Long-Term Wind Variability in the Tropical Pacific, Its Possible Causes and Effects

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ABSTRACT

It is shown that long-term trends in the meridional components of the trade wind circulations in both hemispheres over the Pacific are highly correlated with the precipitation falling in the intertropical convergence zone (ITCZ) over that region. The trends in the trade wind regime, on the one hand, seem to be caused by extratropical sea surface temperature (SST) anomalies in the North Pacific which influence atmospheric meridional temperature and pressure gradients. On the other hand, the release of latent heat in the ITCZ provides a self-enforcing feedback for the trade winds.

A study of the recurrence frequency of precipitation surges over the Line Islands suggests the presence of three epochs (1911–28, 1929–62, 1963 to present) during which the Hadley cell circulation and attendant meteorological and oceanographic features showed different characteristics.

1. Introduction

Wyrtki and Meyers (1975) have recently undertaken the tedious task of processing millions of weather reports from ships of opportunity which have plowed the tropical Pacific during the quarter-century between 1947 and 1972. The information contained in this data set is gradually mined for clues on long-term atmospheric variability (Barnett, 1977) and on ocean-atmosphere interaction (Reiter, 1978a). Our only regret is that this set of tropical meteorological data has not yet been extended to current date. Ship reports from the Atlantic (Hastenrath and Lamb, 1977) also offer a potential gold mine of clues on air-sea interaction, which needs to be tapped.

Our search for the causes of atmospheric interannual variability (Reiter, 1978a) and, ultimately, of climatic change, has stumbled upon this data source from the Pacific. A preliminary—and by no means final—analysis provides powerful indicators of an intricate mechanism of oceanic-atmospheric feedback which has been postulated earlier by Bjerknes (1966, 1969).

In searching for possible causes for interannual atmospheric variability we decided to suppress short-term and small-scale noise as much as possible from our meteorological and oceanographic data bases by forcing a great deal of smoothing on these data. The smoothing was accomplished by taking monthly longitudinal averages of our parameters over the width of the Pacific longitude sector. Such large-area smoothing was advocated, because in our present investigation we were not as much concerned with local air-sea interaction processes as with the detection of large-scale ocean-atmosphere feedback mechanisms. Furthermore, we wanted to eliminate seasonal trends from our data base, following the assumption that the ocean-atmosphere system—in first approximation—is well attuned to the seasonal cycle, but not to anomalies therefrom. We realize that this assumption is crude, and that some of the correlations which we have found may well be a function of season. The seasonal trends were removed from our data by computing monthly departures from long-term monthly mean values. The sets of departure values thus obtained were quite noisy for several reasons, such as poor data coverage (especially true for the tropical wind data), biases in the seasonal trend removal due to the relative shortness of some of the records, high-frequency atmospheric noise, etc. A seven-month running-average filter effectively removed most of this noise. This time period of smoothing was chosen for the following reasons (Reiter, 1978a):

1) Since seasonal trends were already removed from the record, the period for additional smoothing should be shorter than 12 months.

2) The search for feedback mechanisms which persist for longer than a season and a semiannual period call for a smoothing period of the order of half a year.

3) The choice of an odd number of months for the smoothing period facilitates the assignment of each smoothed value to a discrete month on a graph.

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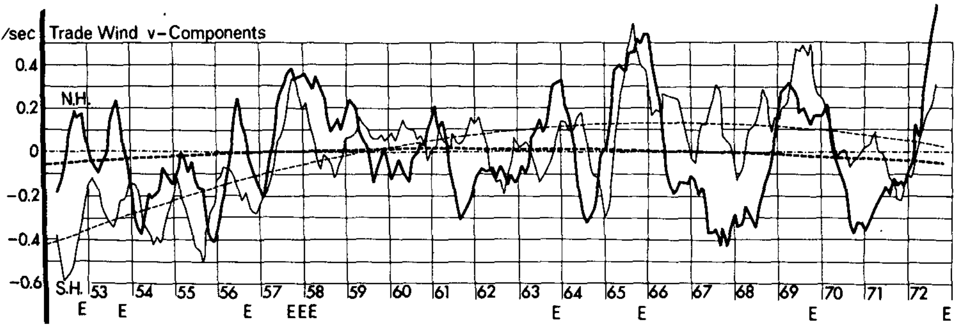

FIG. 1. Monthly departures from 21-year monthly means of trade wind *v* components averaged over the areas 5–19°N, 125°E–95°W (heavy line) and 1–15°S, 125–75°E (thin line). Data were subject to seven-month running averaging. Positive anomalies indicate stronger-than-normal flow *toward* the equator. Least-squares parabolic trends are indicated by heavy (Northern Hemisphere) and thin (Southern Hemisphere) dashed lines. Vertical lines indicate January of each year. E marks approximate dates of El Niño occurrences.

