A POSSIBLE EXPLANATION OF ANOMALOUS EVENTS OBSERVED IN THE OCEAN/ATMOSPHERE SYSTEM OF THE NORTH PACIFIC 1955–1960

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1.0 *Introduction*

In 1958, the CalCOFI Conference conducted a symposium on the anomalous oceanographic and meteorological events that occurred during 1957–58 in the eastern North Pacific Ocean. During that time period the sea surface temperature over much of the eastern North Pacific was abnormally high and the wind systems were associated with unusual pressure patterns during the winter months. The physical models that were formulated to explain the evolution of these observed anomalous events were of such a nature that Isaacs and Sette (1960) were prompted to remark that no dynamical theory then in existence could account for the observed sequence of events. That statement was certainly true then because scientists before the symposium, except for J. Namias (1960) and a few others, did not interpret the 1957–58 anomalous events as adjustments of an *ocean/atmosphere coupled system.*

The consensus that the ocean and atmospheric anomalies were somehow intimately coupled was perhaps the most important result to come out of the 1958 CalCOFI Symposium. It was also realized how little effort was being expended to investigate the large-scale, air-sea interaction problem. In response to this latter point, Professor John D. Isaacs in 1965 initiated the North Pacific Study at Scripps Institution of Oceanography. The purpose of this study was to investigate large-scale, air-sea interaction over the North Pacific.

Since the inception of the North Pacific Study, a large amount of historical data and more recent deep-moored buoy data has been collected. From this body of data Namias (e.g., 1969) and others have begun to describe the mechanics of large-scale ocean/atmosphere coupling in the mid-latitude North Pacific. Working independently, Bjerknes (1966a,b, 1969) has made notable contributions to the study of large-scale ocean/atmosphere interactions in the equatorial Pacific Ocean. More recently, White and Barnett (1972) analyzed oceanic and atmospheric data contained in the North Pacific Study data bank for the decade of the 1950's, and from this developed a theory describing the physics of one type of large-scale, mid-latitude feedback mechanism (a servomechanism) which may have initiated widespread anomalous conditions over the Pacific.

The present undertaking combines the ideas of Namias, Bjerknes, and White and Barnett into a coherent discussion on the possible evolution of these anomalous events. The ocean/atmosphere interaction mechanisms important to the sequence of the anomalous events observed during this period formed a cycle, wherein the geographical distribution of heat flux from the ocean to the atmosphere maintained a stable balance with the oceanic transport and with the atmospheric pressure systems. In outline, the sequence of events was as follows: an unusually large zonal westerly wind stress in 1955 induced an anomalous distribution of heat flux from ocean to atmosphere along the subarctic frontal zone off the east coast of Asia in the fall and winter of 1955–56. This, in turn, caused a large perturbation of the westerly wind regime. The perturbation profoundly affected the ocean/atmosphere heat flux distribution in both the central regions of the mid-latitude North Pacific and the tropical regions for the next few years. Stability factors inherent in the Pacific-wide ocean/atmosphere system brought conditions back to their initial state in 1960.

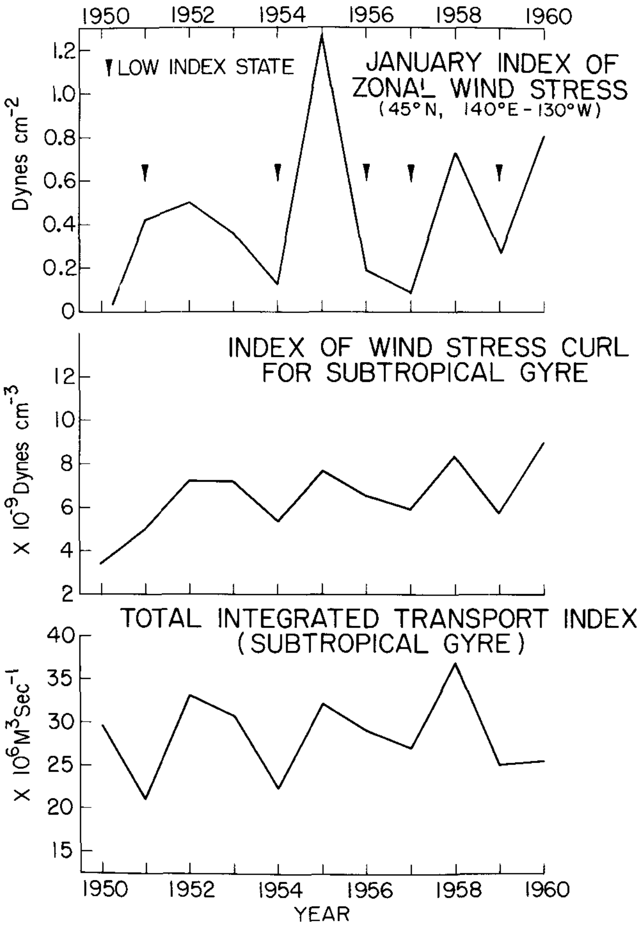


Figure 1. Time history of ocean/atmosphere indices of motion in the North Pacific for the decade 1950–60 (Fofonoff, 1960; Fofonoff and Dobson, 1963). Upper panel: January index of zonal wind stress at 45°N, averaged between 140°E and 130°W. Middle panel: Annual index of wind stress curl for subtropical gyre averaged from 140°E to 130°W between latitudes 20° and 30°N. Lower panel: Annual index of total integrated transport for subtropical gyre calculated near 160°E.

2.0 *The Initial State, 1955–1956*

The variations of three fundamental descriptors of the ocean and atmosphere during this period are shown in Figure 1. These graphs have been computed from the work of Fofonoff (1960) and Fofonoff and Dobson (1963). Beginning in January, 1955, the westerly wind stress index had a very large value, the largest of the decade. In association with this was a peak in the index of wind stress curl for the subtropical gyre. According to Sverdrup's (1947) theory, the large wind stress curl in 1955 and 1956 was the reason for the consistently higher transport in the subtropical gyre in those same years (shown in the lower panel of Figure 1). This high value of transport would be expected to have significantly affected the characteristics of the subarctic frontal zone off the east coast of Asia. The subarctic frontal zone is the zone of contact between the Oyashio and Kuroshio western boundary currents, the latter of which completes the western part of the subtropical gyre. As the Sverdrup transport of the subtropical gyre increased in 1955 and 1956, the subarctic frontal zone off the east coast of Asia extended farther north than at any other time in the decade, as observed in the upper panel of Figure 2 by the meridional position of both the 60°F isotherm and the Kuroshio extension. At the same time the meridional temperature gradient increased (lower panel of Figure 2) thus maintaining the necessary geostrophic balance.

