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ATMOSPHERIC TELECONNECTIONS FROM THE EQUATORIAL PACIFIC[1]

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ABSTRACT

The "high index" response of the northeast Pacific westerlies to big positive anomalies of equatorial sea temperature, observed in the winter of 1957–58, has been found to repeat during the major equatorial sea temperature maxima in the winters of 1963–64 and 1965–66. The 1963 positive temperature anomaly started early enough to exert the analogous effect on the atmosphere of the south Indian Ocean during its winter season.

The maxima of the sea temperature in the eastern and central equatorial Pacific occur as a result of anomalous weakening of the trade winds of the Southern Hemisphere with inherent weakening of the equatorial upwelling. These anomalies are shown to be closely tied to the "Southern Oscillation" of Sir Gilbert Walker.

1. INTRODUCTION

In a paper by Bjerknes (1966) it was shown that the great positive water temperature anomaly observed along the Equator in the central and eastern Pacific from November 1957 to February 1958 was accompanied by an anomalous strength of the midlatitude westerlies over the northeast Pacific. It was suggested as an explanation that the anomalously great heat supply from the equatorial ocean to the ascending branch of the atmospheric Hadley circulation would intensify that circulation and make it maintain more than the normal flux of angular momentum to the midlatitude belt of westerly winds. This reasoning should apply to the Hadley circulation in both hemispheres, but the strongest response ought to appear in the winter hemisphere with its greater baroclinicity.

These ideas based on a study of one isolated case can now be checked by a study of the years 1963–67, which also provided fluctuations of sea temperatures of great amplitude in the equatorial belt of the central and eastern Pacific.

2. THE NORTH PACIFIC OCEAN-ATMOSPHERE INTERACTION DURING 1963–67

Time series of sea and air temperature from 1950 to 1967 at the tiny atoll of Canton Island are shown in figure 1. Situated at 2°48′S, 171°43′W, Canton Island represents mid-Pacific equatorial conditions. Most of the time water of equatorial upwelling origin reaches Canton Island, but the major maxima of sea temperature in late 1957, early 1958, late 1963, and late 1965 are proofs of the occasional elimination of the upwelling process. At the times of warmest ocean the sea temperature is higher than the air temperature (dashed curve in fig. 1) and favors the flux of sensible and latent heat from the ocean to the atmosphere. In the much longer periods of cool ocean the air is warmer than the sea, and there is, on the average, no resultant upward flux of heat and moisture across the interface.

The precipitation record from Canton Island, also in figure 1, bears witness to the assumed big year-to-year fluctuations in the upward flux of water vapor. Big monthly totals of rain can be seen to occur only during the periods when the ocean is warmer than the atmosphere. Under those conditions the maximum upward transfer of moisture takes place, and an intensive convection brings the moisture to the level of condensation and farther up into towering shower clouds. The much lighter precipitation that does occur in the periods of water colder than the surface air may have fallen from cloud drifting in from the warm water area adjacent to the strip of cold water. But in many instances that kind of rain also fails, so that real aridity results month after month.

The Canton Island type of rainfall regime is known to prevail along the Equator from about 165°E eastward to the coast of South America (Doberitz, 1967). The aridity gradually increases eastward, but even in the driest locations, like northern Peru, occasional wet years occur. The season for the wet spells, when they do materialize at the South American coast, is December to February (El Niño

[1] Progress Report on N.S.F. Contract GP-3193.

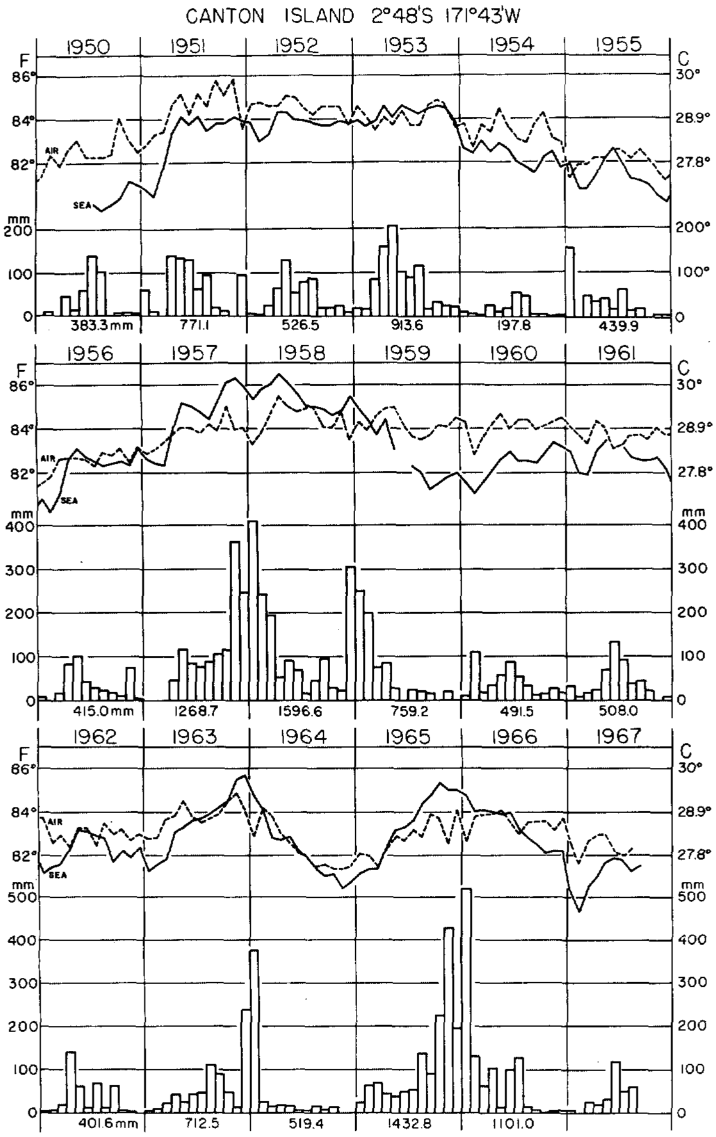

FIGURE 1.—Time series of monthly air and sea temperatures and of monthly precipitation at Canton Island from 1950 to 1967.