2. Pacific trade winds and precipitation in the ITCZ

Fig. 1 shows the mean monthly *v* components, time-averaged in the fashion indicated above, in the two Pacific trade wind regions 5–19°N, 125°E–95°W and 1–15°S, 125°E–75°W. The latitudinal boundaries of these two "boxes" were chosen to accommodate the zones of strongest surface easterlies in the North and South Pacific (Reiter, 1978a). The longitudinal boundaries were dictated by the availability of the data processed by Wyrtki and Meyers (1975) and received from the National Center for Atmospheric Research (NCAR). Grid points over land areas were excluded from these "boxes." [For the long-term behavior of the trade wind *u* component, which is of no immediate relevance to this discussion, see Reiter (1978a).] The data in Fig. 1 have been plotted so that above-normal flow intensity *toward* the equator carries a positive sign. We note that the behavior of the *v* components in both hemispheres reveals similar trends, a fact that also emerges from analyses carried out by Barnett (1977). Not only are the long-term trends (least-squares parabolic approximations are indicated in Fig. 1 by dashed lines) similar in both hemispheres, but also shorter term anomalies have a tendency to appear in the North as well as in the South Pacific. The varying sign of the time lag between these anomalies in the two hemispheres suggests that some of the *v* component pulses originate in the Northern, some in the Southern Hemisphere. The lag-correlation diagram shown in Fig. 2 indicates that in the Pacific sector the Southern Hemisphere trade wind *v* component more frequently lags that in the Northern Hemisphere than *vice versa*.

From the similarity of v_{NH} and v_{SH} we conclude that the intensity of the intertropical convergence zone (ITCZ) of the Pacific undergoes a pronounced interannual variability. Such a variability should reflect itself in the precipitation trends over the equatorial Pacific.

In Fig. 3 we compare the average *v* component behavior of both hemispheres [i.e., the average of the two curves shown in Fig. 1, $(-\bar{v}_{NH}+\bar{v}_{SH})/2$] with the monthly, time-smoothed precipitation index (PI) anomalies for the Line Islands. The latter data were obtained from a publication by Meisner (1976), and include the stations Washington Island, Fanning Island and Christmas Island. The use of a precipitation index, advocated by Solot (1950), instead of the absolute precipitation amounts, has the advantage of

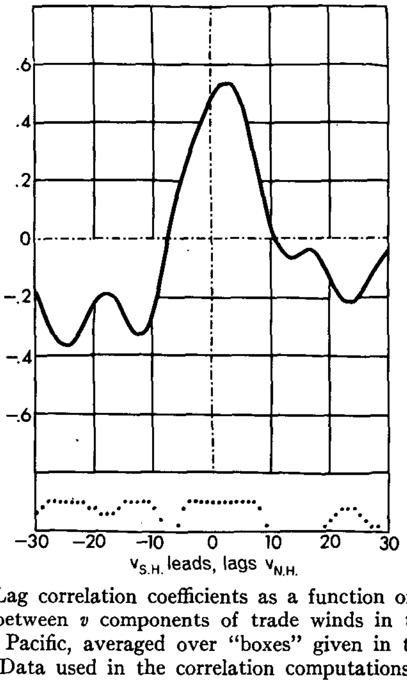

FIG. 2. Lag correlation coefficients as a function of lag time (months) between *v* components of trade winds in the North and South Pacific, averaged over "boxes" given in the legend to Fig. 1. Data used in the correlation computations were detrended and subjected to seven-month running averaging. Significance levels of the correlation are given by the dots along the bottom of the diagram: dot on first level, >50% significance; dot on second level, >80% significance; dot on third level, >90% significance; dot on fourth level, >95% significance; dot on fifth level, >99% significance.