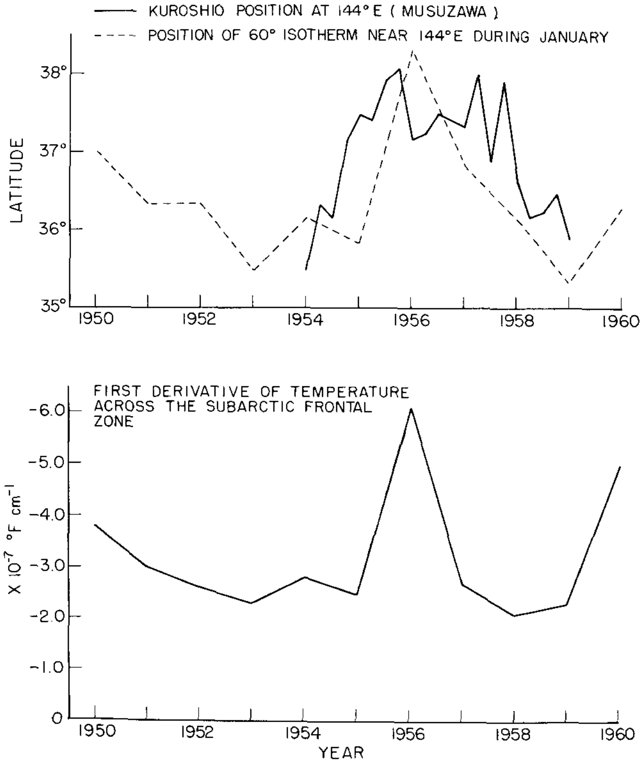


Figure 2. Time history of subarctic frontal zone characteristics for the decade of 1950–1960. Upper panel: Latitude of Kuroshio extension at 144°E (Masuzawa, 1960) and position of 60°F isotherm near 144°E. Lower panel: Index of first derivative of sea surface temperature across the subarctic frontal zone $\left(\frac{\partial T}{\partial y} \approx \frac{T_{50°F} - T_{60°F}}{\Delta y}\right)$ from 150°–170°E.

Both Rossby (1939) and Namias (1959) have discussed how quasi-stationary long waves in the upper-level westerly wind system respond to the large amounts of heat given up to the atmosphere at the subarctic frontal zone. The matter has been expressed quantitatively by Fisher (1958) who showed that the increase with time in upper-level (700 mb) cyclonic vorticity is proportional to the Laplacian of the upward surface heat flux ($\nabla^2 Q$). The distribution of the sum of latent and sensible heat transfer (Q) over the North Pacific (upper panel in Figure 3), is such that the subarctic frontal zone possesses the maximum $\nabla^2 Q$ intensity found in the North Pacific during the winter season. The substantial intensity of $\nabla^2 Q$ at the subarctic frontal zone would be expected to increase significantly the cyclonic vorticity of the upper-level westerly wind system which, in turn, affects the amplitude and wave length of the quasi-stationary long waves.

Sensible and latent heat flux data (kindly provided by Dr. N. Clark, National Marine Fisheries Service, La Jolla) were used to calculate $\nabla^2 Q$ in the vicinity of the subarctic frontal zone (lower panel in Figure 4) from 1950 to 1957 (the extent of the data). These data show that in the winters of 1955–56 and 1956–57, the subarctic frontal zone was characterized by intensities of $\nabla^2 Q$ that were over *twice* those occurring in any of the five preceding years. The large intensity of $\nabla^2 Q$ was associated with large absolute values of the second meridional derivative of sea surface temperature, $|\partial^2 T/\partial y^2|$, across the subarctic frontal zone (upper panel in Figure 4). This relationship suggests that the large intensity of $\nabla^2 Q$, that induced cyclogenesis in the upper-level westerly wind system was principally due to the sea surface temperature distribution, which has previously been related to the intensification of the wind-generated transport in the subtropical gyre during 1955 and 1956.

The injection of cyclonic vorticity into the upper-level westerly wind system induced by the anomalously large $\nabla^2 Q$ in 1956, according to White and Barnett (1972) caused the formation of an amplified, quasi-stationary, long wave (right hand panels in Figure 5). This amplified long wave was, in turn, associated at sea level with a split Aleutian low pressure system. This is to be compared with the low amplitude long wave at 700 mb found in 1955 (left hand panels of Figure 5). The transition from high (1955) to low (1956) index situation observed in the upper panel of Figure 1 may be attributed to the formation of this amplified long wave in response to the increased cyclogenesis at the subarctic frontal zone.

3.0 *The Sequence of Anomalous Events, 1956–1958*

The main source of cyclogenesis that initially induced the amplified long wave in 1956 comes from the subarctic frontal zone. The continued large $\nabla^2 Q$ in 1957 is responsible for the recurrence of the amplified long wave in 1957 and the continuation of the low index state of the ocean/atmosphere system. However, the anomalous atmospheric conditions in 1956 produced dramatic changes in the heat flux at other strategic locations around the North Pacific that promoted other anomalous conditions. The principal locations for these centers of influence were the central mid-latitude North Pacific and the tropical and equatorial Pacific.

