A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature

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(Manuscript received January 18, 1966)

ABSTRACT

Weakness and temporary elimination of the equatorial easterly winds over the eastern and central Pacific in late 1957 and early 1958 brought about a brief cessation of equatorial upwelling which in turn caused the occurrence of above-normal surface water temperatures in the tropical Pacific from the American coast westward to the dateline. This sudden introduction of a large anomalous heat source for the atmosphere intensified its thermodynamic circulation, especially in the wintertime (northern) hemisphere. Record intensity of the westerlies resulted in the eastern North Pacific. The anomalous depth of the Low in the Gulf of Alaska had the downwind effect of weakening the Iceland Low and setting the stage for a cold winter in northern Europe.

Introduction

The concept of the Hadley circulation as used in this article refers to the rising motion at the thermal equator and simultaneous sinking motion in the belt of subtropical highs mutually connected by the equatorward component of the tradewinds in the lower troposphere and by compensating flow away from the equator in the upper troposphere. Such a statistically averaged meridional circulation results from a variety of instantaneous flow patterns at different longitudes and different times. The work-producing sense of the Hadley circulation results from the statistical dominance of parcel histories unfolding schematically as follows: The sample parcel ascends in low latitudes in the rear part of an easterly wave trough and gradually moves away from the equator while rising. This brings the parcel into the realm of upper westerlies where it next passes north of an upper high pressure center (stationary or eastward moving). In that part of its trajectory the parcel travels above the central and eventually the eastern part of a surface high pressure and is meanwhile sinking. Upon arriving to the low latitude easterlies at low level the sample parcel will have completed one circuit in the Hadley circulation.

The meteorological reasoning in the following article is based on the assumption that a warmer than normal equatorial ocean over a wide span of longitude will make the Hadley circulation run faster than normal in the affected longitude sector and transport absolute angular momentum to the subtropical jet stream at a faster rate than normal. The continued poleward flux of absolute angular momentum and the downward flux of the same in the belt of surface westerlies can then also be assumed to maintain stronger than normal westerlies in the middle latitudes of the longitude sector under consideration.

These ideas will be tested against observations from the period of greatest known positive sea temperature anomalies over the eastern half of the equatorial Pacific in recent years.

The first part of the article describes the normal field of sea surface temperature and gives suggestions about the atmosphere-ocean interaction that brought about the great and widespread positive anomaly in the winter of 1957–58.

The normal annual field of surface temperature in the northern and equatorial Pacific

A map of annual average of the surface temperature of the equatorial and northern Pacific Ocean is shown in Fig. 1. The low-latitude part of the temperature field is strikingly different in the western and eastern parts of the ocean. In the west a large and uniformly warm reservoir of water straddles the equator, whereas in