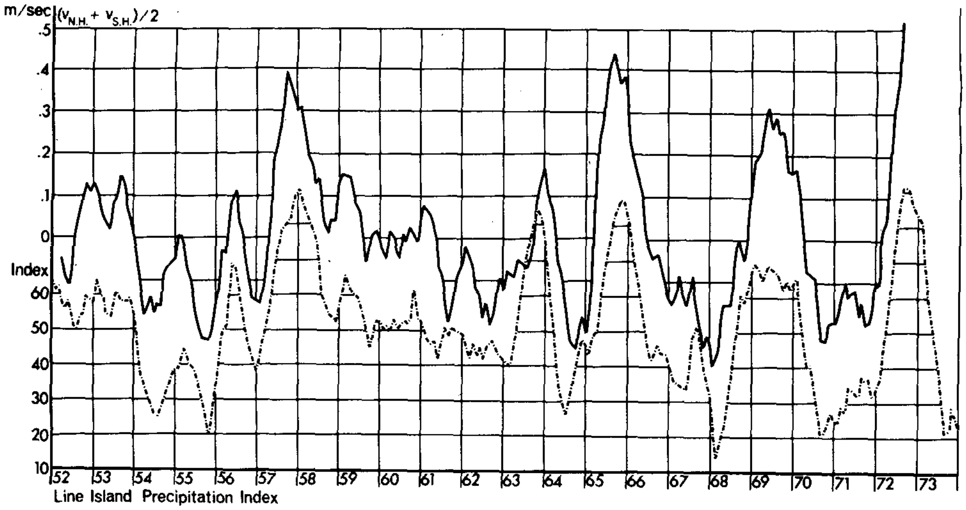

FIG. 3. Mean Pacific trade wind v component anomalies $(-v_{NH}+v_{SH})/2$ (solid line) and precipitation index for Line Islands (dashed-dotted line). Seven-month smoothing was applied to both data sets.

not unduly weighting stations with heavy precipitation over those with light precipitation. The index is derived by assigning the value 100 to the wettest monthly value and zero to the driest monthly value of a particular month in a long time series from a given station. By considering monthly index values the seasonal trend is eliminated from the data.

Fig. 3 indicates a remarkable agreement between the divergence and convergence in the trade wind v components of the two hemispheres with below- and above-average precipitation regimes in the Line Island region. This agreement is tested further by the lag correlation shown in Fig. 4. It should be pointed out that each of the peaks in the wind anomalies of Fig. 3 coincides with an El Niño event off the Peruvian coast. The El Niño is characterized by warm water replacing cold upwelling water in this region, causing an imbalance in the oceanic ecology which leads to a sharp reduction in the anchovy harvest. El Niño episodes have been observed toward the end of the years 1952, 1953, 1956, 1957, 1958, 1963, 1965, 1969, 1972 (extremely strong), 1975 (weak) and also 1976 (Bjerknes, 1969; Flohn and Fleer, 1975; Blackmon, 1977, personal communication; Ramage, 1977).

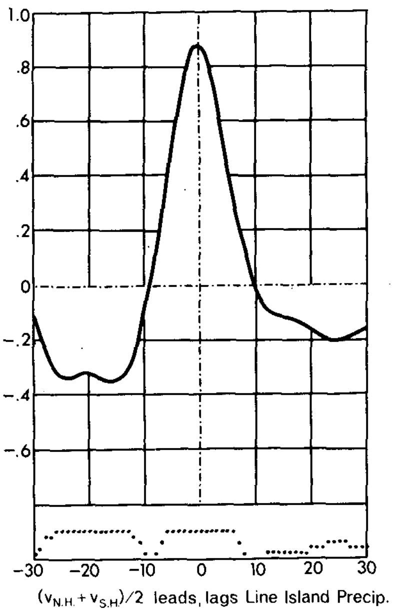

FIG. 4. Lag correlation between $(-v_{NH}+v_{SH})/2$ of Pacific trade winds and Line Island precipitation index. For further explanation see legend to Fig. 2.

Doberitz (1968) has shown that a zone of highly correlated precipitation events extends from Nauru in the equatorial west Pacific, through the Line Islands to Puerto Chicama on the Peruvian coast. From this evidence it appears that the heavy rains in the Line Islands and in Ecuador and Peru, associated with a strong El Niño, are not so much a local phenomenon as a consequence of a Pacific-wide adjustment in the ITCZ. Ramage (1977) also speculated that precipitation surges in the Line Islands were not simply tied to local SST changes.