3.1 *Anomalous Events in the Central North Pacific*

The ocean/atmosphere system in the central North Pacific during 1956–1958 has been described by Namias (1959, 1960) who found evidence indicating that the anomalous atmospheric circulation which began in 1956 developed anomalous sea surface temperatures in an area centered near 40°N, 180°. The resulting abnormal surface temperature gradients and unusual heat flux from ocean to atmosphere, according to Namias, promoted increased cyclogenesis in the overlying air masses that influenced the position and strength of the amplified long wave through 1956–57. However, in light of the work of White and Barnett (1972) the principal effect of this influence in 1957 seems to have been to position the ridge of the long wave farther to the east of its 1956 position. Using arguments based on planetary long wave dynamics and anomalous Ekman drift, Namias (1959) showed that the local ocean/atmosphere feedback system would result in a slow migration of the coupled area of anomalous sea surface temperatures and atmospheric long wave system eastward across the North Pacific exactly as was observed (see Figure 6) from 1956 to 1957.

By the winter of 1957–58 the values of ∇^2Q at the subarctic frontal zone were small (as indicated by the low values of $|\partial^2T/\partial y^2|$ in Figure 4). This resulted in the reduced amplitude of the planetary long wave and the return to a high index year (Figure 1). Furthermore, the large area of anomalous temperatures in the central North Pacific had diminished in both intensity and size and now occupied an area east of 140°W (see Figure 6). This movement seems to have been the result of southward displacement of the westerly wind regime that brought unusually warm air into this region. To understand the southward shift in the westerly wind regime, we must turn attention to events near the equator.

3.2 *Anomalous Events in the Tropical and Equatorial North Pacific*

The meridional displacements experienced by the atmospheric pressure field over the central North Pacific in the winter of 1955–56, and to a lesser

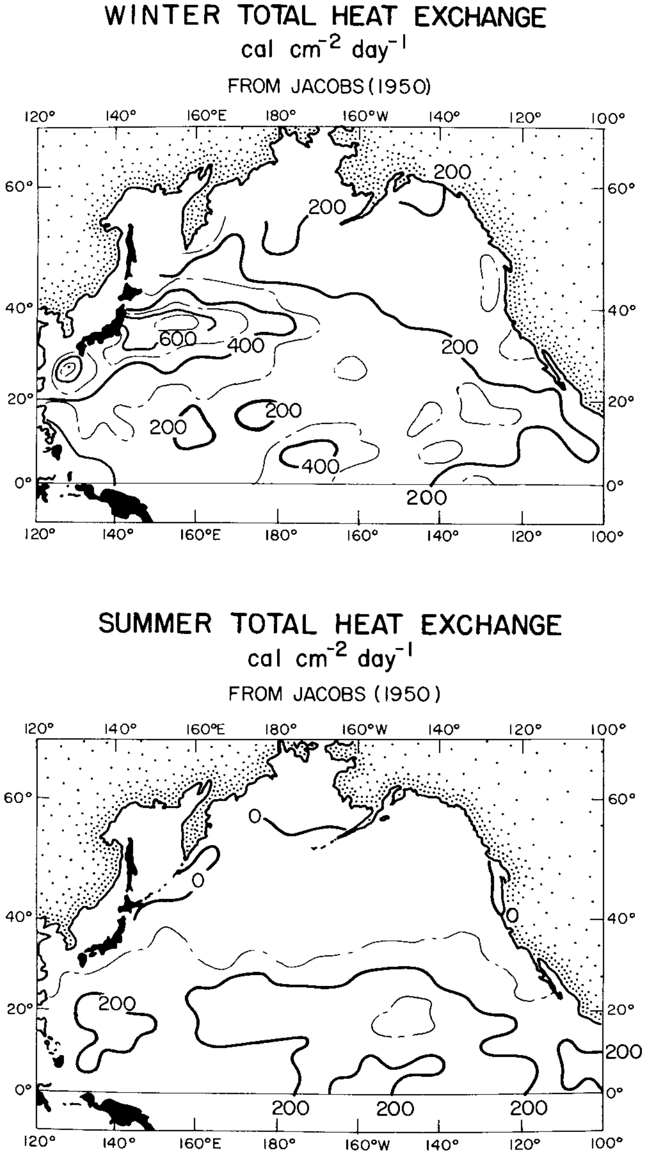


Figure 3. Mean geographical distribution of the sensible and latent heat exchange between the ocean and atmosphere in summer and winter for the North Pacific (Jacobs, 1950). Positive values indicate heat gain by the atmosphere.

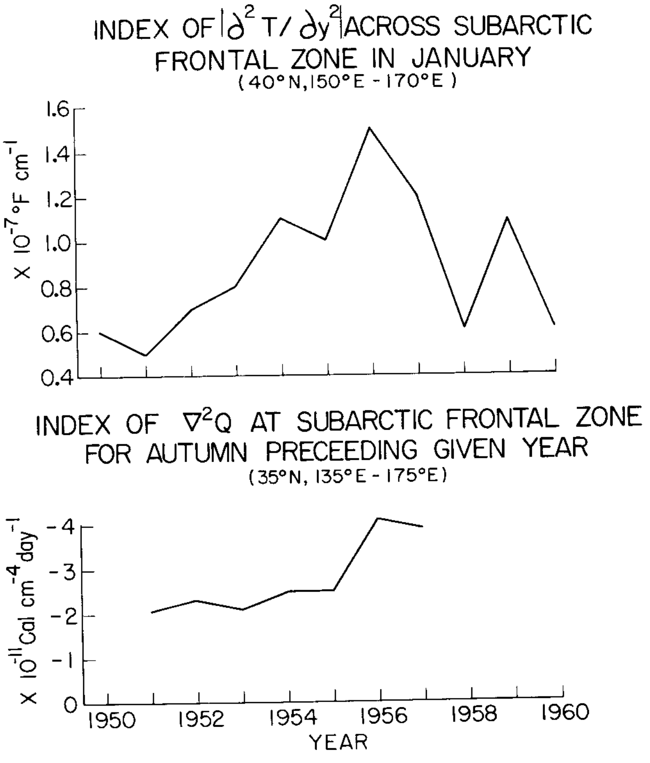


Figure 4. Upper panel: Index of the second meridional derivative of sea surface temperature at the subarctic frontal zone for January at 40°N, 150°–170°E. Lower panel: Index of the Laplacian of autumn heat flux (∇^2Q) near the subarctic frontal zone averaged between 135° and 175°E (Q values courtesy of Dr. N. Clark, National Marine Fisheries Service La Jolla).

extent in the winter of 1956–57, were mirrored in the tropical pressure patterns north of the equator. This may be seen by comparing the second panel of Figure 7 with Figure 1, where the *zonal* indices of northeast trade wind stress and westerly wind stress are seen to have fluctuated in unison.