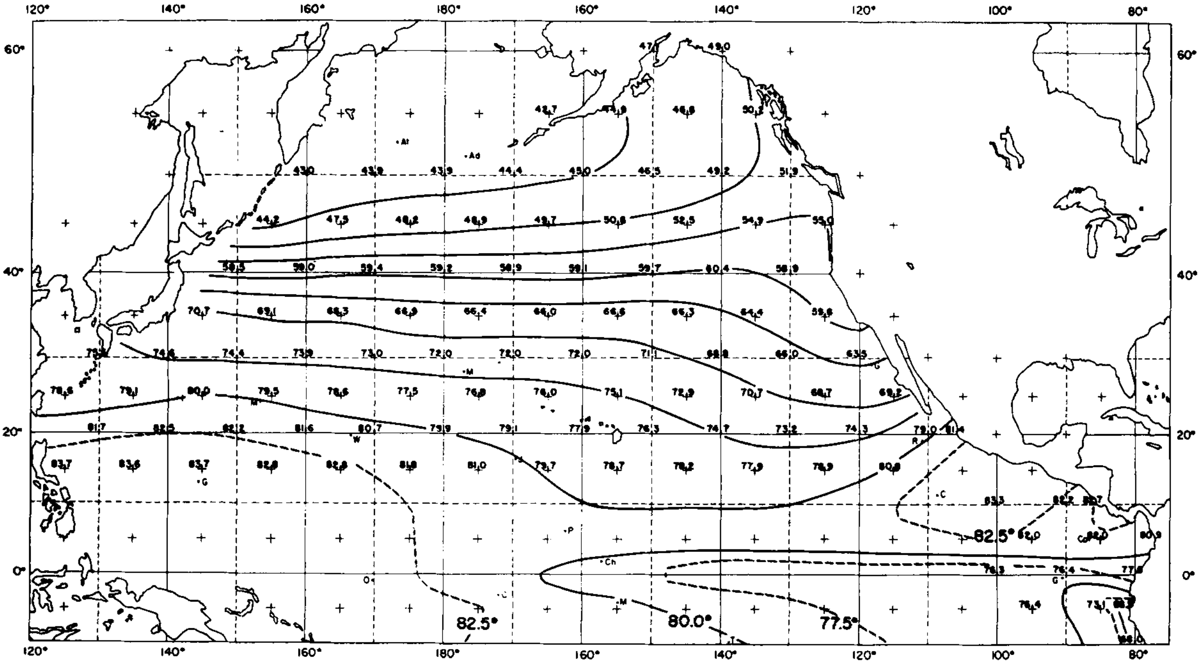

FIG. 1. Annual average sea temperature for the pentade 1955–59. Extension of isotherms into the area of scarce shipping south of 15° N and west of 100° W is based on the maps of SCHOTT (1935).

the eastern half only a narrow zone between 4° and 10° N remains above 80°F (26.7°C) in all longitudes. That narrow belt of warmth is occupied by the North Equatorial Countercurrent, transporting warm water from the western reservoir. Where the Countercurrent approaches the American continent the warm water again spreads over a wider area although much smaller than that of the western reservoir, and also extending to lesser thermocline depth than in the west (see Fig. 5).

The described warm-water area is the core of the heat source for the Pacific section of the atmospheric circulation, and hence provides most of the thermal energy for the operation of the Hadley circulations of both hemispheres. The western warm-water reservoir is reached by the tradewinds of both hemispheres the whole year round, while the narrow warm-water zone farther east is reached by the northeast trades only in winter and spring of the northern hemisphere and by the northern fringe of the southeasterly trade system during the winter and spring of the southern hemisphere. This is documented by the statistical diagram in Fig. 2 which shows, for longitude 120° W, an oscillation of the line of intertropical convergence of winds between 12° N in August and 2° N in March, whereas the Countercurrent stays in a more constant latitude. The diagram moreover shows the disappearance of the eastward surface flow during the winter when the north-east trades are strong enough to maintain a westward Ekman drift equal and opposite to the geostrophic Countercurrent.

The individual monthly maps of surface winter temperature in the eastern tropical Pacific

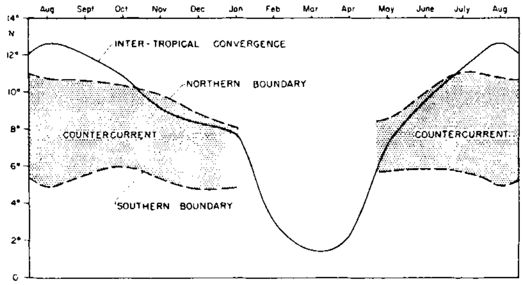

FIG. 2. Seasonal variation of the position of the intertropical wind convergence and of the northern and southern boundary of the Equatorial Countercurrent at 120° W. From CROWE (1951).