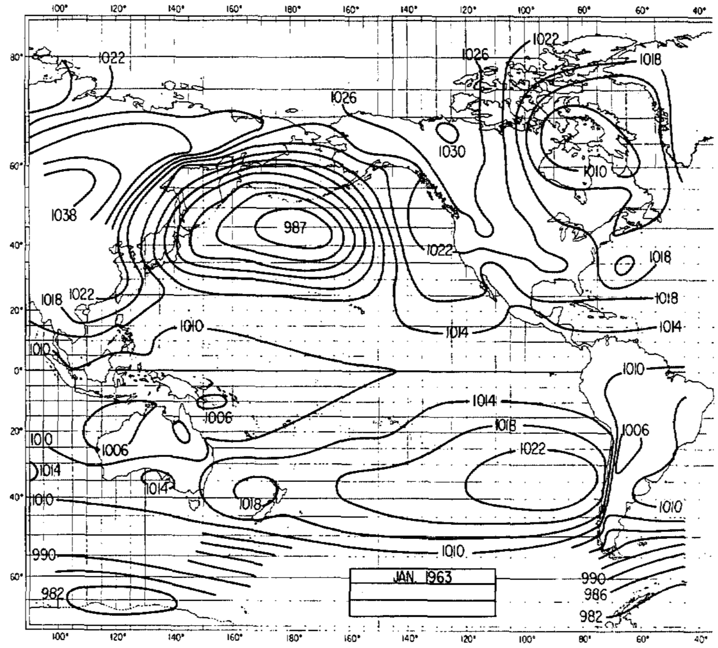

FIGURE 2.—January 1963 distribution of pressure (millibars) at sea level.

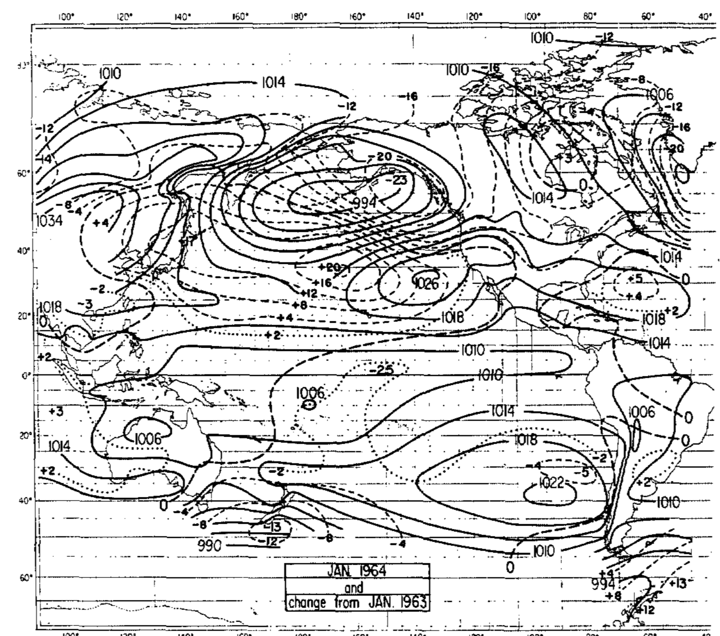

FIGURE 3.—January 1964 distribution of pressure (millibars) at sea level. Change from January 1963 in dashed isallobars.

season). All the big rainfall maxima at Canton Island in figure 1 occur at the same season.

It is likely that the strong interannual variability of rainfall shown by Canton Island applies to a rather large equatorial area of the central Pacific. Within that area, accordingly, the supply of released heat of condensation may vary interannually to such an extent that a visible response of the Hadley circulation should result. To test this idea the large-scale surface pressure field, averaged for each of five successive Januaries, over the Pacific and adjacent continents is presented in figures 2–6.

The selection of the January maps of 1963, 1964, 1965, 1966, and 1967 brings into focus the anomalies of the large-scale flow that evolved together with the extreme coolness and dryness of the central Pacific equatorial belt in January 1963, 1965, and 1967 and the extreme warmth and rain surplus of the same belt in January 1964 and 1966.

Concentrating first on the pressure change from map to map at the Equator, we find on alternate maps a fall in the eastern and a rise in the western Pacific and vice versa. The zero isallobar intersects the Equator at 175°E in figure 3, 170°W in figure 4, 168°E in figure 5, and 178°E in figure 6, in other words a little west of the dateline on the average. At that longitude the maximum westward pressure gradient along the Equator and presumably also the maximum equatorial easterlies were observed in January 1963, 1965, and 1967. These were then also the

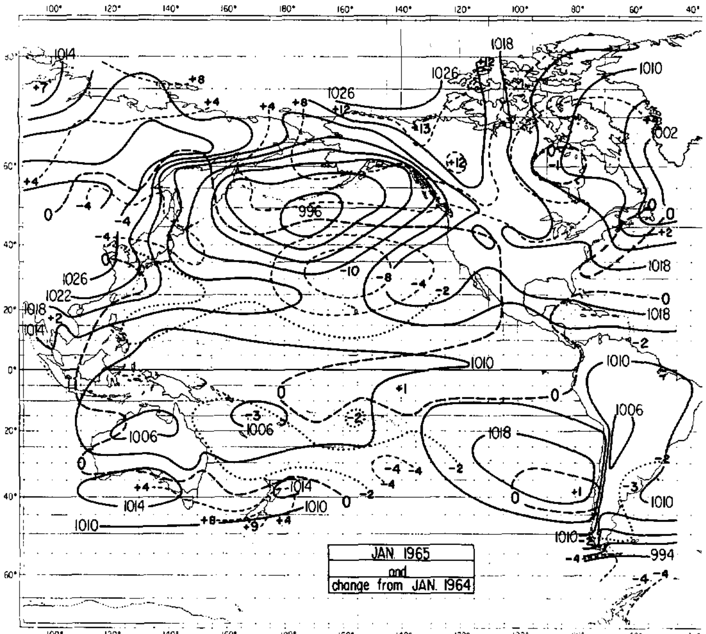

FIGURE 4.—January 1965 distribution of pressure (millibars) at sea level. Change from January 1964 in dashed isallobars.

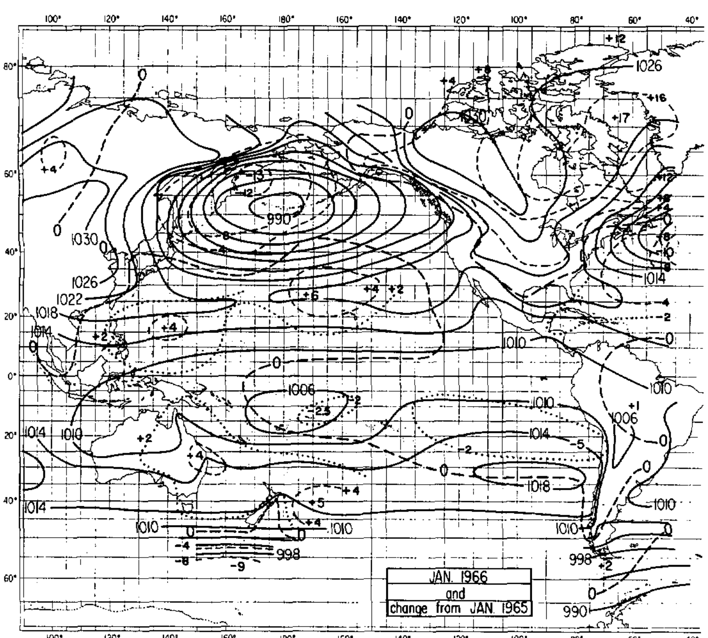

FIGURE 5.—January 1966 distribution of pressure (millibars) at sea level. Change from January 1965 in dashed isallobars.

cold Januaries over the whole mid-Pacific part of the equatorial belt.