The drop in the zonal northeast trade wind stress in 1956 should have resulted in the reduction of the fluxes of sensible and latent heat from the underlying waters to the atmosphere (Namias, 1972; Bjerknes, 1966b). Under such conditions the surface temperature under the northeast trade wind should have increased. The data of Bjerknes (1966b) and Allison *et al* (1971) indicate that east of 180° this warming was small but marginally significant. West of 180°, the surface temperature stayed about the same. However in general over the entire period the surface temperature fluctuations of the eastern and western portions of the equatorial ocean were *out* of phase with each other.

The surface cooling in the western tropical Pacific from 1956–58 (Figure 8, lower panel) was due to the fact that as the northeast trade wind increased in strength, and the fact that its mean direction rotated counterclockwise (upper panel of Figure 7). The index of the southward component of the mean northeast trade winds in the western tropical Pacific Ocean increased from a minimum in January 1956 to a maximum in January 1957. This indicates an unusual flow into the tropics of cool, dry air from the north. The increased rate of heat flux from sea to air due to the large air-sea temperature difference enhanced that which would have already accompanied the higher zonal wind speed.

The lowering of the sea surface temperature over the west tropical and equatorial North Pacific resulted in reduced thermal convection in the atmosphere and a corresponding reduction in the rainfall, as reported by Quinn and Burt (1970) and Allison *et al* (1971). Furthermore, a reduction in the rainfall in the western equatorial Pacific would be expected to lower the amount of latent heat energy available to both the Pacific Hadley Cell and the Pacific zonal equatorial Walker Cell. Since this geographic area provides most of the energy for both of these atmospheric circulation features (Flohn, 1971; Krishnamurti, 1970) one would expect them to weaken beginning in 1956 and extending through 1957. The zonal pressure gradient along the equator, the driving force for the Walker Cell, did indeed decrease, eventually reversing itself (Rowntree, 1972). In the absence of any hard evidence, we have to assume that the Hadley Cell in the Pacific also decreased. This weakening of the Hadley Cell and Walker Cell beginning during the late winter of 1955–56 were followed by a weakening of the southeast trade wind (lower panel of Figure 7).

An inverse relation between the strength of the southeast trade wind and the sea surface temperature in the equatorial region has been demonstrated (Hires and Montgomery, 1971). However an increase in sea surface temperature was observed in 1956–58 along the equator at both Canton and Christmas islands (Figure 8). This relation was explained physically by Bjerknes (1966b) as due to reduction of both (a) wind-induced equatorial upwelling and (b) advection of cold water from upwelling areas off Peru. Part of