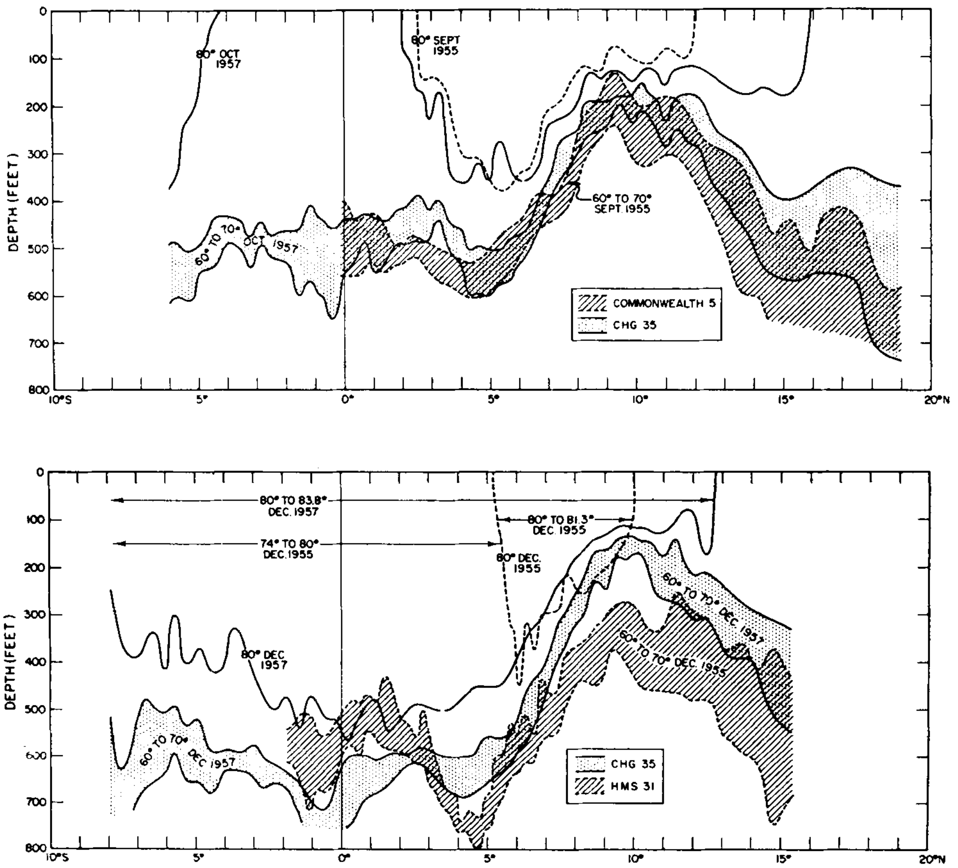

Fig. 3. Transequatorial profiles of temperature (80°, 70° and 60°F isotherms) from bathythermograph soundings in the longitude sector 140°–150° W. *Upper diagram:* September 1955 (dashed isotherms) and October 2–7, 1957 (solid isotherms). *Lower diagram:* December 1955 (dashed isotherms) and December 1957 (solid isotherms). From Thomas S. Austin (1960).

(not shown) maintain the warm-water zone between the latitudes 5° and 10° N also during the disappearance of the Countercurrent at the surface. For our following meteorological discussion of the eastern tropical Pacific we can thus think of an oceanic warm belt normally remaining between 5° and 10° N and supplying thermal energy to the atmospheric Hadley circulation of the northern hemisphere from December to May and to that of the southern hemisphere from June to November.

South of the oceanic thermal equator a tongue of cold water flows westward aided by the wind stress exerted by the equatorial easterlies. The lowest surface temperatures of this tongue are centering right along the geographical equator from where the Ekman drift diverges to the north and south as a result of the change in sign of the Coriolis parameter from one hemisphere to the other. The low temperatures at the equator are also in part due to advection from the cold Peru Current, but the assessed importance of that cooling factor has had to be lowered considerably after the eastflowing Equatorial Undercurrent and southeastflowing Peruvian Undercurrent were discovered. In the discussion in this article, which deals mainly with the ocean west of the Galapagos Islands, we will assume that the coolness of the equatorial surface waters is mainly due to the upwelling.

The equatorial upwelling has its seasonal maximum in the late winter of the southern hemisphere when the doldrums are at their