The two warm Januaries, 1964 and 1966, differed from the cold ones by the presence of low-pressure systems in the latitude belt of 10° to 15°S. These Lows eliminated the geostrophic easterlies south of the Equator over a span of longitude straddling the dateline. The lack of upwelling and resultant high water temperatures at Canton Island in those two Januaries are therefore easy to understand.

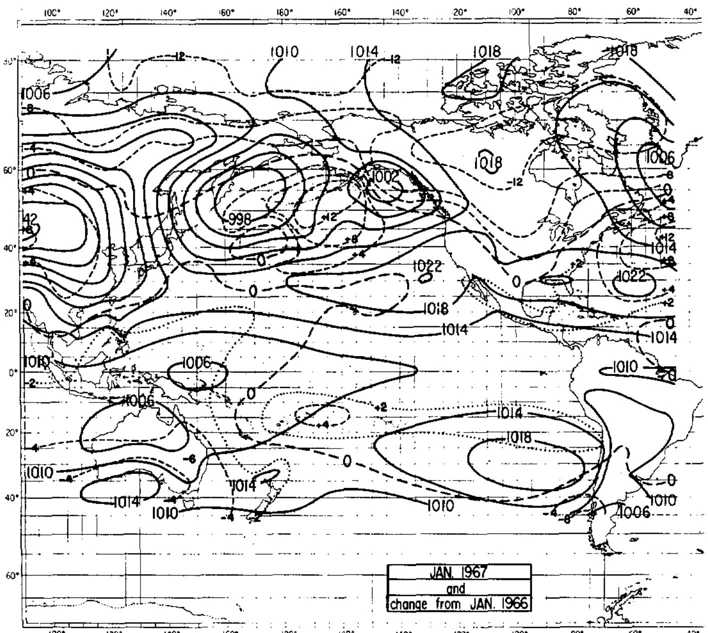

FIGURE 6.—January 1967 distribution of pressure (millibars) at sea level. Change from January 1966 in dashed isallobars.

The pressure gradients maintaining the northeast trade winds had their maximum strength in the Januaries 1964 and 1966 when the equatorial water was at its warmest. We may conclude from this that the strength of the wintertime Hadley circulation is decided by the heat input from the equatorial ocean. This corroborates the findings in the study of the meteorological effects of the equatorial ocean warming during the 1957–58 El Niño.

The Januaries 1964 and 1966 also excelled over those in 1963, 1965, and 1967 in the strength of the westerlies in the central and eastern North Pacific. This also must be related to the show of strength of the Hadley circulation: a strong Hadley circulation maintains a strong subtropical jet stream from which westerly angular momentum is supplied to middle latitudes by the large-scale meridional eddy flux. It is the convergence of that angular momentum flux over middle latitudes that makes it possible for the atmosphere to maintain the prevailing surface westerlies, as it evidently did efficiently in January 1964 and 1966 and less efficiently in the Januaries of 1963, 1965, and 1967.

Blocking of the surface westerlies, of course, occurred preferentially during the three low index Januaries, most definitely so in January 1963 when the monthly averaged map shows no pressure gradient for westerlies over the ocean east of 145°W.

The time lag of the large-scale atmospheric response to the initial anomaly of heat input from the equatorial ocean appears to be quite small and would have to be identified by daily instead of monthly basic data. Very desirable for checking purposes is, of course, also the eventual numerical simulation of the described ocean-atmosphere interaction by sufficiently realistic dynamic