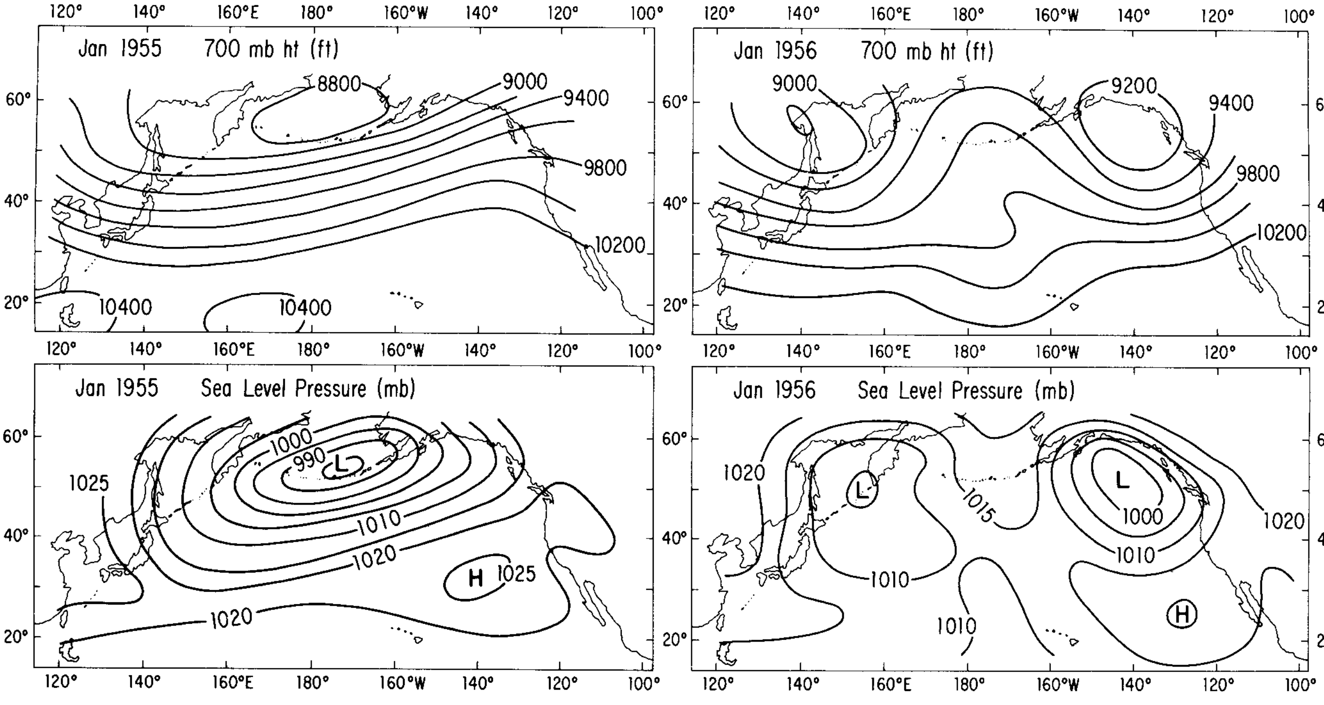
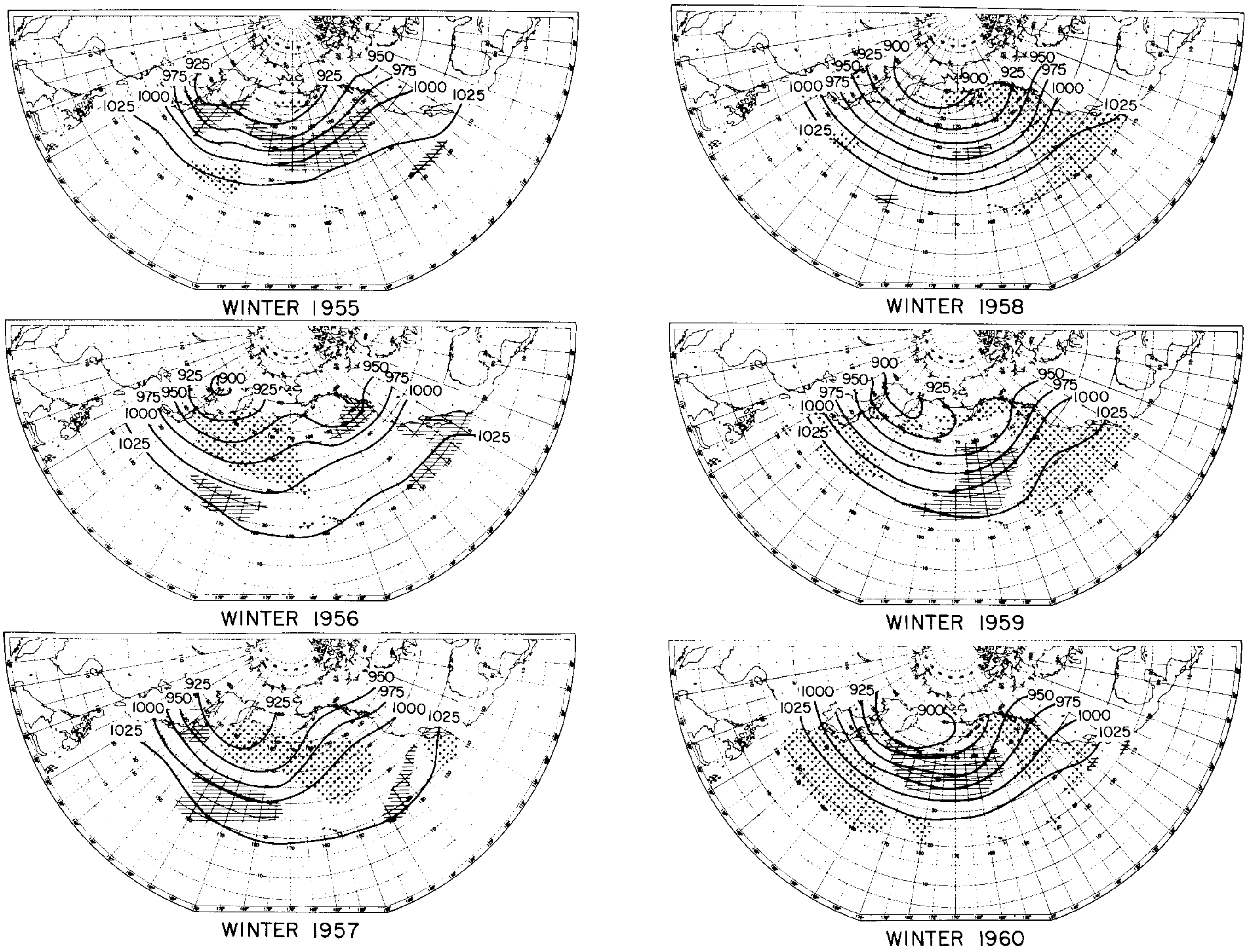


Figure 5. Circulation patterns characterizing the westerly wind system during January 1955 and 1956 at sea level and at a height of 700 millibars (National Weather Service). In each case the isopleths approximate streamlines of the air flow.



WINTER 1955

WINTER 1958

WINTER 1956

WINTER 1959

WINTER 1957

WINTER 1960

Figure 6. January sea surface temperature anomalies (base period 1947–66) superimposed upon 700 mb contours. Stippled areas are more than 1°F above 20-year mean and hatched areas are more than 1°F below.

the equatorial warming may also be attributed to the fact that in the winter of 1957–1958 the winds in the vicinity of the equator developed a westerly component (Figure 9). This component will induce *convergence* of Ekman drift at the equator as opposed to the divergence caused by an easterly component.

The important result of the equatorial warming in the eastern and central Pacific beginning in early 1956 is that it eventually shifted the oceanic thermal equator (associated with the atmospheric intertropical convergence zone) to the south, closer to the geographical equator, during the winter of 1957–58 (Figure 10). In addition, the principal source of heat for the atmosphere located in the western equatorial Pacific Ocean in 1956 had spread eastward in 1958 so that the Hadley Cell was able to receive energy from a band of ocean extending almost entirely across the Pacific.

The fact that the thermal equator coincided with the geographic equator indicates that in 1958 the Hadley Cell axis must have shifted south in correspondence with the intertropical convergence zone. This contention is born out in Figure 9. The data are from Canton Island which was near the middle of the zone during 1958. In this position one would expect maximum convection above Canton, but little horizontal motion. This is exactly what the data show. The alternative explanation of the data in terms of *no* Hadley circulation during 1958 seems quite unlikely.

The result of the major movements by the equatorial atmospheric systems led to a subsequent shift south of the mid-latitude upper-level westerly winds. Such a shift in the winter of 1958 has indeed been observed and documented by Namias (1959). This southerly shift accounts for the positive surface temperature anomalies off the coast of north America in 1958–59 mentioned in the beginning.

4.0 *Stability Factors in the System, 1959–1960*

Observations from many sources indicate that the trend in the sequence of anomalous ocean/atmosphere events of 1955–57 began to reverse itself in late 1958 and early 1959, returning by 1960 to a state not unlike that in 1955. In this section we offer a hypothesis to explain this stability in the ocean/atmosphere system. Since the anomalous activity over the entire North Pacific emanated from the equatorial region in 1958 this hypothesis centers on the inherent stability in the equatorial ocean/atmosphere interaction mechanisms.

