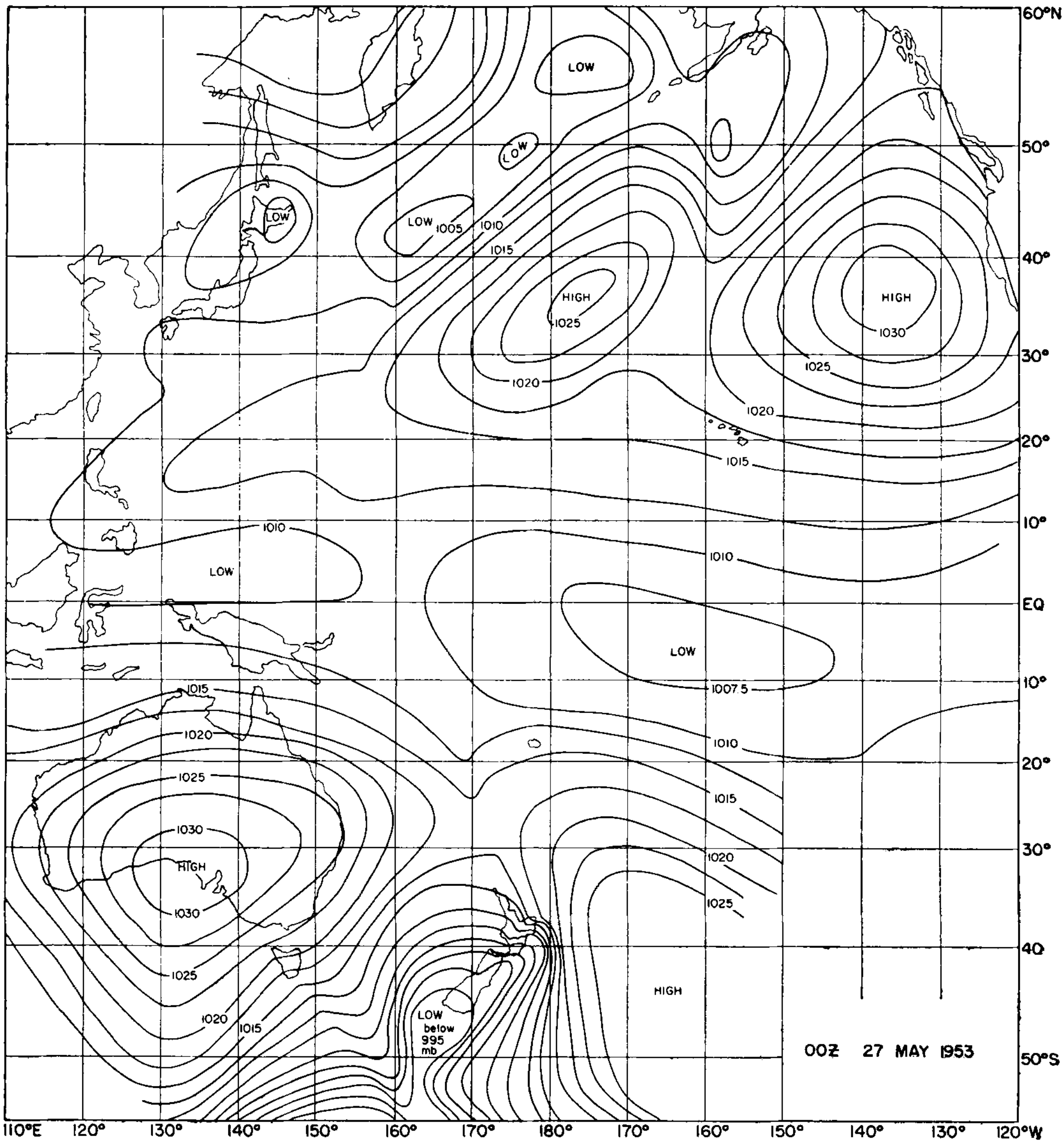

Fig. 9. Sea-level pressure analysis. 00 G.C.T. 27 May 1953.

He then shows a graph in which the pressure variations are correlated with the relative sunspot number, commenting. "The first part of this curve seems to be correlated with the other diagrams; but in order to obtain this correlation . . . we were obliged to assume an advance in phase of the solar varition of about 36 hours. But the similarity of the sunspot variation with the pressure variation is not very great, especially in July."