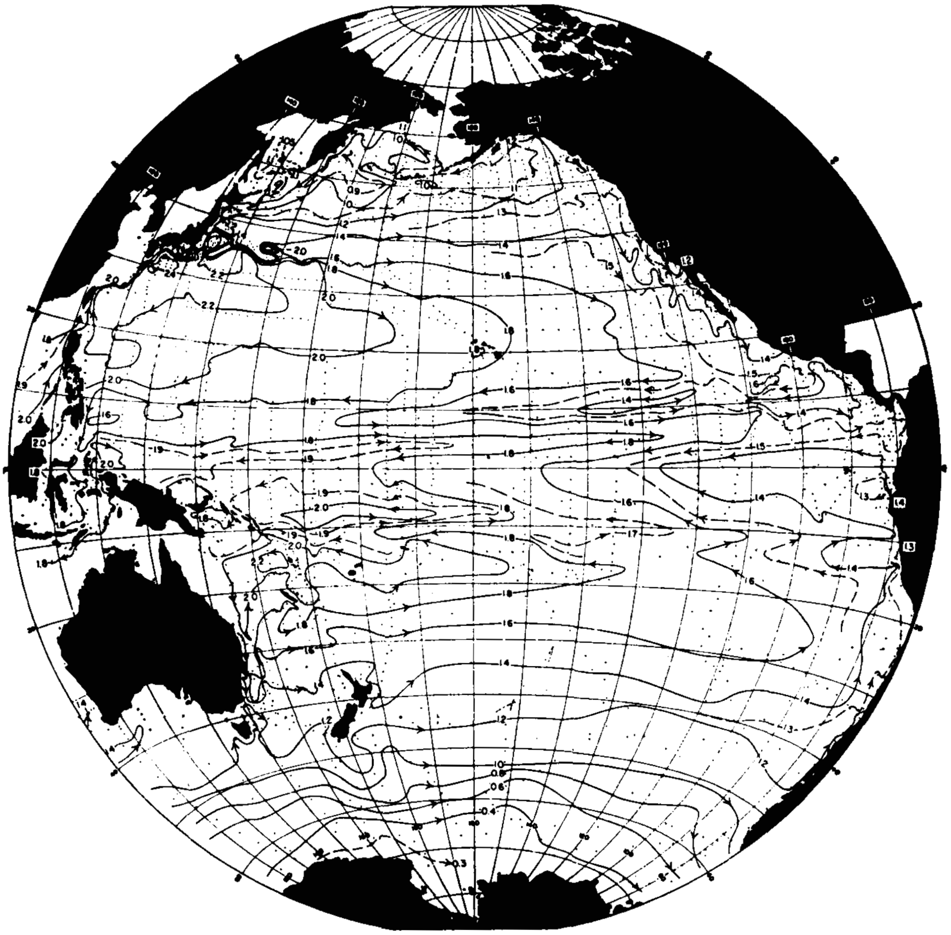

FIG. 4. The anomaly of geopotential distance between the zero- and the 1000-decibar surfaces interpreted as the approximate topography of the ocean surface (unit dyn m). Arrowheads indicate direction of geostrophic flow near the ocean surface. At the equator gravity flow goes eastward in the narrow Equatorial Undercurrent, but is normally overcompensated by opposite wind drift at the surface. From REID (1961).

northernmost position and strong easterlies (or eastsoutheasterlies) blow at the equator. The minimum strength of the easterlies, minimum upwelling, and highest surface temperature in the tongue of equatorial cold water normally occur in March.

The abundance of equatorial warm water in late 1957 and early 1958

Particular meteorological interest is associated with the case of extreme weakness of the equatorial easterlies and resulting elimination of the upwelling, such as seen in Fig. 3. In that composite diagram of transequatorial ocean profiles the 60° and 70°F (15.6 and 21.1°C) isotherms, and the shading between them, show the position of the thermocline. The 80°F (26.7°C) isotherm serves to delineate the space occupied by the warmest water, which mainly belongs to the North Equatorial Countercurrent. That current from the west is in all the separate diagrams in Fig. 3 situated where the thermocline drops from shallow depth at 10° N to greater depth around 5° N. A thermocline sloping in this sense can be considered as a Margules surface between upper water moving geostrophically to the east and deepwater moving very little.

Whereas these Countercurrent features can

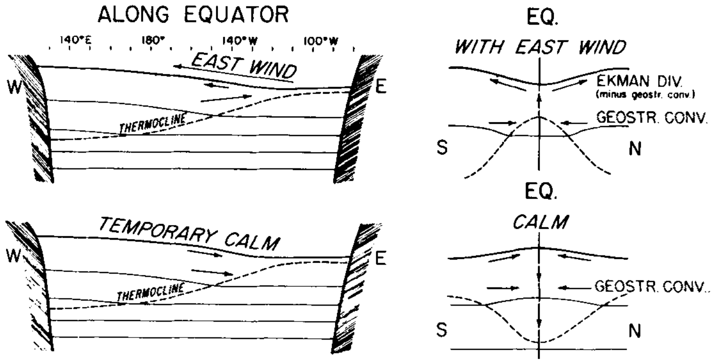

FIG. 5. Schematic equatorial flow patterns, with and without westward wind stress.

be identified without much basic variation from case to case in Fig. 3, quite dramatic differences in thermal structure did take place south of the Countercurrent. The normal condition can be said to be represented by the profiles marked September 1955 and October 1957, both showing upwelling water colder than 80°F at the equator spreading from there two or three degrees northward and about twice as far southward (see Fig. 1). December 1955, part of an unusually cold year, shows a wider equatorial belt of upwelling water colder than 80°F, whereas December 1957 shows no equatorial upwelling at all. The 80°F isotherm actually has its greatest depth of 500–600 feet at the equator. The great equatorial warming down to such a depth from October to December 1957 must have come about by sinking motion, possibly aided somewhat by anomalous water advection from the west.

This brings us to a consideration of what mechanism is involved in creating sinking water motion instead of the normal upwelling at the equator.

