TELECONNECTIONS BETWEEN NORTHEASTERN PACIFIC OCEAN AND THE GULF OF MEXICO AND NORTHWESTERN ATLANTIC OCEAN

JAMES H. JOHNSON AND DOUGLAS R. MCLAIN[1]

ABSTRACT

Anomalous large-scale air-sea interactions that took place over the Gulf of Mexico and the Atlantic Ocean off the southeastern coast of the United States in the winter of 1957-58 caused a change of sea-surface temperatures from near average values to cold anomalies of nearly 3.0°C in some regions. Evidence suggests that the mechanism for the anomalous change in sea temperatures derived from frequent outbreaks of cold, North American continental air flowing over the Gulf and ocean waters with consequent anomalously high evaporation and sensible heat exchange. A contributing factor may have been divergence of surface waters with associated upwelling in regions of high cyclonic activity.

These severe outbreaks of cold continental air over the eastern seaboard may be related to air-sea interactions in the Pacific, thousands of miles distant. It is not clear what the full consequences of these events are to fisheries. The evidence which is available suggests that they are significant and warrant continued investigation.

In recent years large-scale air-sea interactions have captured the interest of a number of oceanographers and meteorologists. Motivated by the desire to develop and improve extended meteorological forecasts, Namias (1959, 1963, 1972, and in numerous other articles) has been one of the foremost investigators in studying these interactions. Most of his work has centered in the temperate latitudes of the northern hemisphere. Bjerknes (1966a, b, 1969) has studied large-scale interactions in the tropical Pacific Ocean, especially, processes associated with the El Niño phenomena. He has shown a relationship of fluctuations in the atmospheric Hadley circulation to large-scale anomalies of ocean temperatures. He suggests that an anomalously high heat supply in the equatorial Pacific, characterized by high equatorial ocean temperatures, intensifies the Hadley circulation providing more than normal flux of angular momentum to the mid-latitude belt of westerly winds, thus affecting the weather over the North American continent. He suggests that regular monitoring of sea temperatures in the eastern tropical Pacific is indispensable in long-range weather forecasting for North America.

Also motivated to develop improvements in long-range weather forecasting, Quinn (1972) has shown that large-scale interactions over the equatorial Pacific may affect the weather over the continental United States. He suggests that extensive dry-zone developments in the equatorial zone, which are associated with low sea-surface temperatures, may contribute to ridge development in the upper air circulation over the Northeast Pacific and, conversely, wet-zone developments (high equatorial sea temperatures) are associated with trough formation. Furthermore, he describes the effects downstream over the United States following development of these troughs and ridges and implies that now it may be possible, if these extreme developments are detected early enough, to make long-range weather predictions over North America.

Rowntree (1972), recently carrying out computer model studies, has confirmed that a sea temperature maximum in the tropical eastern Pacific leads to a persistent trough in the mid-latitude flow to the north.

Regions of the ocean particularly responsive to the overlying atmosphere lie to the east of large continental land masses. Jacobs (1951), Manabe (1957), Wyrtki (1966), and Hishida and Nishiyama (1969) have shown that in wintertime the temperate western Pacific Ocean loses large amounts of heat through evaporation and sensible heat exchange because of the overflow of cold, dry Siberian air masses. Parker (1968) pointed out a similar effect in the winter of 1966 in the northwestern Gulf of Mexico.

[1]Pacific Environmental Group, c/o Fleet Numerical Weather Central, National Marine Fisheries Service, NOAA, Monterey, CA 93940.

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This paper extends the findings of several of the authors mentioned above by describing the development of large-scale sea-surface temperature anomalies in the winter of 1957-58 in the Gulf of Mexico and off the U.S. eastern seaboard and suggests that these anomalies are associated with ridges and troughs in the upper air circulation. These, in turn, are associated with air-sea interactions in the Pacific. It further describes conditions in other winters where similar situations developed and suggests that changes in abundance and distribution of some fish populations both in the Pacific and Atlantic may be caused by events of this nature.