On the other hand, Frolow is aware of the fact that, "Pressure waves resulting from the uniform resonance of the atmosphere could not be the same as ones caused by the sun and connected with the varying periodicity in sunspots" and also, "Because they are synchronous within a large region they cannot be explained by simple advection of air masses." In reading the entire section of Frolow's work entitled "Hypothesis and Consequences" one

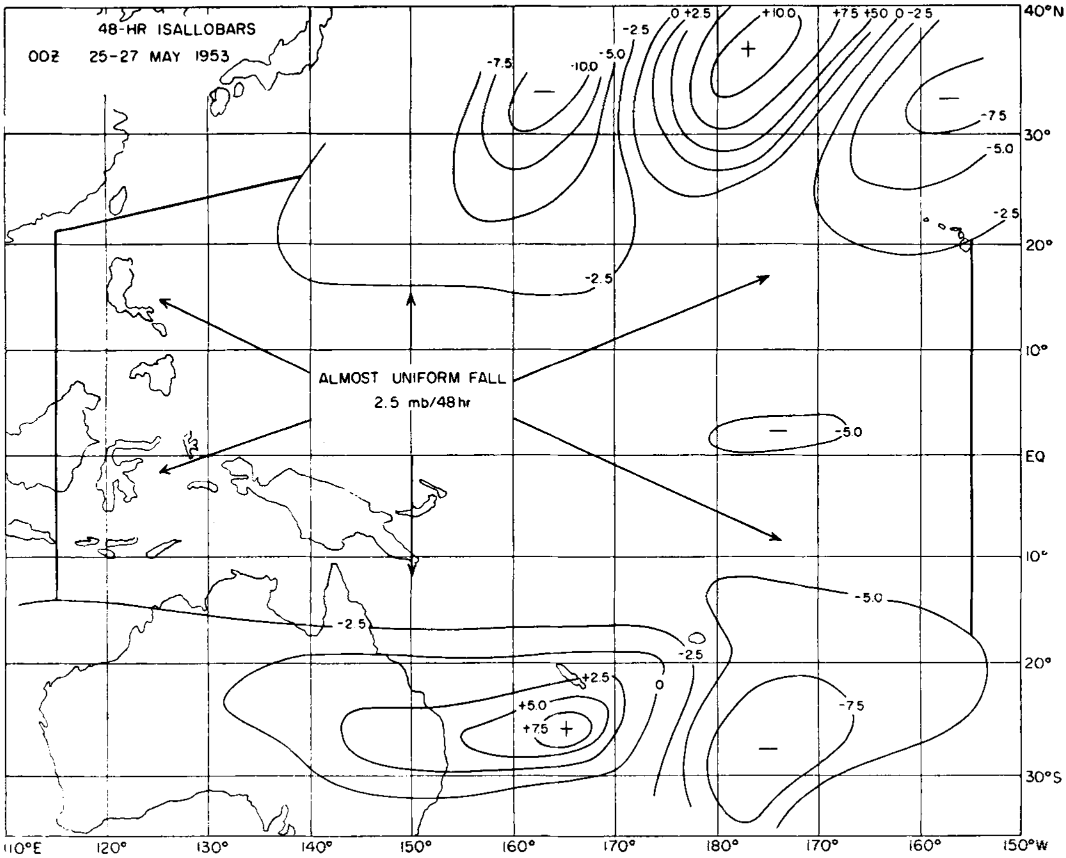

Fig. 10. Sea-level isallobars (25 May 1953—27 May 1953).

gets the impression that he inclines toward an hypothesis linking solar activity with the oscillations chiefly because other explanations, attributing the changes to resonance or the advection of air masses, fail to account for the geographical features of the oscillations, but that he is unable to offer good evidence of a causal connection between the solar and terrestrial variations.

It is now generally recognized that the relative sunspot number, while valuable as an index of solar activity in studies extending over many years, and involving seasonal and annual data (usually smoothed) is of little use in work correlating day to day changes in the sun's activity with corresponding changes in a terrestrial measure. For this reason, before rejecting the cosmic hypothesis entirely, as we were inclined to do on the same grounds as made Frolow cautious, we thought it advisable to check the most recent pressure data (1955) against a more modern index of solar activity. For the latter we chose a measure of solar radio noise, since some little success has attended efforts to correlate this parameter with changes in zonal shear in the upper troposphere over the northern Marshall Islands (PALMER 1956).