4.1 *The Equatorial System*

On the basis of Bjerknes' (1966a,b) description of the equatorial ocean/atmosphere system, it can be shown how equatorial processes act to return a perturbed ocean/atmosphere system to its initial state. These processes may be thought to constitute a stable servomechanism (our term) involving a triple interaction between sea surface temperature (governed principally by wind-induced equatorial upwelling), the heat given up to the Hadley Cell circulation, and the resulting strength of the trade winds. Physically the excess evaporation from an anomalously warm tropical ocean increases the release of latent heat in the atmosphere (via rainfall) and increases thermal convection in the Hadley Cell which intensifies trade wind stress. The latter intensification increases equatorial upwelling and thus cools the equatorial sea surface. The resulting reduced sensible heat transfer weakens convective action in the Hadley Cell and lessens trade wind stress. In the presence of weakened equatorial upwelling local solar heating begins the cycle again. If one considers these processes occurring simultaneously then a steady state equilibrium can be established. When an external perturbation disturbs this equilibrium, the above mentioned processes will act to restore the system to its initial state.

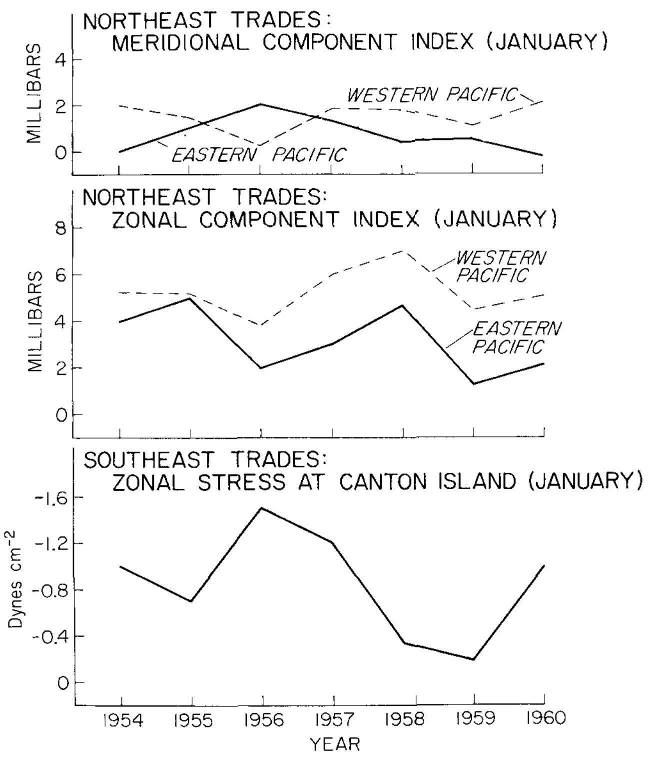


Figure 7. Trade wind indices for January. Upper panel: Meridional component of northeast Trades estimated from pressure difference between 155° and 165°W at 15°N in the eastern Pacific, and from pressure difference between Wake Island (19°17'N, 166°34'E) and Legaspi (13°8'N, 123°44'E) in the western Pacific. Middle panel: Zonal component of northeast Trades estimated from pressure difference between 10° and 20°N at 165°W in the eastern Pacific, and from pressure difference between Wake Island and Tarawa Island (1°21'N, 172°56'E) in the western Pacific. The western Pacific data for both panels came from Bjerknes (1966b). Lower panel: Zonal stress for southeast Trades as measured at Canton Island (2°48'S, 171°43'W) (Data from GEOTAPE courtesy of W. Munk).

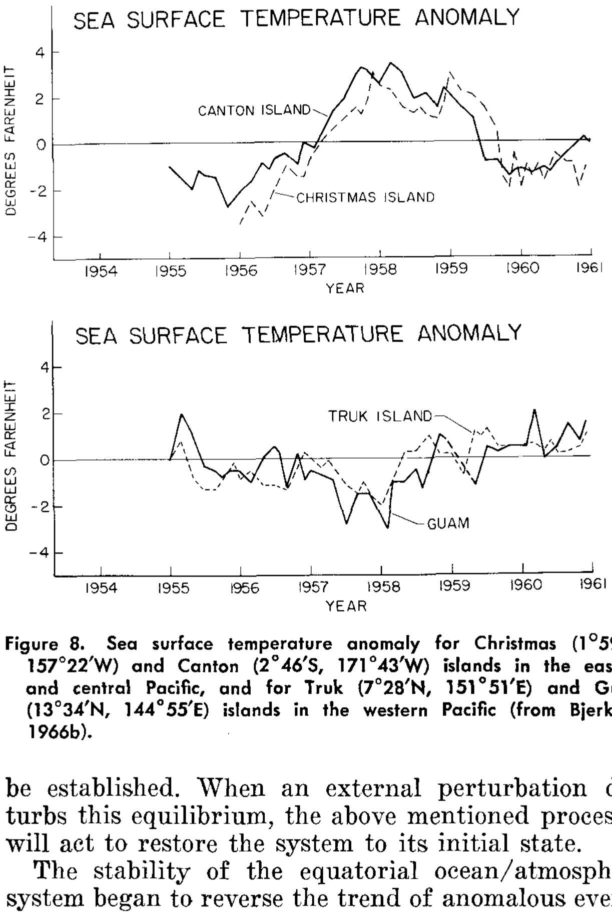


Figure 8. Sea surface temperature anomaly for Christmas (1°59'N, 157°22'W) and Canton (2°46'S, 171°43'W) islands in the eastern and central Pacific, and for Truk (7°28'N, 151°51'E) and Guam (13°34'N, 144°55'E) islands in the western Pacific (from Bjerknes, 1966b).