Suggested models of normal and anomalous flow patterns in the equatorial ocean

Reid's map of the normal topography of the surface of the Pacific Ocean (Fig. 4) is by definition also a streamline map of the geostrophic flow of the water near the surface. In the low latitudes with which we are concerned the zonal components of the geostrophic flow dominate. Passing from north to south on the map we see the westward flowing North Equatorial Current as the southern part of the large subtropical anticyclonic gyre centered south of Japan. South of the topographic depression extending from the Mindanao coast at 8° N to the Central American coast at 10° N the meridional slope of the ocean maintains the eastward geostrophic flow of the North Equatorial Countercurrent. The southern flank of that current runs along a topographic ridge located only one or two degrees north of the equator in the western Pacific but roughly 5° N in the eastern half of the ocean. Finally, a trough of the surface topography runs along the geographical equator straight across the ocean and maintains the westward component of geostrophic flow both north and south of the trough line.

Along the equatorial trough the ocean level is rising from South America to New Guinea by about 0.7 dynamic meters due to the wind stress of the prevailing equatorial easterlies. The largely zonal geostrophic flow on either side of the equator therefore has a systematic, albeit small, component towards the equator. Such geostrophic convergence of surface water must prevail at the equator at all times, because the zonal slope of the equatorial ocean, although somewhat variable with time, never ceases to be directed downhill from west to east.

We can now combine the geostrophic and the wind drift motion into a composite schematic flow model applicable in the vicinity of the equator (Fig. 5). The profile along the equator in the upper left drawing shows the sea surface sloping down from west to east with maximum inclination near 130° W longitude in accordance with Reid's topographic map in Fig. 4. The thermocline has the opposite slope whose locus of maximum inclination is also near 130° W.

The inclination of the thermocline is between two and three orders of magnitude steeper than that of the sea surface and is adjusted such that the isobaric surfaces are refracted from their tilting position, induced by the tilting sea surface, into a quasi-horizontal position in the deep water. With that kind of pressure field the zonal flow component of the water must be negligible below the thermocline, while being eastward directed and rather strong just above the thermocline. This is the Equatorial Undercurrent. It does not normally extend up to the surface because there it is over-compensated by the westward wind drift.

In the extreme case of a cessation of the easterly wind the wind drift would immediately cease too, while the eastward gravity flow would continue as long as the ocean surface is tilting. This condition is illustrated in the lower left part of Fig. 5. All the water above the thermocline would then flow to the east. This is the so-called "surfacing" of the Equatorial Undercurrent which does occur temporarily when the westward wind stress becomes too weak to balance the eastward downhill component of gravity.

The two right hand sketches in Fig. 5 show the flow components in meridional profiles applicable where the ocean surface has a definite zonal tilt. In the normal case with westward wind drift (upper right) there is a divergence of the wind drift from the equator. This wind drift divergence is rapidly decreasing with depth and is over-compensated by the geostrophic convergence in the lower part of the mixed layer. Approximately at the thermocline also the geostrophic convergence vanishes and the deepwater remains virtually motionless. Upwelling at the equator from depths not exceeding that of the thermocline completes the meridional flow picture.

The cessation of the easterly winds (Fig. 5, lower right) permits the geostrophic convergence to act unopposed also at the ocean surface. If remaining sufficiently long such flow would make the ocean surface bulge upward at the equator instead of downward, and the water sinking at the equator would depress the thermocline. The latter process was probably responsible for most of the descent of the thermocline from October to December 1957 shown in Fig. 3. However, also the horizontal water advection from the west, if extending a little beneath the thermocline, would contribute somewhat toward the observed change with time of the field of temperature.

The anomalous flow indicated in December 1957 by the BT-profile at 145° W must have been represented in more or less pronounced form along most of the equatorial zone of the eastern half of the Pacific. At the Peruvian coast a major El Nino raised the sea surface temperature 3°–4°C above normal in January and February 1958. A little less of a positive anomaly was observed by ships in Galapagos waters (0°90° W). West of the longitude of the BT-profiles there is again evidence of great warming. At Christmas Island (2° N 157° W) where the existing short sea temperature record shows a 1954–56 "normal" for January of 77°F (25°C), January 1958 averaged over 83°F (28.3°C). Similar positive anomalies were observed as far west as Canton Island, 3° S 172° W. The north-south extension of the positive temperature anomaly over the open ocean is best seen in Fig. 3, where water warmer than 80°F is seen to cover a belt of at least 25° of latitude in December 1957 compared to a belt of only 5° of latitude in December 1955. Hence the equatorial heat source for the atmospheric circulation over the eastern half of the Pacific Ocean must have been operating at considerably greater than normal efficiency during the 1957–58 summer season of the southern and winter season of the northern hemisphere.