What causes the fluctuations in the trade wind v components? We can envision two mechanisms. In another study (Reiter, 1978a) we have shown that pressure gradient variations in the west-wind belt north of the subtropical high-pressure belt exert a certain dynamic forcing effect on the intensity of the Hadley cell as measured by the v component of the trade wind circulation (see also Charney, 1963). In Fig. 5 we can, indeed, detect a certain agreement in the trends revealed by the 850 mb height-gradient anomalies between 20 and 50°N over the Pacific sector and the trend of $(-\bar{v}_{NH})$. These height gradient anomalies, in turn, are correlated with mid-latitude meridional air temperature and SST gradients.

But, obviously, extratropical forcing on the trade wind circulation does not tell the whole story. The second mechanism calls for a self-enforcing feedback between the intensity of the ITCZ, or the pressure depression in the equatorial trough, the rainfall caused by the convergent flow into that depression and the intensity of the Hadley cell circulation (Bjerknes, 1966, 1969). A similar feedback has been postulated to exist during the growth stage of a hurricane (Charney and Eliassen, 1964). The data presented in Fig. 3 give strong evidence for such a feedback mechanism to exist in the ITCZ of the equatorial Pacific. In 1971, for instance, a strong peak appeared in the extratropical height gradient of the 850 mb surface (Fig. 5). This peak was reflected only weakly, however, in the *v* components of the two trade wind systems, and as can be seen from Fig. 3, below-normal precipitation fell in the Line Island region. Extremely strong extratropical meridional pressure gradients prevailed during the winter of 1969/70 in the Pacific region. A peak also appears in the *v* component data as well as in the Line Island precipitation index, but with lesser amplitude than would be suggested by extratropical pressure-gradient forcing.

I have shown in another study (Reiter, 1978a) that the collpase of the surges in the trade wind *v* component, evident from Fig. 3, is heralded by increased upwelling of cool water in the equatorial Pacific which appears to be forced by the curl of the zonal wind stress. Each of these collapses signals a major El Niño occurrence. Thus it appears that the self-intensifying feedback between Hadley cell and trade wind intensities, and precipitation in the ITCZ, as postulated by Bjerknes, carries the seed for its own destruction. As the trade wind *v* components intensify, so do the trade wind systems as a whole, increasing the curl of the wind stress in the tropics and the chance for cold-water upwelling. As the strength of the Hadley cell collapses with a decreased moisture supply, major adjustments take place in the atmospheric and oceanic circulation systems. The El Niño along the