Three equatorial atoll stations were chosen: Tarawa, Canton and Christmas. As before, the pressure departures for each station were computed, but now the mean of all pressure departures for each station for each Greenwich day was taken, giving a "mean daily pressure departure" at the three stations. Finally the average of the three mean daily pressure departures was taken; this we have called the "daily equatorial pressure departure". It seems to be the best index of the stationary pressure oscillations in the Pacific, short of taking means for the entire equatorial zone from well ana-

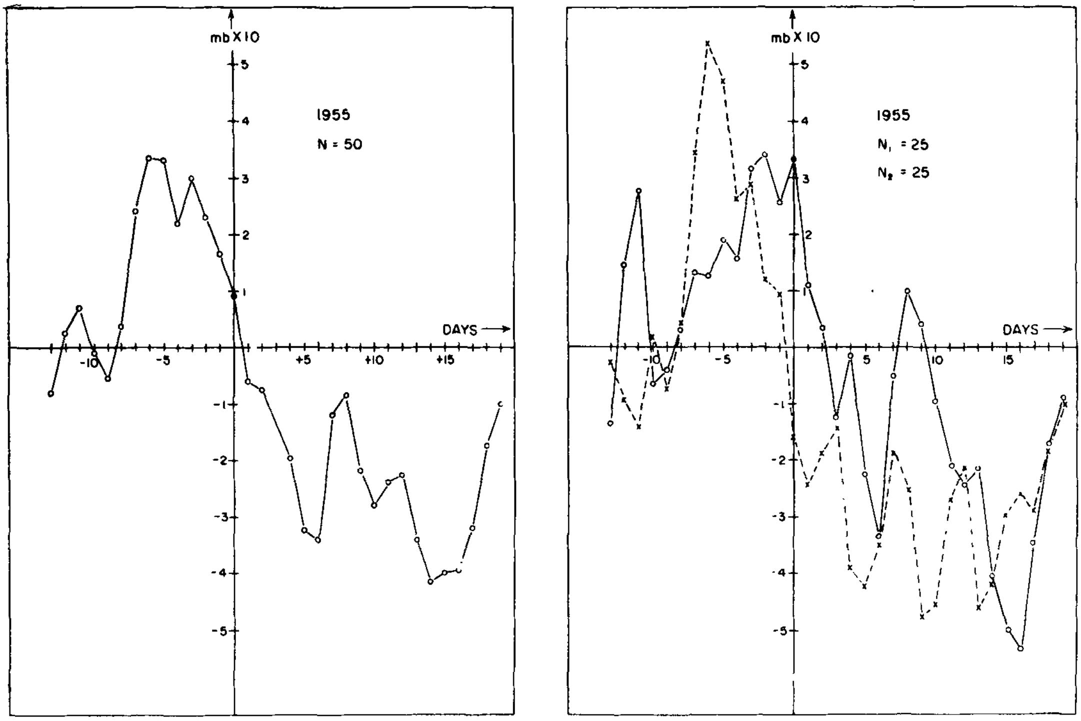

Fig. 11. Chree graphs: Average equatorial pressure departure for the thirteen days before and nineteen days after a solar "outburst". On the left the entire sample of 50 cases in 1955; on the right two sub-samples (Group 1 shown as dashed line, Group 2 as solid line) each of 25 cases chosen by lot.

lyzed pressure maps, a proceeding not only laborious but also open to the objection that judgement on the part of the analyst would be involved.

Days upon which "solar outbursts" occur were reported as a routine measure by the High Altitude Observatory and the National Bureau of Standards, Boulder, Colorado, U.S.A. between 14 January 1955 and 13 October 1955 in the "Preliminary Report of Solar Activity" (TROTTER, 1955).