The stability of the equatorial ocean/atmosphere system began to reverse the trend of anomalous events in late 1958 and 1959. This is demonstrated by the following observations. In 1958 the positive surface temperature anomaly along the equator in the eastern and central Pacific was directly correlated with high equatorial rainfall at the remarkable level of 0.93 (Allison *et al*, 1971) and low values of the southeast trade wind stress (Hires and Montgomery, 1971). This rainfall was not confined to the western equatorial region, but occurred in a broad belt across much of the eastern and central equatorial Pacific (Doberitz *et al*, 1967). Hence, the energy provided to the atmosphere through the conversion of latent heat would be expected to be released also in a broad belt across much of the equatorial Pacific. In view of this, one would further expect rather marked increases of velocity in both the trade winds and westerly winds from the winter of 1957–58 through 1959. Figures 1 and 7 show that the westerly wind stress and northeast trade wind stress did, in fact, increase rather

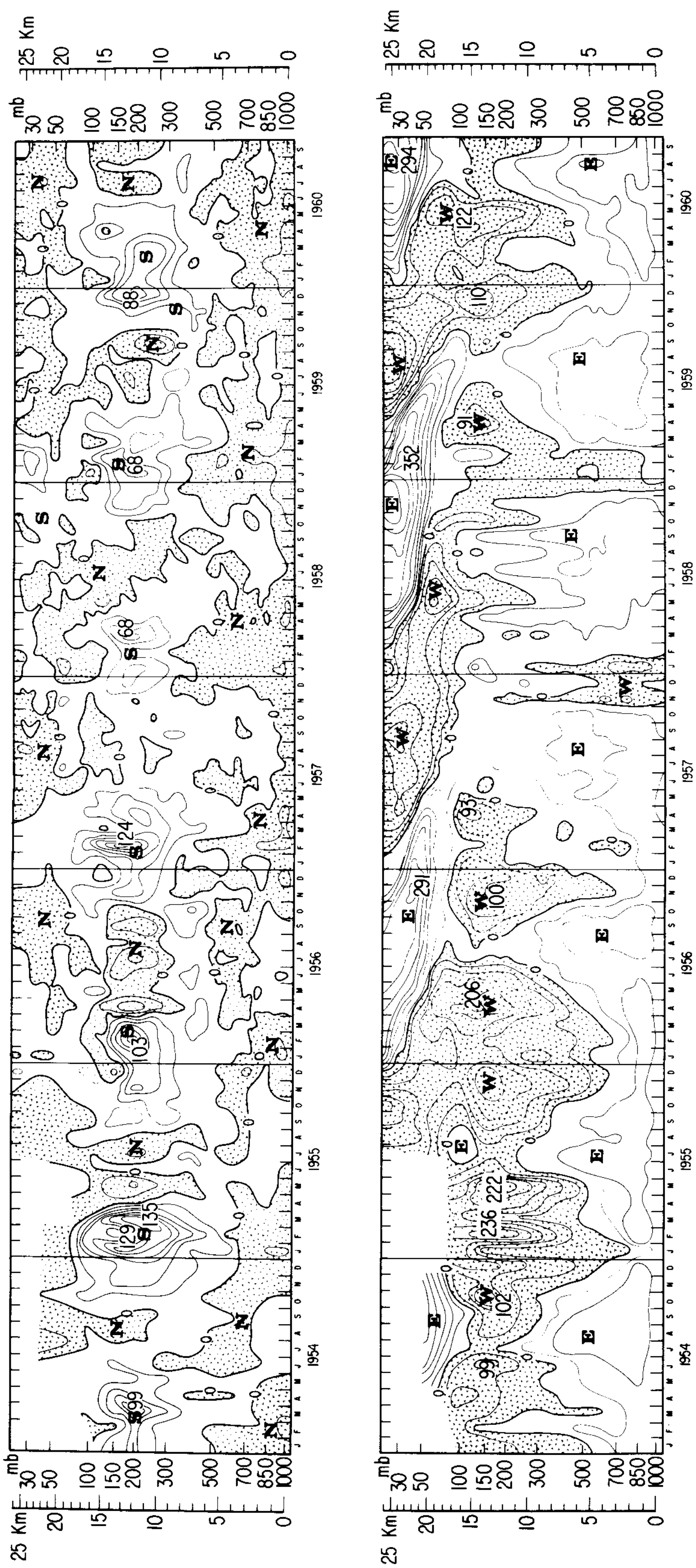


Figure 9. Upper air data from Canton Island. Upper panel: North-south component of monthly averaged 1200 GMT wind velocity. The stippled areas denote northward (N) flow and the contour interval is 20 decimeters/sec. Lower panel: East-west component of monthly averaged wind velocity. The stippled areas denote westward (W) flow and the contour interval is 40 decimeters/sec. The data for this illustration were generously supplied by Dr. D. Henning, Inst. Meteorology, Univ. Bonn.