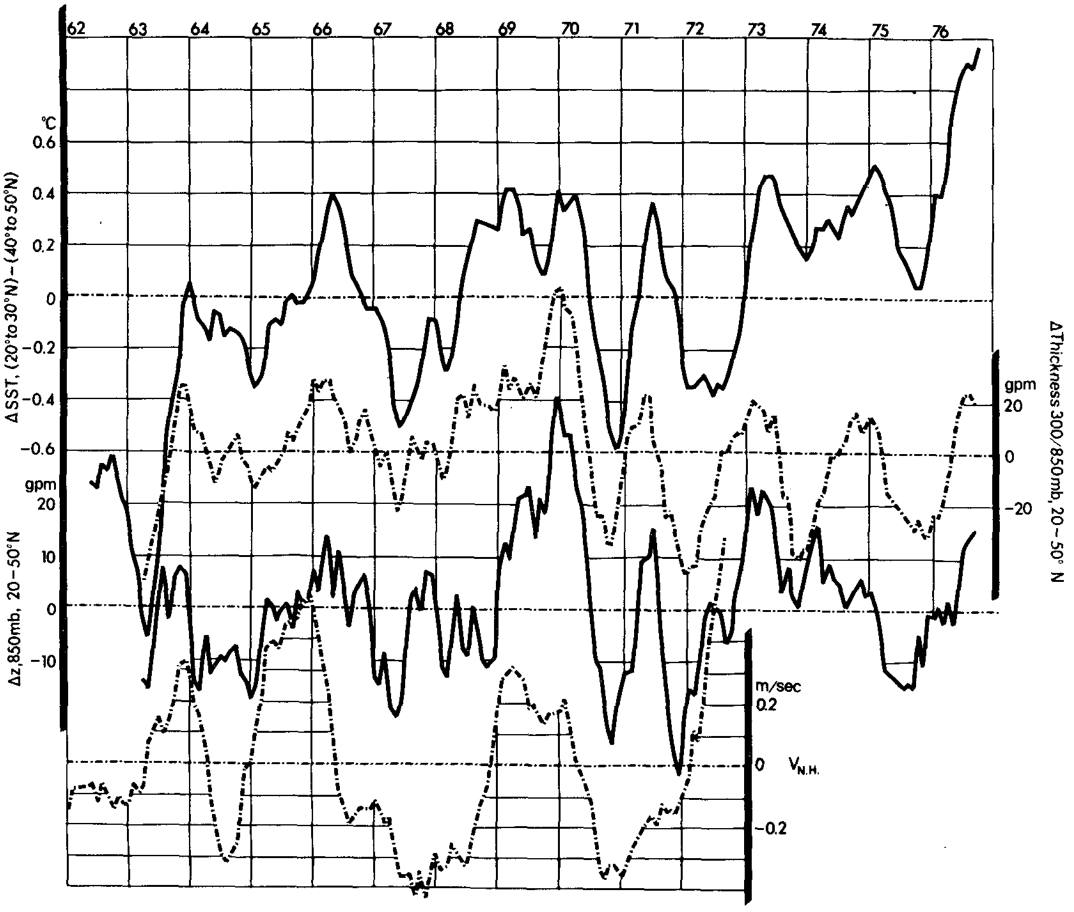

FIG. 5. Seven-month time-smoothed anomalies of Pacific SST gradients between the latitude bands 20–30°N and 40–50°N (top curve; °C scale on left side; positive values mean larger-than-normal temperature differences). Vertical lines indicate January of each respective year. The remaining curves are: atmospheric meridional thickness gradient 300–850 mb between 20 and 50°N (dashed-dotted curve, geopotential meters, scale on right side); height gradient between 20 and 50°N of the 850 mb surface (geopotential meters, scale on left side); *v* component of trade winds over the North Pacific (dashed-dotted curve, meters per second, scale on right side).

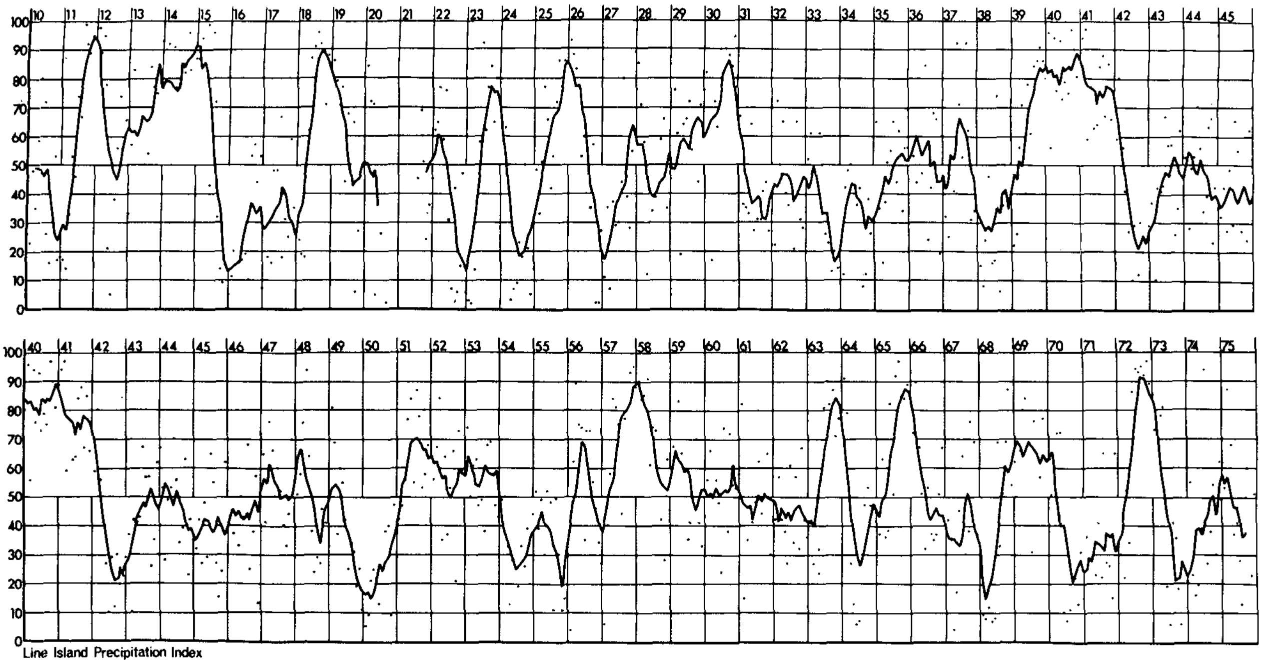

FIG. 6. Line Island precipitation index for the years 1910–75. Dots indicate monthly values; the heavy line stands for a seven-month running average.

coasts of Equador and Peru is but one manifestation of these adjustments.