We tabulated the days on which the report specifically mentioned, in plain language, that solar outbursts or a series of bursts or a noise storm had occurred at Boulder on one or other of the three frequencies 167, 200 or 460 mc/s. The reports of solar outbursts ceased to appear in the *Report* after 13 October 1955; for the period 14 October 1955 to 31 December 1955, therefore, we depended upon teletype reports of solar radio noise disturbances transmitted to us in Hawaii by courtesy of the National Bureau of Standards. While these messages enabled us to complete our list of "outburst days" during 1955, the list is not quite homogeneous, since the teletype messages include reports from radio observatories other then Boulder and sometimes the information from Boulder is not available. While the list, therefore, specifies days upon which, somewhere on the earth, radio telescopes observed major solar disturbances, it is not exhaustive; undoubtedly there were other days during which disturbances occurred and of which we have no record. The important point, of course, is that these days were selected, not by us, but by independent authorities working on problems unrelated to equatorial barometric pressure.

The 50 outburst days of 1955 were taken as zero days for the application of a superposed epoch, or Chree, test. In this test the equatorial pressure departures for each of the 50 outburst days were summed and averaged; similar averages for the equatorial pressure departures for all 50 days one day after zero day were taken;

the process was repeated for a range up to 19 days after and 13 days before the outburst days. The result is shown as the left-hand graph of Fig. 11. The graph distinctly shows a connection between solar activity and the equatorial pressure departures such that the pressure is lower than the mean for the month after solar "outbursts" and higher before.

The exhibition of graphs of this type usually elicits from critics the claim that the results are due to "chance". It is always possible to justify this claim since there is always a finite probability that sampling fluctuations can lead to a fictitious order in a sample, the order being absent from the parent universe. The question, then, is not whether the order is or is not due to chance, but rather what the probability is that it is so attributable. Student's *t*-test may be applied to the data of Fig. 11, and it shows that the chances that the pressure departures of the sample for the days -1 to -13 inclusive and those of the sample 0 to $+19$ inclusive were drawn from the same (normal) universe by chance is less than 10^{-7}. It might be objected that statistical tests based directly or indirectly upon the assumption that the means of the pressure departures form a normal universe, and are independent, are unjustified, since the pressure departure on any given day may be expected to show a high positive correlation with that of the day before and the day after. But, far from vitiating the conclusions to be drawn from Fig. 11, the argument from the persistence of the pressure departure enormously enhances the value of the statistical analysis. On the basis of persistence alone, no-one would expect the pronounced pressure fall that is displayed as occurring between days -3 and $+5$.

This matter was investigated more closely by dividing the 50 cases into two groups of 25 each. The groups were selected by lot, the last two digits of the numbers in the right hand column on page 149 of the 1956 Edition of the Honolulu Telephone Directory being used as a set of random numbers. Chree analysis of the two groups (Group 1 and Group 2) are shown on the right hand side of Fig. 11. Although the samples are rather small, the general character of the correlation between the pressure changes and the solar disturbances is preserved in each—pressure is lower than the monthly mean after a solar disturbance and higher before.

The significance of the pressure changes does not depend, however, upon this minor statistical enquiry; if it did, it could be dismissed as belonging to meteorological *curiosa*, of which the literature of the past hundred years is full. Since the war, however, statistical investigations of surface pressure changes in high latitudes and their correlation with a variety of measures of solar activity (DUELL, B., and DUELL, G., 1948; CRAIG, R. A., 1952; SHAPIRO, R., 1954, 1956) and the theoretical work of HAURWITZ (1946) and WEXLER (1950) show beyond doubt that there is *some* connection between disturbances on the sun and subsequent pressure changes at the surface. Unfortunately, the changes in high and middle latitudes are so overlaid and obscured by large interdiurnal changes due to travelling pressure systems that data gathered over many years and subject to laborious analysis are required to demonstrate the connection. In the equatorial region travelling disturbances of the pressure field have the least effect on the barometer. We should be able, then, to study the solar—induced pressure changes synoptically, something which has so far proved to be impossible in high latitudes, and a short run of observations is sufficient to delineate the chief features of the connection.

Relation of the Surface Changes to the Circulation Aloft

Clearly, much more statistical work, as well as synoptic analyses of individual situations, will be necessary before the properties of the solar—trophospheric relationship that lead to the surface pressure falls could be suggested even in the barest outline. At this stage, however, it may be profitable to see what can be deduced from an assumption that the relationship that holds in 1955 will be found valid in other years and that future statistical work will set the empirical connections described here upon a firm foundation.