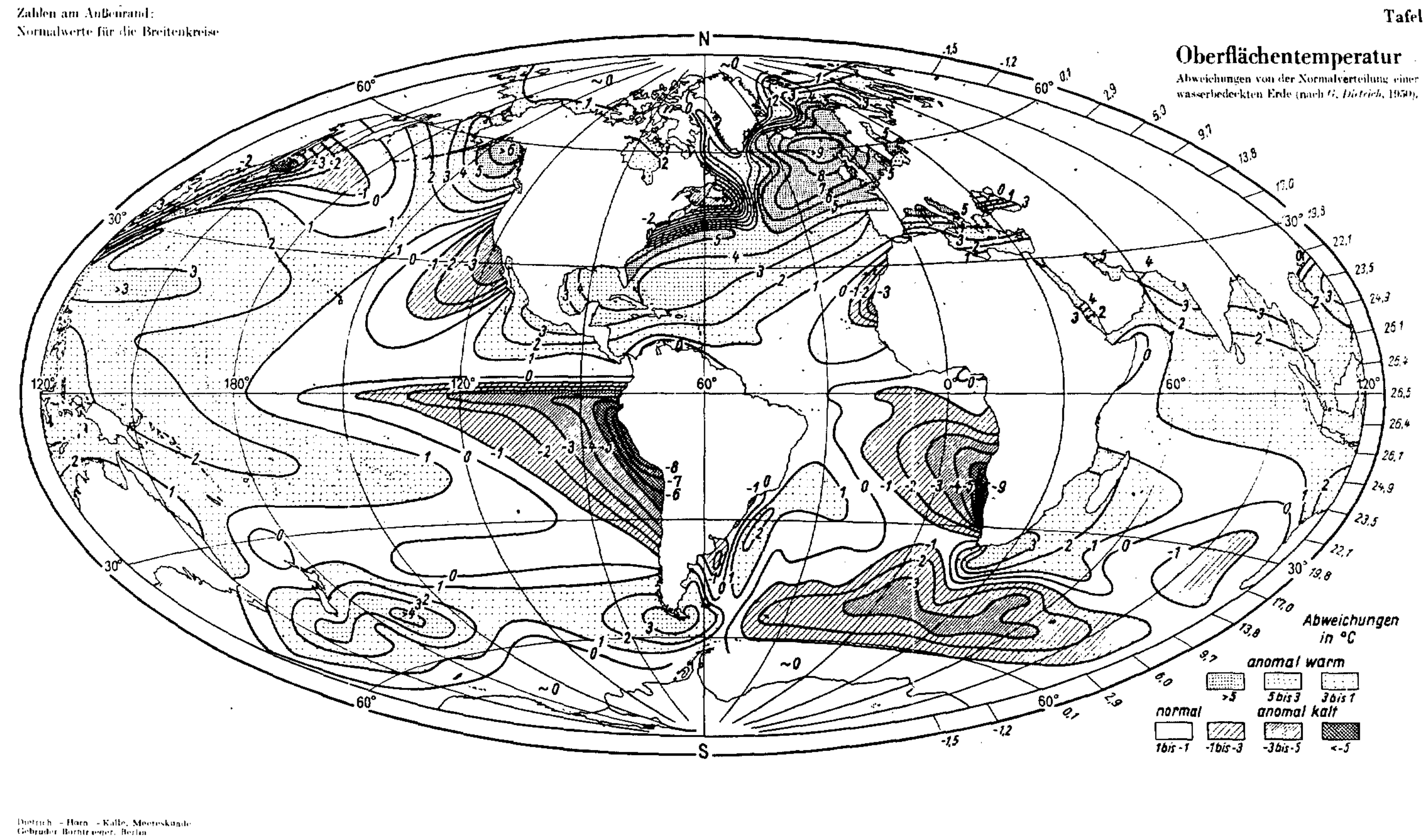

FIGURE 7.—Sea-surface temperature represented as deviation from the average at each latitude (from Dietrich and Kalle, 1957).

models. The scope of this article does not go that far, but purports to describe some of the empirical facts that must be built into the models to make them resemble nature.

In general, it is to be expected that longer time lags will be found in the oceanic response to an atmospheric impulse than vice versa. One sign to that effect can probably be seen by a comparison of January 1963 (fig. 2) and January 1965 (fig. 4). In both of those Januaries the Canton Island water temperature was at the lower end of its range of variation, and also in both months the aridity prevailed. Nonetheless, January 1965 did not exhibit quite as weak a Hadley circulation as in January 1963. The reason probably must have been that about 4 yr of cool equatorial waters had preceded January 1963 (from the end of 1959). The long uninterrupted upwelling and spreading of the cold water at the surface must have made the tongue of cold water wider in January 1963 than in January 1965 when the upwelling had only just begun to reestablish the cold tongue. If this explanation holds true it is obvious that a regular monitoring of the temperature of the tropical east Pacific is indispensable for long-range forecasting in North and South America. We will see subsequently that such monitoring of the thermal state of the tropical east Pacific will have implications also for the understanding of climatic anomalies in the tropical countries bordering the west Pacific.

3. BRIEF GEOGRAPHICAL SURVEY OF THE EQUATORIAL COLD WATER

Figure 7 (Dietrich and Kalle, 1957) shows the geographical extent of the equatorial cold water in a map presentation of the quantity $\Delta T_S = (T_S - \overline{T}_S)$, where T_S is the sea-surface temperature and $\overline{T}_S$ is its average global value along the part of each latitude circle situated over the oceans. The value of $\overline{T}_S$ is marked at the right-hand edge of the world map. For the Equator $\overline{T}_S$ is 26.5°C or 79.7°F.

The Pacific equatorial cold water is by far the most extensive and the coldest of its kind. Delineated by the zero line of ΔT_S, it covers about 85° of longitude of the Equator extending westward from the coast of South America. Defined the same way, the Atlantic equatorial cold water covers 40° of longitude extending westward from the coast of Africa. The negative value at ΔT_S there, however, barely exceeds −1°C, whereas ΔT_S at the coast of Equador is −3.5°C and along most of the coast of Peru exceeds −8°C. The corresponding coastal cold water off southwest Africa has an equally big negative ΔT_S as that off Peru, but it does not extend with appreciably negative ΔT_S to the Equator. The Indian Ocean has no equatorial cold water, as such, but due to the alternate monsoons from north and south along the east African coast, ΔT_S is there a degree or two lower than at the coast of Sumatra.

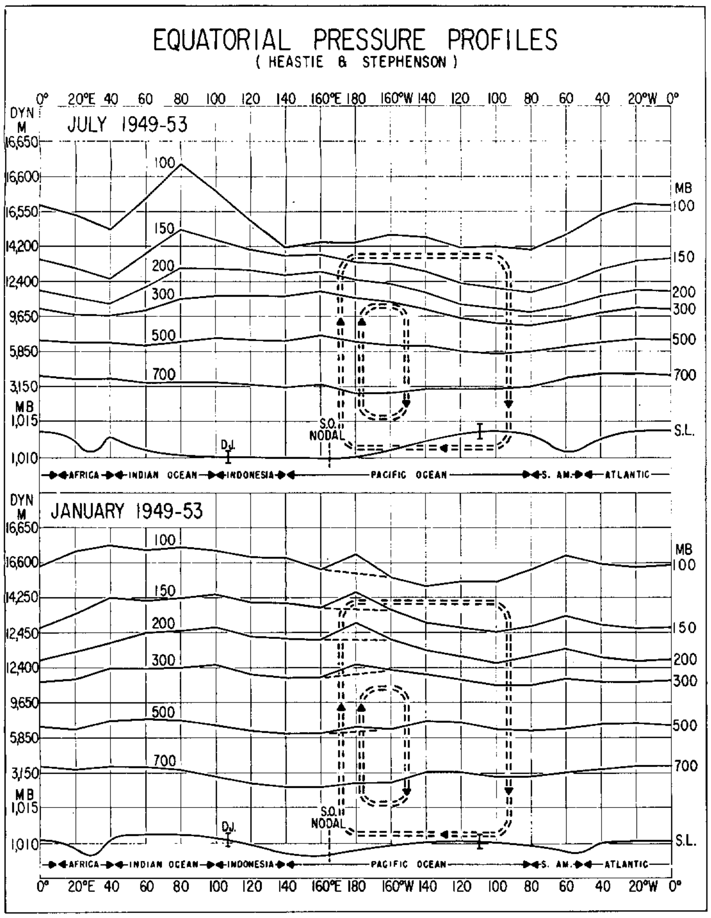

Figure 8.—Profile of height (dynamic meter) of standard isobaric surfaces along the Equator in January and July, based on data from Heastie and Stephenson (1960). "Walker Circulation" over the Pacific entered as suggested in the present article. The narrow maximum at 180° in January and the big maximum at 80°E in July are possibly spurious features.

All these geographical anomalies of equatorial water temperatures have their meteorological side effects. As far as the Pacific is concerned the equatorial cold air is unique in its large areal coverage. It also exhibits the greatest negative air temperature anomaly for an equatorial location, namely in the region of the Galapagos Islands. Contributing to the anomalously low equatorial air temperatures in that region is also the water and air advection from the southeast in the zone of upwelling along the coast of South America. The continued cold water advection westward from the Galapagos Islands is also important, but the quantitative assessment of that cooling factor has had to be lowered considerably after the discovery of the Equatorial Countercurrent a mere 50 m on the average under the ocean surface.