DATA SOURCES

Data used in heat budget calculations and in the description of sea-surface temperatures and anomalies were obtained from Tape Data Family 11 obtained by Fleet Numerical Weather Central and the Navy Oceanographic Office from the National Climatic Center, Asheville, N.C. This file contains merchant ship weather reports, some of which date back to 1854. Computer programs were developed to compute monthly averages by year of sea-surface temperature and heat exchange by 5° blocks.

Numerous studies have been made to determine the accuracy of sea-surface temperatures reported by merchant vessels in their weather reports. Saur (1963) found that in the Pacific the average injection temperature bias from that of a bucket temperature taken at the surface was about +1.2°F, and Franceschini (1955) noted similar results in the Gulf of Mexico. The latter suggested, however, that commercial vessel reports could be used for practical purposes such as meteorological and oceanographic research and for forecasting air mass modification over the Gulf. Because uncertainties remain concerning the relation between temperature at the sea surface and that at the injection intake depth of merchant vessels, no attempt was made in this study to apply a correction.

OBSERVATIONAL EVIDENCE OF ANOMALOUS AIR-SEA EVENTS

The Anomalous Winter of 1957-58

Charts of the height of the 700-mb (millibar) pressure surface (on the average about 10,000 feet above the surface of the earth in temperate latitudes) are particularly significant in air-sea interaction studies because the mass circulation of the atmosphere can be inferred from them including areas of cyclogenesis and movement of storms. Furthermore, mean 700-mb heights over the ocean are highly correlated with 700-mb temperatures, which in turn are measures of the vertical stability in the atmosphere over the ocean. For example, low temperatures at the 700-mb level, associated with negative 700-mb height anomalies, indicate instability in the atmosphere and loss of heat from the ocean through convective processes in the atmosphere.

O'Connor (1958) reported that the heights of the 700-mb surfaces during the winter of 1957-58 were very unusual. He reported the following three abnormalities in the 700-mb circulation in January 1958 (Figure 1) which persisted into February:

1. A trough in the east-central Pacific with 700-mb heights 550 feet below normal 700 miles south of Kodiak, Alaska,
2. A block in the Davis Straight where the 700-mb heights averaged 520 feet above normal and,
3. A trough in the southeastern United States (having 700-mb heights about 300 feet below normal) accompanied by strong northerly surface flow.

The trough along the eastern seaboard is particularly important. It suggests greater than normal penetration of cold continental air masses over the southeastern United States and adjacent waters. Indeed, the winter of 1957-58 will be remembered as one of the most severe of the century. Data taken at National Weather Service stations in the southeastern United States show slightly higher than normal air temperatures in November 1957 (Table 1). A small negative anomaly developed in December which increased substantially in January 1958 and reached a maximum in February. Monthly deviations of air temperature ranged up to 5.8°C below normal at stations along the northeast coast of the Gulf of Mexico.

Large negative sea-surface temperature anomalies also prevailed in February 1958 and were greatest in the northeastern Gulf in the same general area where shore station air temperature anomalies were highest (Figure 2). Stearns' (1964,