First, as has already been remarked, the rate of pressure fall from day zero to day five, the maximum, is still very small. If the upper level mass divergence that causes it were confined entirely to the layer above the tropopause (approximately 100 mb) observed measures of the divergence in that layer over the Marshall Islands during atomic tests are more than large enough to account for the pressure changes.

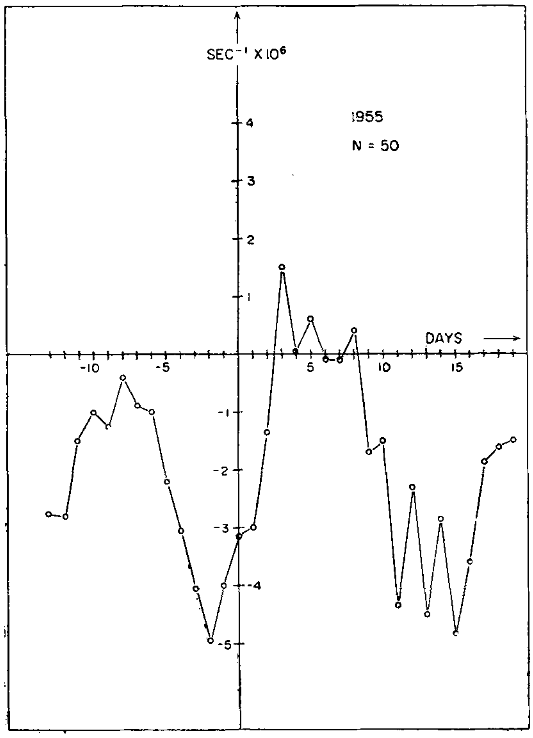

Fig. 12. Chree graph: Average meridional shear of the zonal component of the wind at 30,000 feet between Wake and Eniwetok for the thirteen days before and the nineteen days after a solar outburst. Entire sample of 50 cases.

Thus the theoretical speculations already referred to, which postulate rapid ozonospheric divergence at the sub-solar latitude during solar flares or other heightened emission by the sun, would be quite compatible with the pressure changes described here.

On the other hand, one of us (PALMER 1953, 1956) has suggested that there is a major effect of solar disturbances on the vertical component of the vorticity in and near the quasi-stationary pressure trough of the upper trophosphere in the Central Pacific. This trough varies in position and intensity with the season, but in general the effect of changes in its intensity, and in particular the formation in it of upper level cyclones in the layer 25,000—50,000 feet, can be followed by studying the day to day changes in the meridional variation of the zonal component of the wind at 30,000 feet between Wake and Eniwetok; this parameter gives a very rough measure of the "cyclonicity" of the upper atmosphere in the northern Marshalls—Johnston Island sector. We have continuous measurements of the parameter from 1 January 1953 on and sporadic measurements, chiefly confined to periods during which tests were being carried out in the Marshalls, back to 1946. It is therefore a simple matter to apply the Chree analysis to the data for 1955, using the 50 outburst days already chosen in the pressure study. The results of the analysis are shown in Figure 12. There is a well-marked tendency for the shear at 30,000 feet to become cyclonic three to eight days after a solar outburst. Results from other work indicate an average lag period of five or six days.

In comparing Fig. 11 and 12, we are tempted to suggest that the surface pressure falls along the equator are a reflection of upper level divergence affecting first the ozonosphere and later the upper troposphere, culminating after five or six days in the first minimum of pressure on Fig. 11 and the attainment of cyclonic shear in the upper atmosphere over the northern Marshall Islands. The second pressure minimum at about plus fifteen days would then have to be attributed to upper level divergence associated with movement of the upper level cyclone (or cyclones) and its subsequent development in higher latitudes. But the pressure changes are so widespread that, if there is anything at all in this speculation, one ought to predict that extensive upper air data will show that the formation of upper level cyclones is triggered by solar events, not only in the Marshalls—Johnston Island sector but also other parts of the tropics between the five and fifteen degree parallels, in particular, in the South Pacific and in the region between Central America and the longitude of Hawaii. Upper air data from these regions is so far inadequate or entirely lacking; it is to be hoped that the upper air observing program planned for the equatorial regions during the International Geophysical Year will facilitate the checking of this prediction.

Acknowledgment

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