The atmospheric circulation of the northern hemisphere during the winter 1957–58

The resulting intensification of the northern hemisphere atmospheric circulation in the eastern Pacific sector can be studied in Fig. 6. The surface pressure fields averaged separately for the winters (December, January, February) of 1955–56, 1956–57, and 1957–58 are there shown for the north Pacific area. In the winter of 1957–58 the axis of the subtropical High runs practically due west-east from Asia to America, whereas in the preceding winters the axis has the usual farther north position on the American side. This is just what could have been expected from an anomalous southward displacement of the heat source in the eastern Pacific from the belt 5°–10° N to a position centered near the geographical equator (see Fig. 3) in 1957–58.

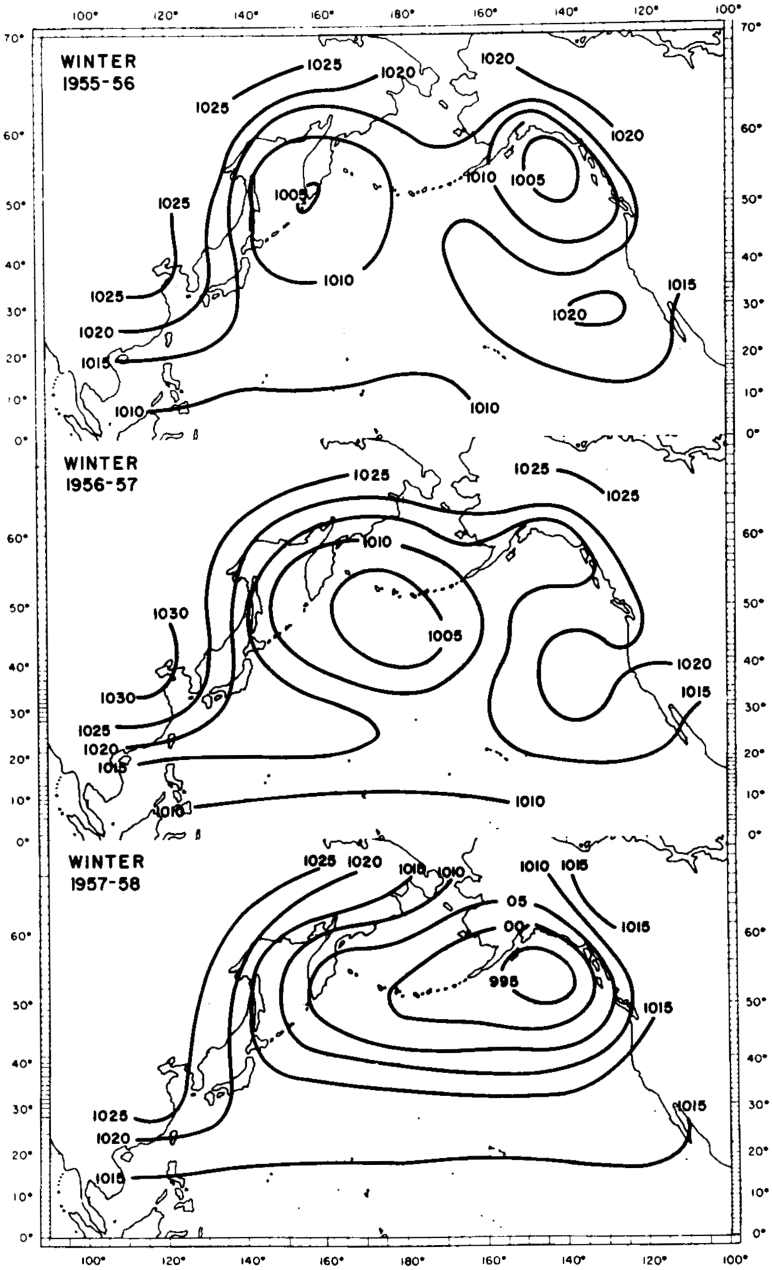

Fig. 6. Average distribution of atmospheric pressure at sea level during the winter seasons, December to February inclusive, of 1955–56 and 1956–57, before the East Pacific equatorial warming, and 1957–58 at the peak of that warming.