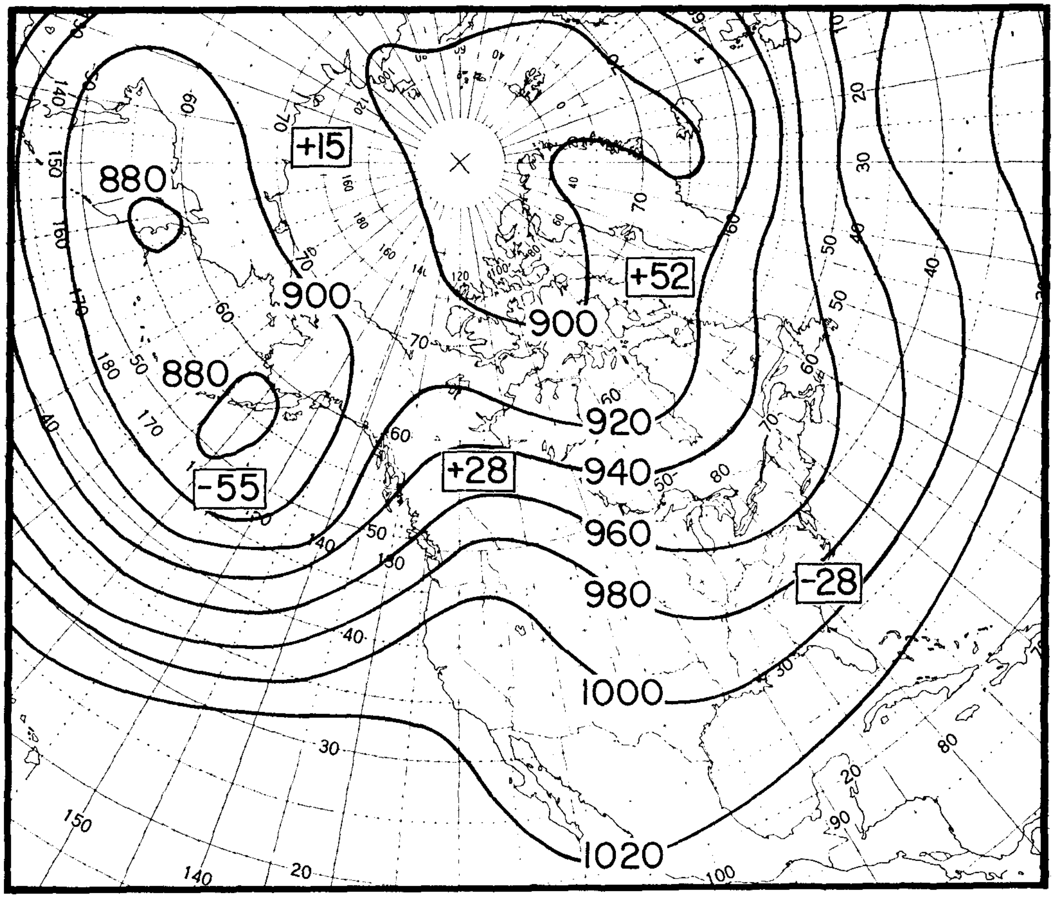

FIGURE 1.—700-mb heights and departures from normal, tens of feet, January 1958. Major departures are enclosed in boxes.

TABLE 1.—Monthly average air temperatures (°C) and departures from average (°C), November 1957-March 1958 at selected National Weather Service Stations.[1]

Station	November 1957 Temper-ature	November 1957 Depar-ture	December 1957 Temper-ature	December 1957 Depar-ture	January 1958 Temper-ature	January 1958 Depar-ture	February 1958 Temper-ature	February 1958 Depar-ture	March 1958 Temper-ature	March 1958 Depar-ture
New York, N.Y.	9.6	+1.6	4.8	+2.7	0.0	−0.4	−2.6	−2.8	4.5	−0.3
Wilmington, Del.	8.1	+0.6	3.3	+1.6	−0.7	−1.4	−2.6	−3.6	3.9	−1.9
Wilmington, N.C.	13.4	+0.2	9.6	+0.4	4.9	−3.8	4.9	−4.3	9.5	−3.1
Charleston, S.C.	15.4	+0.6	10.9	−0.3	7.0	−4.1	6.5	−5.0	11.8	−2.7
Savannah, Ga.	15.0	+0.8	10.3	−0.6	6.6	−4.3	6.8	−5.1	12.2	−2.6
Jacksonville, Fla.	18.5	+2.1	12.1	−1.5	9.1	−4.1	9.0	−5.2	15.1	−1.7
Miami Beach, Fla.	24.1	+0.8	19.9	−1.7	17.7	−3.4	16.6	−4.6	22.0	−0.3
Key West, Fla.	25.2	+1.6	20.3	−1.8	18.5	−3.0	17.5	−4.5	21.3	−1.8
Fort Myers, Fla.	22.0	+1.3	16.5	−2.1	13.9	−4.2	13.1	−5.6	18.8	−1.5
Pensacola, Fla.	16.2	+0.6	11.9	−0.9	8.3	−3.9	7.6	−5.7	14.3	−1.4
Mobile, Ala.	15.2	+0.4	11.2	−0.7	7.3	−4.2	6.9	−5.8	13.6	−1.6
New Orleans, La.	16.5	+0.5	12.9	−0.5	9.8	−3.5	9.1	−4.9	15.3	−1.7
Galveston, Tex.	17.2	−0.3	14.9	+1.3	10.7	−1.7	10.4	−3.6	14.3	−2.3
Corpus Christi, Tex.	17.3	−0.9	16.4	+1.5	12.8	−1.1	13.9	−1.8	15.7	−2.8