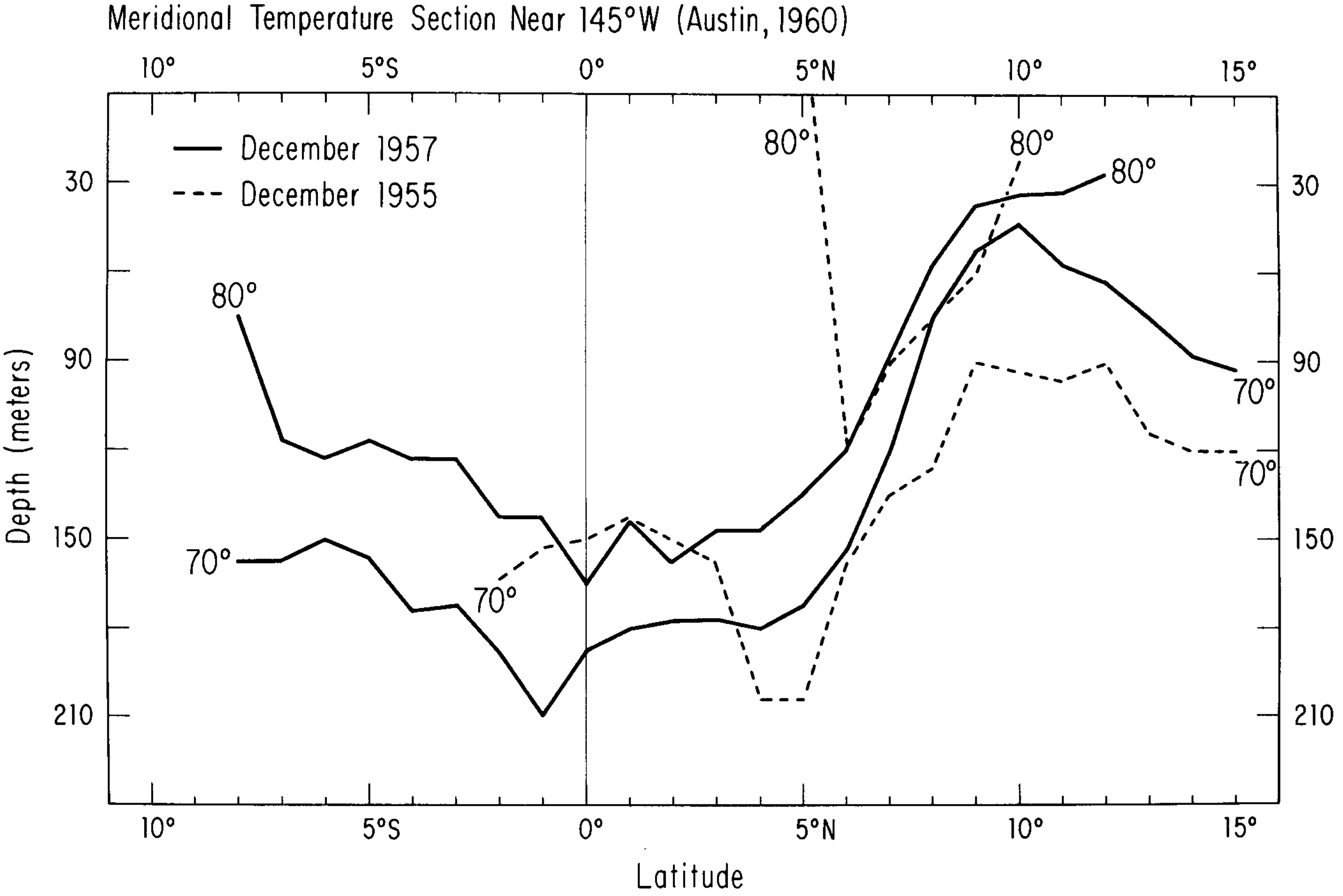


Figure 10. Meridional temperature section near 145°W for December of 1955 and 1957. Note the southward shift in the thermal equator, as well as the apparent major alterations of the equatorial current systems. Data for this Figure is from Austin (1960).

dramatically during these years. However, the southeast trade wind stress as observed at the equator (Canton Island) did not exhibit a similar behavior. This occurred because as Figures 9 and 10 indicate, the thermal equator (and the associated intertropical convergence zone) was coincident with the geographic equator. Under such a situation one would expect little trade wind activity over the equator, an area normally dominated by the southeast trade wind regime.

The southern shift in the Hadley Cell circulation in 1957–58 indicates that the center of the southeast trade wind regime was displaced to the south. Nevertheless, the strengthening of the trade winds away from the equator had the effect of increasing the oceanic transport of the Peru current and the upwelling off the west coast of South America. By mid-1958 a resulting drop in sea surface temperature was observed along the coast of South America (Allison *et al*, 1971; Bjerknes, 1966b). The area of decreased sea surface temperatures spread from the west coast of South America to a longitude of 180° in about 6 to 9 months (Allison *et al*, 1971). The partial reduction in sea surface temperatures along the equator during late 1958 allowed the intertropical convergence zone to shift gradually north into its normal position near 7° N. This shift apparently spread from east to west in correspondence with the surface temperature changes. The shift brought the southeast trade wind regime again to the equator where the normal surface temperatures were reestablished by the winter of 1960 (Figure 8).

4.2 *The Mid-latitude System*

During the time that the equatorial anomalies were going through one cycle from 1955–1960, the mid-latitude region went through two cycles; high index states were found in 1955, 1958, and again in 1960. The 1955 and 1960 high index years were in phase with the "normal" state of the equatorial system, where the Walker Cell was well developed and the intertropical convergence zone in the central and eastern equatorial ocean was positioned between 5° and 10°N. However, the 1958 high index was out of phase with the normal equatorial systems and the mid-latitude anomaly pattern in 1958–1960 was somewhat different from that in 1956–1958.

During the winter of 1958, the westerly winds had a high stress index, but were shifted south about five degrees of latitude from their normal position in association with a similar shift in the Hadley Cell over the central and eastern equatorial ocean. A positive sea surface temperature anomaly was located off the west coast of North America, as a result of anomalously *warm* air being advected over this region. In the following winter of 1958–59, the Laplacian of the heat flux at the subarctic frontal zone rose again, but less so than in 1955–56. This resulted in an amplification of the upper level long wave in the westerly wind system and the development of the split Aleutian low. These circulation patterns characterized the low index state in both the westerly wind and northeast trade wind systems.

Also during the winter of 1958–59 the stability of the equatorial ocean/atmosphere servomechanism was sufficient to restore the initial state in the equatorial Pacific. The fact that the mid-latitude and equatorial air-sea interaction mechanisms were still out of phase, plus the overriding control exerted by the central and eastern equatorial Pacific on mid-latitude conditions resulted in disappearance of the mid-latitude anomaly in late 1959.

By the winter of 1959–60 conditions in the North Pacific had generally returned to those of 1955. The wind stress index for both the westerlies and trade winds (Figure 1) were high as in 1955. The distribution of temperature anomalies (Figure 6) over the mid-latitude North Pacific was similar to that in 1955. Furthermore, the equatorial sea surface temperatures (Figure 8) returned to values that were found in 1955.

5.0 *Concluding Remarks*

An attempt has been made to combine data and theory to heuristically explain the unusual events that occurred in the North Pacific during the latter half of the 1950's. Our basic role has been to *integrate* the ideas of previous authors (particularly Namias and Bjerknes), old and new oceanographic and meteorological data, and additional theoretical results into a physical framework that can explain the interaction of the major ocean/atmosphere systems over the North Pacific.

We hold no illusion that our explanations are complete or entirely correct. However, this seems to be one of the first attempts to relate data and theory on the scale with which we have been concerned. If our primitive efforts encourage additional discussion, research and more sophisticated explanations, then our major goal in writing this paper will be realized.

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