4. THE "WALKER CIRCULATION"

When the cold water belt along the Equator is well developed, the air above it will be too cold and heavy to join the ascending motion in the Hadley circulations. Instead, the equatorial air flows westward between the Hadley circulations of the two hemispheres to the warm west Pacific. There, after having been heated and supplied by moisture from the warm waters, the equatorial air can take part in large-scale, moist-adiabatic ascent. The dynamic conditions governing that kind of motion can be analyzed in the schematic figure 8, which presents a vertical profile of the pressure field along the Equator.

In the Pacific part of that round-the-world profile, the horizontal pressure gradient is directed westward along the ocean surface (except locally near the South American coast) and eastward in the upper troposphere. If the equatorial air were enclosed between zonal vertical walls, a simple circulation as shown by the schematic streamlines in figure 8 would develop. The moist-adiabatically ascending motion in the west would be adjusted so as to occupy less space than the descending motion in the east, whereby a steady-state field of temperature can be maintained (the warming by descent $-w(\gamma_d-\gamma)$ being compensated by the net radiative heat loss).

Without the zonal walls, this equatorial circulation does enter into exchange of absolute angular momentum with adjacent parts of the atmosphere to the north and the south; and, since the equatorial belt of the atmosphere is always endowed with a greater absolute angular momentum than adjacent zonal belts, a divergence of absolute angular momentum must result at the Equator. Under steady-state conditions this loss of absolute angular momentum in the equatorial atmosphere is compensated by the frictional torque about the axis of the earth at the interface of atmosphere and ocean.

The resultant streamline picture of the zonal wind components in the equatorial vertical profile will be the vectorial sum of the thermally driven circulation in figure 8 plus a field of easterly wind components whose strength depends on the intensity of the divergence of the meridional and vertical fluxes of absolute angular momentum.

Wind measurements have identified the upper tropospheric equatorial westerlies over the Pacific. Sadler (1959) states: "The upper tropospheric flow reverses near 150°E where the west components increase toward the east and the east components toward the west. The reversal region is a semipermanent feature with a seasonal and annual longitudinal variation . . . Recent data show that the west flow continues to increase to beyond 160°W. The easterlies increase to beyond Singapore where they are a persistent feature averaging greater than 90-percent steadiness for most of the year." The span of longitude occupied by upper tropospheric westerlies thus may extend from 150°E, which is over the warmest part of the equatorial Pacific (see fig. 7) to well beyond 160°W, in other words to the cold part of the equatorial Pacific. It seems reasonable to assume that it is the gradient of sea temperature along the Equator which is the cause of the thermal circulation entered in figure 8. Hereafter, in the present article that circulation will be referred to as the "Walker

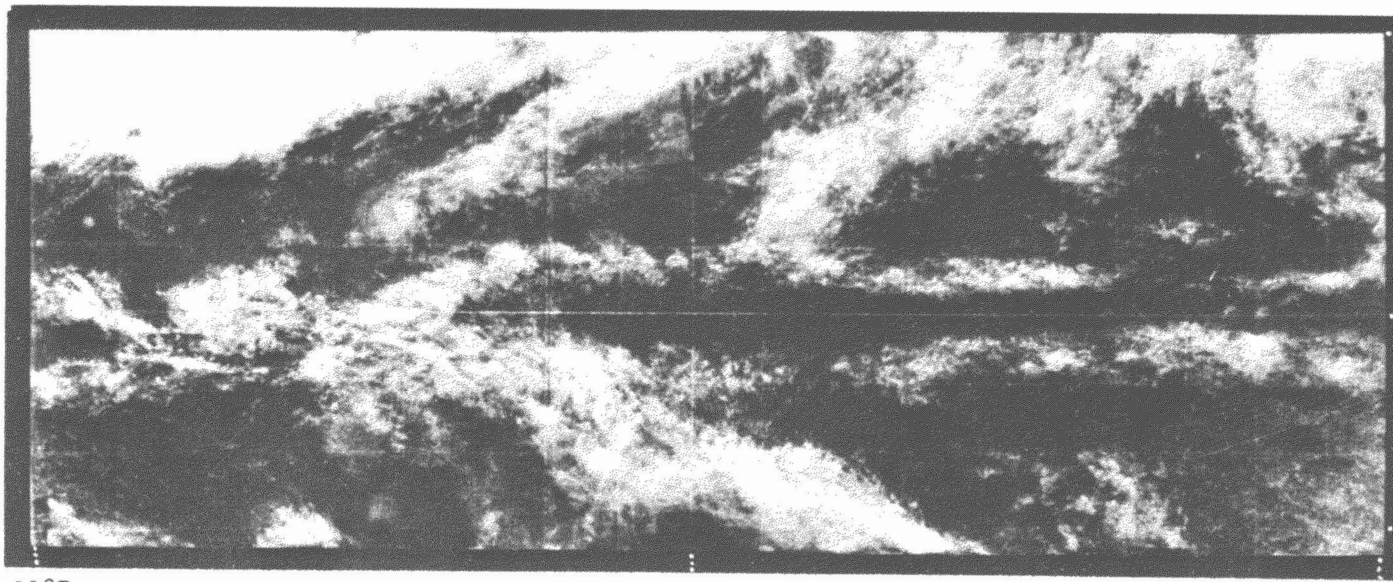

FIGURE 9.—Tropical Pacific cloudiness (Mercator projection) Mar. 16–31, 1967, from Kornfield et al. (1967).

Circulation" since it can be shown to be an important part of the mechanism of Walker's "Southern Oscillation."

The great variability of the precipitation record at Canton Island in figure 1 reflects the fact that the western end of the Walker Circulation varies in longitudinal position from year to year. When the equatorial cold water and the arid regime reach Canton Island, that is a sign that the axis of the Walker Circulation is west of 172°W, so that subsiding air prevails over the island. When the Walker Circulation axis is located east of 172°W, Canton Island is under the rising air column with frequent rain from midtropospheric cloud as well as from convective cloud favored by the positive sea-minus-air temperature difference.

Figure 9 is a composite cloudiness picture of the tropical Pacific from ESSA 3 and 5 obtained by superposition of daily pictures during the equinoctial period Mar. 16–31, 1967 (Kornfield et al., 1967). As can be seen from figure 1, the period was characterized by cold water and a relatively arid climate at Canton Island, 172°W. The axis of the Walker Circulation must have been located approximately at 160°E where the equatorial easterlies begin to show cloud after having been rather cloudless all the way from the coast of South America, at 80°W. The sinking air in the Walker Circulation thus in this case seems to occupy about 120° of longitude and the rising air some 20° to 30° of longitude.