[1]Source: Local Climatological Data reports, U.S. Department of Commerce, National Weather Service.

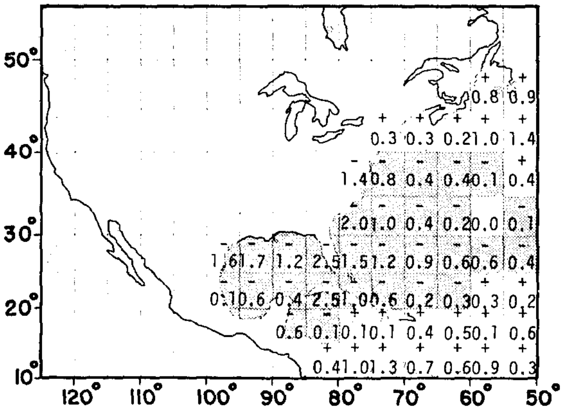

FIGURE 2.–Sea-surface temperature anomalies (°C) Gulf of Mexico and western Atlantic Ocean, February 1958. Shaded area colder than 20-yr (1948-67) mean.

1965) analysis of sea temperatures at coastal stations confirm the large winter sea temperature anomaly in coastal areas of southeastern United States. The extent of the anomaly was large, indeed, extending from below the Yucatan Straits northward throughout the Gulf to lat. 40°N off the eastern seaboard and to over a thousand miles offshore.

Important in this study is the anomalous change in sea temperatures in the winter of 1957-58 (Figure 3). The change from November to February shows that much higher than average cooling occurred over a broad expanse of the ocean during this winter. For example, the 1948-67 average change in sea-surface temperature in winter (November average - February average) is about -2.7°C in the area lat. 25° to 30°N, long. 80° to 90°W. In the winter of 1957-58, however, the change in this area was -4.7°C–an anomalous change of -2.0°C.

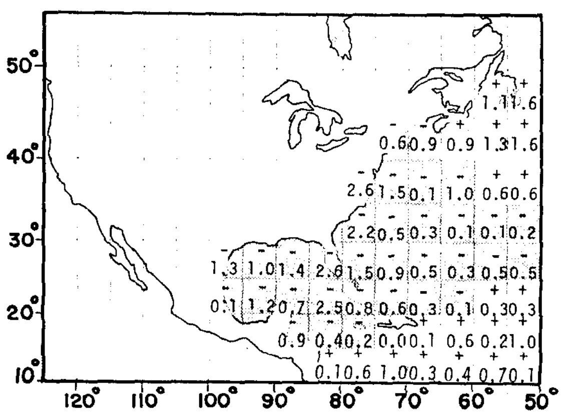

FIGURE 3.–Anomalous sea-surface temperature change (°C) November 1957 to February 1958. Shaded area indicates anomalous cooling.