Moreover, the westerlies in the middle latitudes of the eastern Pacific are much stronger than normal in the winter of 1957–58, presumably indicating that the northward flux of angular momentum operated by the Hadley cirulation did achieve above-normal efficiency when fueled by an above-normal equatorial heat source. Finally, with the subtropical High rather far south and the westerlies strong, the eastern Pacific by necessity got a deep Low established

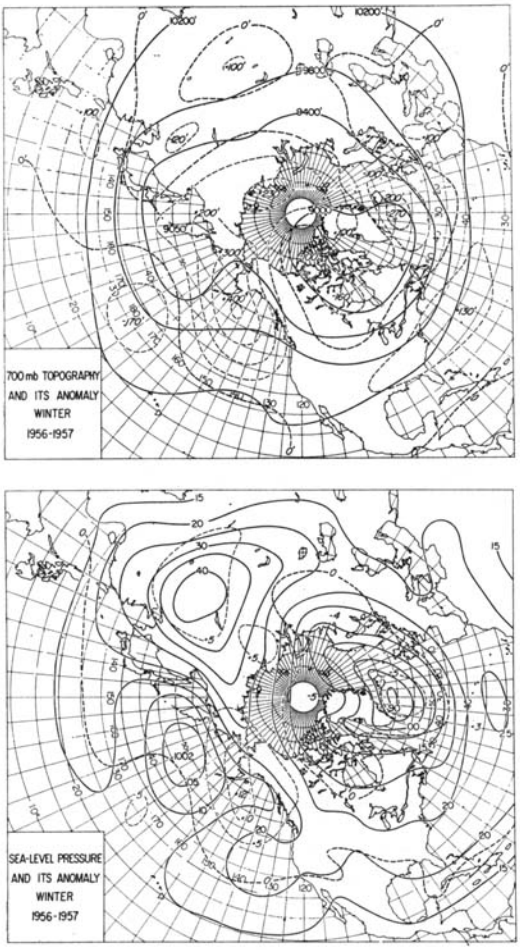

Fig. 7

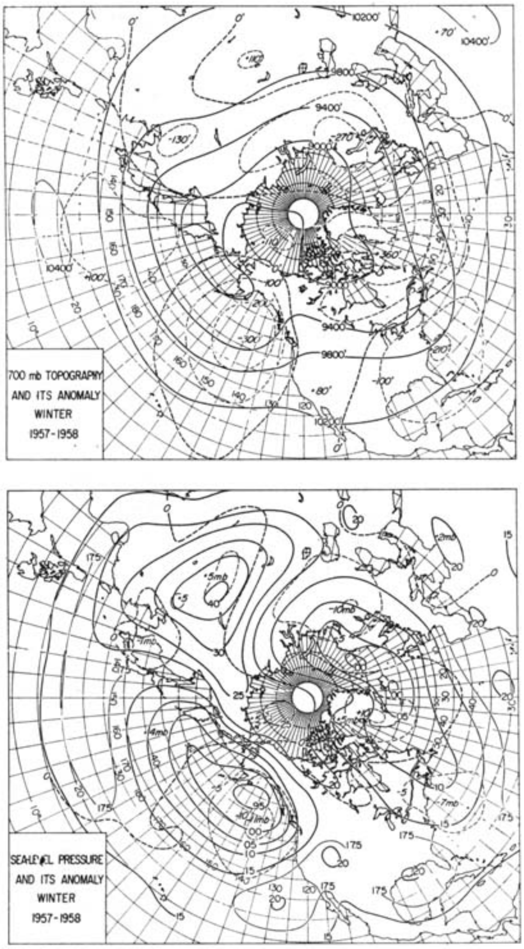

Fig. 8

FIG. 7. Extra-tropical northern hemisphere atmospheric circulation averaged for the winter period 1956–57. From NAMIAS (1960).

FIG. 8. Extra-tropical northern hemisphere atmospheric circulation averaged for the winter period 1957–58. From NAMIAS (1960).

The east-Pacific equatorial warming in 1957–58 stimulates the Gulf of Alaska Low and by teleconnection in the westerlies weakens the Iceland Low and intensifies the cyclonic activity in the Barents Sea.

in the Gulf of Alaska during most of the winter 1957–58. The Aleutian Low in that situation loses its normal role as the deepest depression in the Pacific sector of the northern low-pressure belt.

Such a large-scale anomaly in the pressure pattern of the North Pacific is bound to have large-scale downwind effects carried by the upper westerlies. Figs. 7 and 8 illustrate this.