The arid zone is flanked to the north and south by almost straight, narrow cloud bands at the equatorward edges of the Hadley circulations of the Northern and Southern Hemispheres.

Satellite cloud pictures from the wet-warm periods in figure 1 show the transition from cloudy to much less cloudiness at the Equator well east of the Canton Island longitude, for instance near 160°W in January 1964 During the longer lasting wet-warm period in 1957–58 there was evidence of warm water at the Equator as far east as 145°W (Austin, 1960), and the South American coast had then one of its major El Niño occurrences, perhaps indicating that there was warm water all along the Pacific Equator. Under those extreme conditions the water temperature gradient along the Equator must have vanished temporarily. The Walker Circulation, which derives its propulsion from the longitudinal temperature contrast, also seems to have stopped, because westerly surface winds were occasionally observed at 145°W on the Equator in November 1957 (Austin, 1960).

A more permanent display of westerly surface winds at the Equator is known over the Indian Ocean as first described by Fletcher (1945) and amply verified by the International Indian Ocean Project in 1963–64. The dynamical justification for these equatorial westerlies could be sought in the fact that the surface temperatures of the equatorial belt of the Indian Ocean are a little lower at the African coast than at the coast of Sumatra. A weak thermally driven air circulation along the Equator with sinking air off Africa and rising air over Indonesia is therefore a possibility.

The equatorial Atlantic is analogous to the equatorial Pacific in that the warmest part is in the west, at the coast of Brazil, but the west-east contrast of water temperature is much smaller than in the Pacific. However, satellite pictures indicate that in the season of greatest rainfall (January) in interior equatorial Brazil, a thermally driven equatorial circulation is operating from the Gulf of Guinea to the Andes. The axis of that circulation is near the mouth of the Amazon, leaving the dry northeast

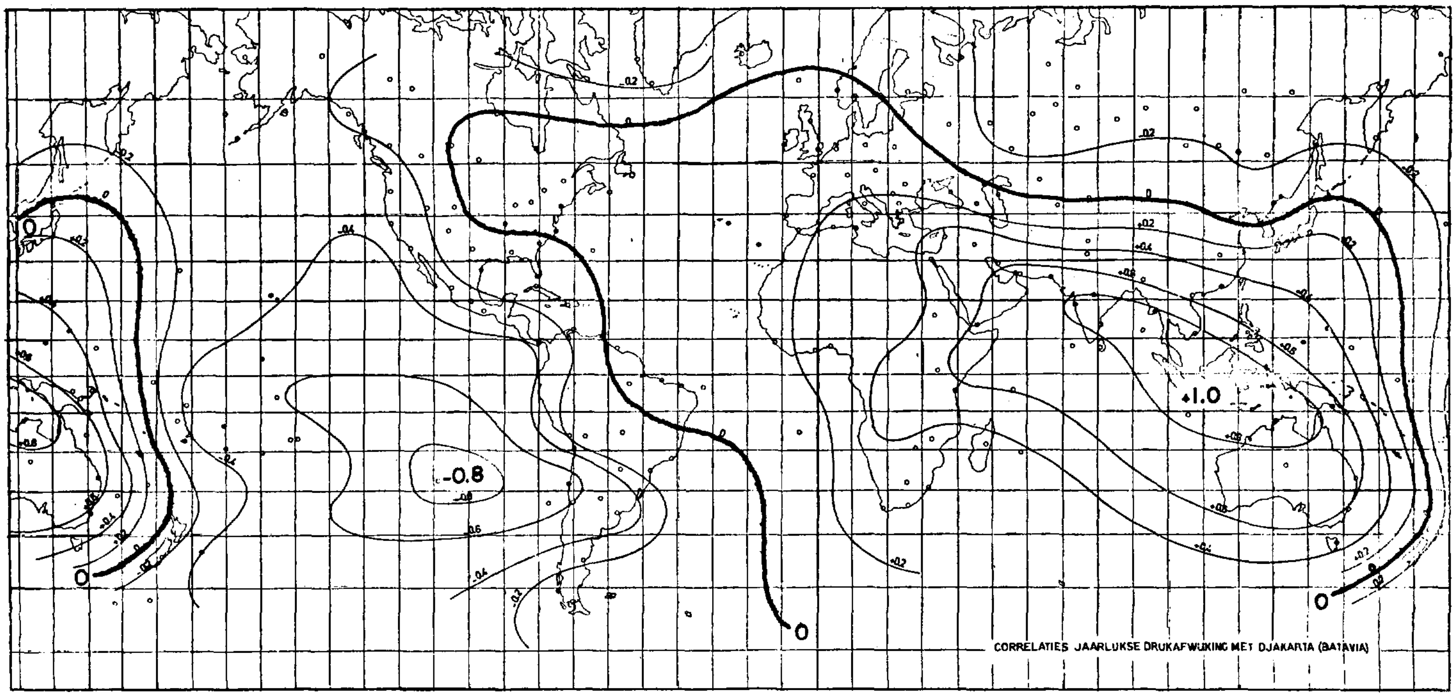

FIGURE 10.—Walker's Southern Oscillation as presented by Berlage (1957). The map shows the worldwide distribution of correlations of annual pressure anomalies with simultaneous pressure anomalies in Djakarta, Indonesia.

corner of Brazil (province of Ceara) and the equatorial Atlantic under sinking air.

Further discussion of the relatively weak thermal circulations along the Equator in the Atlantic and the Indian Ocean is beyond the scope of this article. In what follows, we endeavor to trace the tropical teleconnections emanating from the equatorial Pacific.

5. WALKER'S "SOUTHERN OSCILLATION"

The Walker Circulation described in section 4 must be part of the mechanism of the still larger "Southern Oscillation" statistically defined by Sir Gilbert Walker (1923, 1924, 1928, 1937) and Walker and Bliss (1930, 1932) in the World Weather I to VI sequence of research reports. Whereas the Walker Circulation maintains east-west exchange of air covering a little over an earth quadrant of the equatorial belt from South America to the west Pacific, the concept of the Southern Oscillation refers to the barometrically recorded exchange of mass along the complete circumference of the globe in tropical latitudes. What distinguishes the Walker Circulation from other tropical east-west exchanges of air is that it operates a large tapping of potential energy by combining the large-scale rise of warm-moist and descent of colder dry air. The fluctuations in the running of the Walker Circulation are therefore likely to initiate some of the major pulses of the Southern Oscillation.