Cause of Sea-Surface Temperature Change in the Winter of 1957-58

A variety of processes can cause changes in sea-surface temperatures. Some of these are horizontal and vertical advection and heat exchange at the air-sea interface.

In studies in the eastern Pacific Ocean, Clark (1972) has found that horizontal advective heat transfer processes in winter and spring have a greater effect in causing anomalous sea-surface temperature change than nonadvective processes. The latter have a greater effect in summer and fall. The area that he studied, however, was not subject to influence of a large continental land mass interacting with atmospheric circulation upstream from where heat exchange processes were calculated.

Horizontal advection into the Gulf of Mexico is mainly through the Yucatan Straits. Sea-surface temperature anomalies in these Straits ranged from -0.2°C to +0.4°C (Table 2) for a year preceding the maximum development in February 1958 of the severe cold anomalies in the Gulf of Mexico and along the eastern seaboard. This clearly suggests that horizontal advection was not the cause of the development of the cold anomalies.

Klein (1958) noted that the intensification of blocking in the 700-mb circulation in the northwest Atlantic in the winter of 1957-58 was associated with frequent outbreaks of cold air in the

TABLE 2.–Sea-surface temperatures and anomalies (°C) in 1° square (long. 85° to 86°W and lat. 21° to 22°N) in Yucatan Straits.

Date	Sea temperature °C	Anomaly °C
1957:		
January	26.2	−0.2
February	26.6	+0.3
March	26.4	−0.1
April	27.0	+0.1
May	28.0	+0.2
June	28.7	0.0
July	29.3	+0.1
August	29.7	0.0
September	29.5	−0.1
October	28.8	−0.2
November	28.0	0.0
December	27.5	+0.4
1958:		
January	26.2	−0.2
February	25.6	−0.7

eastern two-thirds of the United States. The contrast between this cold air and the air heated by the Gulf of Mexico and western Atlantic waters led to baroclinic deepening of coastal storms. In these regions of cyclonic activity, vertical advection may have caused some cooling through divergence of surface water and consequent local upwelling. Leipper (1967) has shown that hurricane Hilda, passing over the Gulf of Mexico in the early fall of 1964, indeed did cause significant cooling of surface waters through upwelling processes. However, the large area covered by anomalously low sea-surface temperatures in the winter of 1957-58, and other factors such as the frequent cold outbreaks over the entire eastern seaboard and the fact that the sea temperature anomalies appeared to occur over large areas contemporaneous with the overflow of cold air, suggests that the high rate of sea surface cooling was due to anomalously high loss of heat through evaporation and conduction of sensible heat.

To test this supposition formulae for calculation of the heat exchange at the air-sea interface have been employed. Laevastu (1965), Seckel (1962) and many others have provided these formulae. In this study the procedures for calculation of the energy exchange as presented by Johnson et al. (1965) are used. It is not the intent here to review the accuracy of the various techniques for estimating air-sea energy exchange. Because of the possible inaccuracies of input data and of the formulae, the exchange values should be viewed with caution and should be considered only as relative indices of the magnitude of energy flux at the air-sea interface. They appear, however, to be sufficiently accurate to permit detection of large-scale seasonal and nonseasonal variations.

The equation for the heat exchange at the air-sea interface is

$$Q_T = Q_I - Q_R - Q_B - Q_E - Q_H$$

where:

Q_T = Net heat gained or lost at the sea surface
Q_I = Incident solar radiation corrected for cloud cover
Q_R = Reflected radiation
Q_B = Back radiation
Q_E = Evaporation
Q_H = Conduction of sensible heat.