The winter of 1956–57 had very weak westerlies over the eastern Pacific and a concomitant positive pressure anomaly south of Alaska (Fig. 7). The train of alternate negative and positive anomalies extending eastward formed a short-wave system. A moderate negative anomaly was to be found over the Hudson Bay and a stronger negative one over the Iceland cyclone.

The winter of 1957–58 brought the impact of stormy conditions over the northeastern Pacific represented in the average pressure field as a widespread negative pressure anomaly extending from the dateline into western Canada (Fig. 8). Under the influence of this quadrant-wide anomaly the downwind short-wave system was replaced by a long-wave system of about 180° wave length marked by the centers of pressure anomaly of +10 mb at the west coast of Greenland and −10 mb over western Russia. These large-scale teleconnections caused the Iceland Low to weaken considerably and to maintain an average position to the east, instead of southwest, of the island. This, in turn, set the stage for the various anomalies characterizing the European climate during the winter of 1957–58.

Conclusion

The above discussion based on 1957–58 data seems to show that big positive sea temperature anomalies (up to 3° or 4°C) extending over an equatorial zone from South America to the mid-Pacific (about one earth quadrant) do have the effect of strengthening the zonal wind systems within the same quadrant of the wintertime northern hemisphere. This is necessarily associated with a negative pressure anomaly in the extratropical cyclone belt of the earth quadrant of atmosphere under consideration. This negative pressure anomaly, centered in the Gulf of Alaska, in turn anchors the prevailing stationary waves in the upper westerlies in such a fashion that a positive pressure anomaly appears 90° longitude downwind (near SW Greenland) and the next negative anomaly another 90° farther east (over NW Russia).

Similar large-scale remote effects, presumably also attributable to an extensive East Pacific equatorial warming, did occur in 1940–41 and 1952–53. Studies of future analogous happenings are of course needed to verify (or disprove) the admittedly somewhat tenuous reasoning in this article.

So much seems certain, however, that the extensive warmings of the East Pacific equatorial waters are due to a weakening of the equatorial easterly winds to such an extent that (*a*) the normal upwelling appreciably weakens or even ceases, and (*b*) the Equatorial Undercurrent "surfaces". The primary cause for those two kinds of anomaly must probably be sought south of the equator, because the easterly winds at the geographical equator, from South America to the dateline, are part of the Hadley circulation of the southern hemisphere. That circulation always has its minimum strength in the southern summer, and in the summers of 1940–41, 1952–53, and 1957–58 it evidently became too weak to maintain the normal east-Pacific equatorial upwelling. The great gaps in space and time in the meteorological, and even more the oceanographic, mapping of the southern hemisphere make it difficult as yet to pursue the search for the primary causes of these large-scale inter-related anomalies of ocean and atmosphere.

Although this primary triggering may remain obscure, a close watch of the temperature anomalies arising over the eastern tropical Pacific is likely to play an important part in future seasonal forecasting of climatic anomalies, over North America and even over Europe.

Acknowledgement

The ideas presented in this article originate from my study of the excellent reports to the symposium on "The Changing Pacific Ocean in 1957 and 1958" (SETTE & ISAACS, 1960). The contributions by Thomas S. Austin and by Jerome Namias are particularly relevant to my chosen problem and contain much information in addition to that which has been borrowed in this article in connection with Figs. 3, 7, and 8.

I acknowledge furthermore the generous financial support from the National Science Foundation.

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ВОЗМОЖНАЯ РЕАКЦИЯ АТМОСФЕРНОЙ ЦИРКУЛЯЦИИ ХАДЛЕЯ НА ЭКВАТОРИАЛЬНЫЕ АНОМАЛИИ ОКЕАНСКОЙ ТЕМПЕРАТУРЫ

Ослабление и временное исчезновение экваториальных восточных ветров над восточной и центральной частями Тихого океана в конце 1957 г. и в начале 1958 г. вызвало прекращение на короткое время экваториального восходящего движения, что в свою очередь обусловило повышение температуры воды у поверхности в тропической части Тихого океана от берегов Америки до линии дат. Это внезапное появление ненормально большого источника тепла для атмосферы усилило ее термодинамическую циркуляцию, особенно в зимнем (северном) полушарии. Результатом явилась исключительная интенсивность западных ветров в северо-восточной части Тихого океана. Аномальная глубина центра жидкого давления в Аляскинском заливе вызвала подветренный эффект ослабления исландского минимума и холодную зиму на севере Европы.