The Southern Oscillation, as mapped in modernized form by Berlage (1957), is reproduced in figure 10. It shows, essentially, how simultaneous deviations of mean annual pressures from their long-term average have a tendency to be of one sign over the tropical Indian Ocean and the opposite sign over most of the tropical Pacific. The nodal line between the area of positive and negative deviations from long-term averages runs approximately north-south through the west Pacific and intersects the Equator at 165°E. The correlations of annual pressure anomalies with those of the arbitrarily chosen reference station, Djakarta (6°S, 107°E), have the surprisingly large value of −0.8 at Easter Island (29°S, 109°W). Walker did not have the Easter Island data and had to base his discussion on Santiago, Chile, where the negative correlation with Djakarta is not quite as impressive. The present author would suggest that the negative correlation at the approximate longitude of Easter Island but closer to the Equator, and thus out of reach of the extratropical disturbances, would show even better negative correlations than −0.8. Be that as it may (there are no island-based pressure records for the test of the idea), there is a definite tendency for opposite phase of pressure anomalies at Djakarta and over the eastern equatorial Pacific, and the nodal line in the pressure oscillation is located over the western Pacific near 165°E. The equatorial pressure changes between consecutive Januaries in figures 2 to 6 also conform to that pattern. Indonesia and the Indian Ocean had a pressure surplus in January 1964 and 1966 and a pressure deficit in January 1963, 1965, and 1967.

The degree of change of the equatorial pressure profile at extreme phases of the Southern Oscillation can be judged in figure 8 by the length of the marker DJ at the

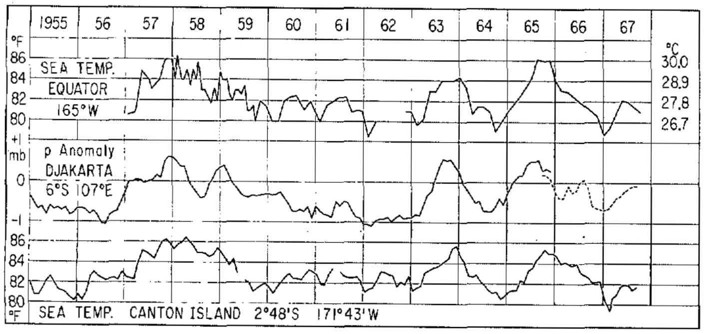

FIGURE 11.—The Southern Oscillation from 1955 to 1967 represented by 6-mo overlapping averages of Djakarta monthly pressure anomalies. Dashed curve based on Singapore data. On same time scale: sea temperature at the Equator at approximately 165°W, and sea temperature by monthly averages at Canton Island.

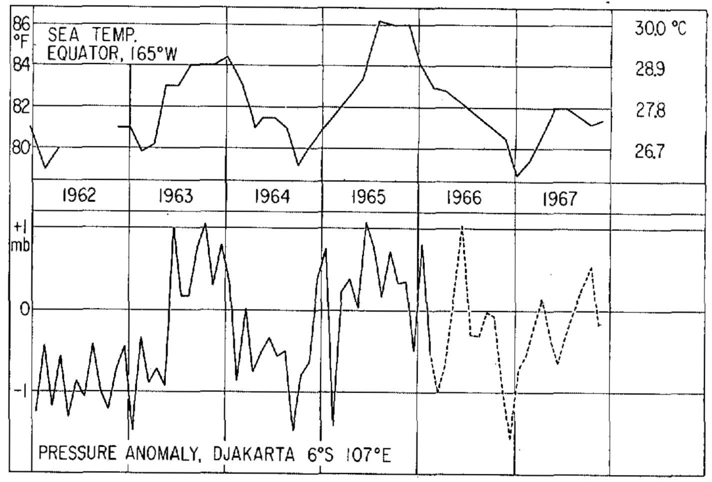

FIGURE 12.—Djakarta monthly pressure anomalies from 1962 to 1965 continued on the basis of Singapore data, and sea temperature at the Equator, 165°W.

longitude of Djakarta and of a corresponding marker at the longitude of the pressure maximum over the eastern Pacific. The markers refer to known recorded extremes of monthly averages, which numerically may deviate about ±1.5 mb from the long-term average for the month under consideration. Since opposite signs of pressure extremes usually occur simultaneously at Djakarta and in the east Pacific, the shape of the pressure profiles in figure 8 may change quite perceptibly. Of particular dynamic significance are the processes connected with the changes in slope of the pressure profile along the bottom of the Walker Circulation.

A change toward a steeper pressure slope at the base of the Walker Circulation is associated with an increase in the equatorial easterly winds and hence also with an increase in the upwelling and a sharpening of the contrast of surface temperature between the eastern and western equatorial Pacific. This chain reaction shows that an intensifying Walker Circulation also provides for an increase of the east-west temperature contrast that is the cause of the Walker Circulation in the first place. Trends of increase in the Walker Circulation and corresponding trends in the Southern Oscillation probably operate in that way. On the other hand, a case can also be made for a trend of decreasing speed of the Walker Circulation, as follows. A decrease of the equatorial easterlies weakens the equatorial upwelling, thereby the eastern equatorial Pacific becomes warmer and supplies heat also to the atmosphere above it. This lessens the east-west temperature contrast within the Walker Circulation and makes that circulation slow down.

There is thus ample reason for a never-ending succession of alternating trends by air-sea interaction in the equatorial belt, but just how the turnabout between trends takes place is not yet quite clear. The study of a sequence of global meteorological maps during typical turnabouts may clarify part of the problem. An additional key to the problem may have to be developed by the science of dynamic oceanography.

6. ANALYSIS OF THE CIRCULATION CHANGES CONNECTED WITH THE WARMING TREND IN THE CENTRAL EQUATORIAL PACIFIC IN 1963

Figure 11 shows the Southern Oscillation during the years 1955 to 1967 as represented by a time series of Djakarta pressure anomalies,[2] smoothed by 6-mo overlapping, and, on the same time scale, two curves representing the temperature of the surface water in the equatorial belt of the mid-Pacific. The bottom curve shows the succession of monthly averaged sea-surface temperatures at Canton Island (the same as shown in fig. 1). The other curve of sea temperature is obtained from ships crossing the Equator near 165°W while plying between Hawaii and Samoa. Ship crossings were more frequent in the late 1950's than in later years, which accounts for the different density of short-period detail along the time series. The longer period trends of the ship curve show a satisfactory agreement with those recorded at Canton Island at 2°43'S, as could well be expected.