3. Secular trends in the Pacific tropical precipitation and circulation regimes

In Fig. 6 the Line Island precipitation index is shown for the years 1910 through 1975 with a seven-month smoothing filter applied to the data. Meisner's (1976) precipitation index data are available as of 1910, but prior to 1922 several gaps appear in the published record. The shorter ones were bridged by linear interpolation; a longer one in 1920–21 was left void. We have plotted the individual monthly values of the precipitation index together with the seven-month running mean curve to demonstrate the appreciable high-frequency noise in these data.

Because of the correlation between $(-v_{\mathrm{NH}}+v_{\mathrm{SH}})/2$ and the Line Island precipitation index demonstrated earlier, we feel encouraged to equate each of the peaks in precipitation with a surge in the trade wind v components. Furthermore, in the light of a previous study (Reiter, 1978a) each major v component peak appears to herald an El Niño episode.

Fig. 6 indicates that between 1910 and 1927 eight major surges appeared in the Line Island precipitation index. They fall into the winter seasons of 1911–12, 1913–14, 1914–15, 1918–19, 1921–22, 1923–24, 1925–26 and 1927–28. Thus, by inference, there were eight El Niño occurrences in 18 years or, on the average, one case per 27 months. This quasi-biennial behavior of tropical precipitation and, presumably, of trade winds and El Niños, "skipped a beat" in 1929–30 and produced a surge toward the end of 1930. From thereon until 1939 a relatively dry regime settled over the equatorial Pacific. A prolonged surge of precipitation and also of very intense El Niño (Flohn and Fleer, 1975) marked the period from the second half of 1939 to the end of 1941. Another prolonged relatively dry and undisturbed period followed until 1956, with minor surges embedded between 1951 and 1953. The years 1956, and especially 1957–58 are witnesses to major El Niño episodes (Ichiye and Petersen, 1963; Bjerknes, 1969; Ramage, 1977) with a quiescent period following. From thereon, we find El Niño events in the winters of 1963–64, 1965–66, 1969–70, 1972–73, 1974–75 and 1976–77 (Blackmon, 1977, personal communication).

It thus appears that during the past 15 years surges in Line Island precipitation and in the trade wind v components over the Pacific, as well as El Niño occurrences, have been almost as frequent as during the period between 1911 and 1928. The time span between these two epochs is characterized by rather irregular, but prolonged precipitation anomaly trends in the equatorial Pacific.

We are beginning to wonder whether this rather different behavior of precipitation regimes and El Niño sequences during the three epochs 1911–28, 1929–62 and 1963 to present might be tied to the behavior of the Pacific anticyclonic gyre. In a different study (Reiter, 1978b) we have described a cooling trend in Pacific SST's north of 30°N during the past 15 years. The ocean temperatures south of 30°N remained relatively unchanged during the same time period. The meridional SST gradient thus increased during the past 15 years in the region of the North Pacific Drift. This increase would suggest an increase in the drift velocities, and hence in the rotation rate of the North Pacific oceanic gyre.

Fig. 7 shows a plot of seven-month smoothed SST anomalies (calculated with respect to monthly mean temperatures for the period 1962–76), for the latitude belt 40–50°N using data received from the Fleet Numerical Weather Central for the period 1962–76, from the Fisheries Research Board of Canada for 1949–62, and from NOAA for 1900–60. Whereas the Fisheries and Navy data match up very well, the NOAA data do not, giving us cause for suspicion as to their accuracy. The Fisheries and Navy data suggest that the present North Pacific cooling trend began during the early 1960's. If we can lend any credence at all to the NOAA data, it appears that a warming trend dominated the North Pacific between the late 1920's and the 1950's. During the 1910's and 1920's there might have been a cooling trend in the Pacific SST's between 40 and 50°N. Thus there is preliminary evidence—admittedly not very trustworthy because of the poor quality of the NOAA data—of cooling and warming epochs in the North Pacific which are similar in duration to the aforementioned epochs characterizing interannual variability regimes of tropical precipitation in the central Pacific and in El Niño recurrence frequencies.