However, the additional similarity of long trends in Djakarta pressure anomalies and those of the sea-surface temperature of the equatorial Pacific, one earth quadrant away, is a remarkable fact of organized teleconnections. That teleconnection, by the way, extends even farther east to the upwelling water at the coast of Peru whose temperature is also most of the time correlated to Djakarta pressure anomalies (see Berlage, 1966, p. 18).

In the case under consideration it is possible to get some information on the lag between the warming in the equatorial Pacific and the pressure rise in Indonesia. This is shown in figure 12, where the Djakarta monthly pressure anomalies from 1962 to 1965 and continued data from Singapore are depicted without smoothing. The change from negative anomalies, which had prevailed for approximately 4 yr, to positive ones took place in one jump of

[2] Djakarta data end with February 1966. The rest of the time series (in dashed curve) is based on Singapore for the time being.

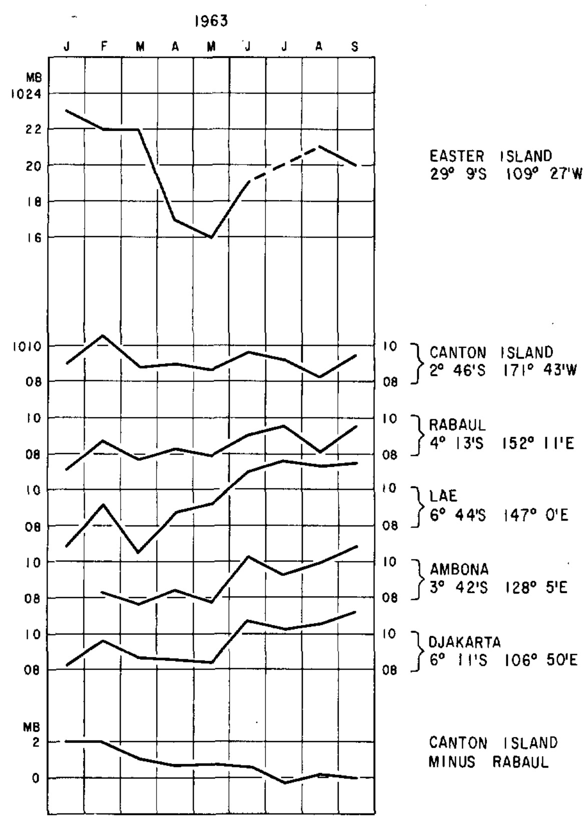

FIGURE 13.—Selected time series of monthly pressure in 1963 at Pacific and Indonesian stations. See text for discussion.

almost 2 mb from May to June 1963. Actually, the normal change between those 2 mo, determined from the period 1866–1942, is +0.43 mb; the real change in 1963 was +2.36 mb and the change in anomaly +1.93 mb.

The warming of the equatorial Pacific, which was also a quick process, took place a full month earlier. This establishes the Pacific Ocean warming as the cause of the lag-correlated adjustment of the pressure field over Indonesia in the Southern Oscillation pulse of 1963. The remote control must have operated through the Walker Circulation, which had to slow down when the east Pacific equatorial tongue of cold water became less cold and provided less east-west temperature contrast within the Walker Circulation. The corresponding automatic pressure response reduces the east to west pressure drop along the Equator and shows up as pressure rise in the western Pacific.

Figure 13 shows by means of selected time series of surface pressure how the chain reaction progressed from the southeast Pacific to Indonesia.

The Easter Island curve indicates a relatively strong southeast Pacific High in the first 3 mo of 1963 during which the upwelling at the South American coast and along the Equator must have been well maintained. Then, from March to April the 5-mb drop at Easter Island must have signaled a weakening of the upwelling all the way along the Equator to the mid-Pacific. The steep rise in the ship-based time series of sea temperature at 165°W occurred at that stage (figs. 11 and 12).

The decrease in the westward pressure gradient along the Equator can only indirectly be represented in figure 13 by the pressure difference between the two stations Canton Island, 2°46′S, and Rabaul, 4°13′S, neither of which is exactly at the Equator; but the decrease with time of the pressure difference of Canton Island minus Rabaul (bottom curve in figure 13) from 2 mb to about zero from February to July is big enough to be strongly indicative of the supposed weakening of the westward pressure gradient also at the Equator. The same, with good reason, can be assumed to take place east of Canton Island where no island-based pressure records are available. Most likely the 5-mb pressure fall shown at Easter Island from March to April must have extended to the Equator with perhaps a 1-mb pressure fall there. The inference from the pressure field (seen together with the simultaneous 2.2-mb pressure rise at Lae, on the Pacific coast of New Guinea) points definitely toward an ocean-wide slowdown of the Walker Circulation. The normal seasonal change from January to July over the equatorial Pacific, according to figure 8, goes in the sense of strengthening the Walker Circulation. Considering this, it can be seen that the year 1963 brought about equatorial Pacific conditions strongly deviating from normal.

It is with this general background in mind that it can be visualized what had to happen when, during the approach of the 1963 Southern Hemisphere winter, the equatorial belt of the Pacific Ocean had become much warmer than normal. Obviously, the southern Hadley circulations would strengthen. That is what happened from May to June 1963. A 3-mb rise started at Easter Island, and a general rise of up to 6 mb took place in the Australian part of the subtropical high-pressure belt. It is the northern fringe of the Australian pressure rise that is also recorded at the Indonesian stations Ambona and Djakarta (fig. 13) from May to June. These two localities were not yet reached by the upward pressure adjustment that was quite strong in eastern New Guinea when the Walker Circulation slowed down from March to April.

It is worthy of note that the strengthening of the southern Hadley circulations from May to June left the region between Easter Island and Australia in its normal cool pattern of isobars. Moving anticyclones may cross that area, but it is not the place for big anticyclones to become stationary and dominate the average monthly flow pattern. This is then also what makes it possible for the positive sea-temperature anomalies in the west Pacific equatorial belt to survive a southern winter season as they did in 1963. The same condition of equatorial heat surplus that started in April 1963 thus remained long enough to vitalize the northern Hadley circulation in the northern winter of 1963–64, as shown in figure 3.

7. CONCLUSIONS

The demonstrated recurrence of cases showing the strengthening of the wintertime Hadley circulations by the injection of surplus heat and latent heat supply from the Pacific equatorial belt now justifies a cautious use of such experience in long-range forecasting. A further support for such attempts lies in the demonstration that the temperature variation at the Pacific Equator are associated with Sir Gilbert Walker's Southern Oscillation. The 1963 case, investigated in some detail, shows that the thermally maintained Walker Circulation along the Pacific Equator initiated a new major pulse in the Southern Oscillation after several years of only minor pulses. Further research is needed to see if the triggering of pulses in the Southern Oscillation regularly does originate from equatorial ocean-atmosphere interaction in the Pacific.

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