The only possible physical link between these different pieces of evidence that we can postulate at this time, is that during periods in which the Pacific gyre accelerates beyond a certain rotation rate the enhanced water transport in the North Equatorial Current system also increases the chances of cold upwelling to occur in the central Pacific (Meyers, 1975). A secular increase of the North Pacific tradewind u component and of the curl of the wind stress in the region of the North Equatorial Current was, indeed, observed during the most recent period of North Pacific cooling (Reiter, 1978a,b). The appearance of cold water seems to presage the disruption of the "Bjerknes mechanism" that enforces the Hadley circulation through the release of latent heat in the ITCZ. Such disruptions are coupled with El Niño episodes off the Peruvian coast. When the Pacific gyre decelerates below a certain rotation rate (warming of the North Pacific), cold water appears to be forced to the surface less frequently and on a more irregular basis. The Hadley cells during such deceleration epochs appear to be somewhat weaker than during acceleration periods, and are less prone to respond to the self-enforcing Bjerknes feedback mechanism.

4. Conclusions

We have demonstrated the existence of a statistically significant correlation between precipitation in the equatorial Pacific, notably in the Line Island region, and the convergence and divergence of the v components in the North and South Pacific trade wind systems. This correlation suggests that the Bjerknes mechanism is at work during the development phase of surges in the trade wind v components. This mechanism calls for a feedback between the release of latent heat in the ITCZ and the intensification of the Hadley cell circulation. When the Bjerknes mechanism is disrupted (most likely due to upwelling of cold water forced by the curl of the zonal wind stress) the convergence between the trade wind cells of the two hemispheres decreases rapidly and at the same time El Niño episodes are observed along the Peruvian coast.

Long-term records of precipitation in the Line Islands suggest that the interannual variability of the ITCZ intensity in that region changed its character between three distinct epochs that prevailed since 1910. During two of these epochs (1911–28 and 1963-present) frequent surges of precipitation (sometimes resembling the quasi-biennial oscillation of the tropical stratosphere) were prevalent. So, presumably, were El Niño occurrences off the coast of South America. The epoch between 1929 and 1962 was characterized by rather irregular and infrequent surges of precipitation.

A tentative hypothesis is presented that these

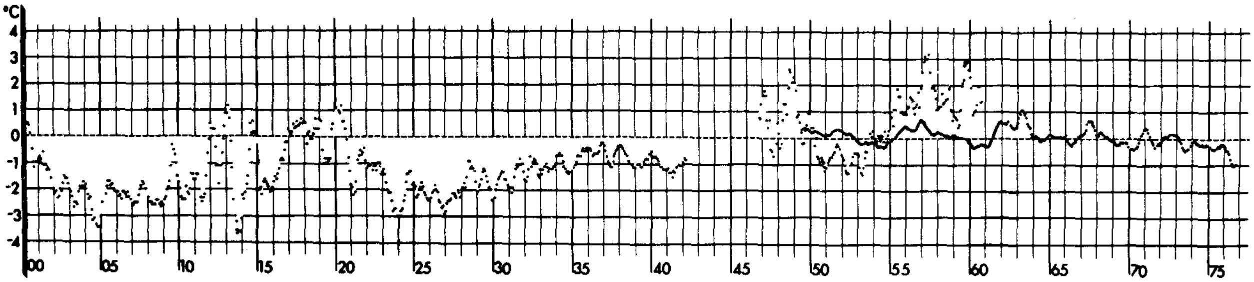

FIG. 7. Seven-month running mean of sea surface temperature anomalies (°C) in the latitude band 40–50°N of the North Pacific, calculated with respect to the 1962–76 monthly mean temperatures. Dots after 1962, data from Fleet Numerical Weather Central; solid line between 1949 and 1962, data from Fisheries Research Board of Canada; dots prior to 1961, data from National Oceanic and Atmospheric Administration.

epochs of tropical precipitation regimes might be tied to North Pacific cooling and warming trends. The quality of the SST data base prior to 1949 will have to be improved drastically, however, before this suggested link between extratropical and tropical climatic trends can be confirmed.

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