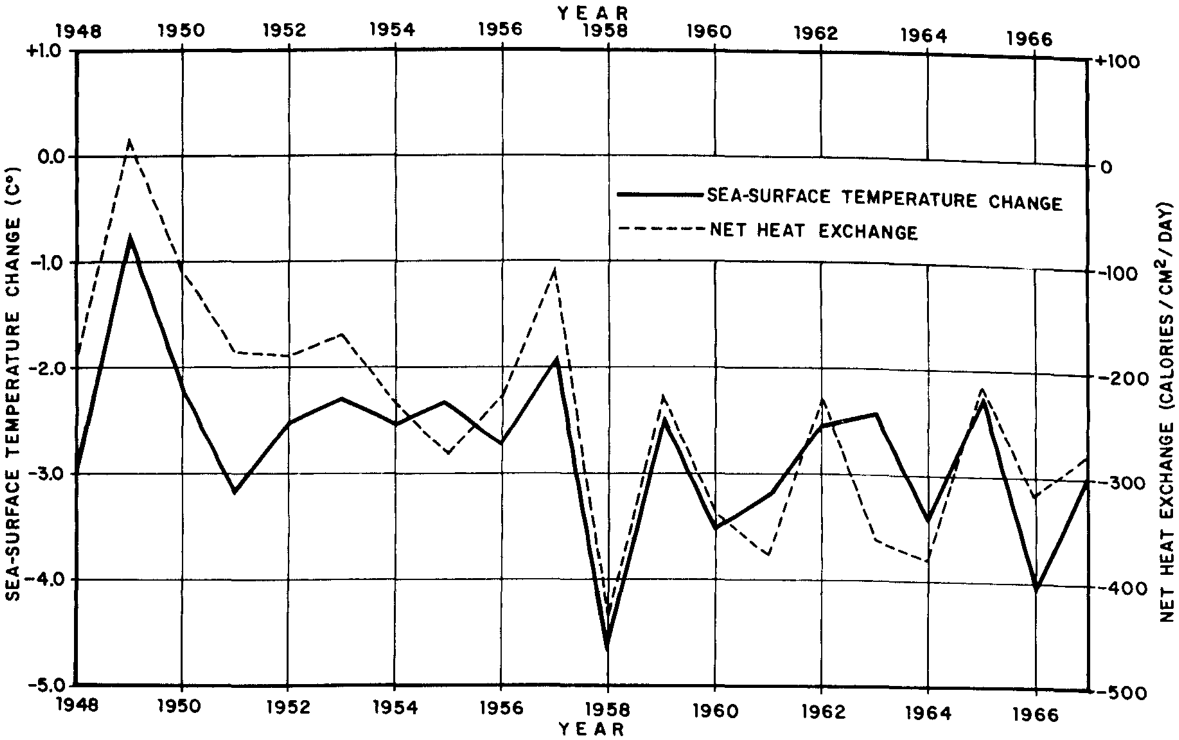

FIGURE 4.—Relation between net heat exchange at air-sea boundary and sea-surface temperature change winters of 1948-67 in the area bounded by long. 80° to 90°W and lat. 25° to 30°N.

The relation between Q_T and sea-surface temperature change in the winters of 1948-67 in the northern Gulf of Mexico is significant (Figure 4). Particularly noteworthy is the large net heat loss in the winter 1957-58 accompanied by the large sea-surface temperature change. The decrease in Q_I reaching the sea surface accounted for about 11% of the anomalous heat loss and increased Q_B about 12%. Q_E and Q_H, however, clearly stand out as significantly more important than the other heat budget elements in contributing to the large net loss of heat. Q_E contributed 57% of the anomalous heat loss and Q_H, 20%.

Data are not available that indicate the depth to which the sea temperature anomaly extended. One might speculate that it should extend throughout the mixed layer which on the average in the area of study is about 80 m in winter (Robinson 1973). For the three months December 1957-February 1958, the anomalous heat loss in the Gulf of Mexico in the area of lat. 25° to 30°N, long. 80° to 90°W was approximately 19,000 cal/cm^2. This should reflect an anomalous change in water temperature of about -2.4°C throughout the mixed layer which is very close to the anomalous -2.0°C change observed at the surface.

Though the immediate cause of the development of the cold anomaly appears to have been the flow of cold continental air over the Gulf and western Atlantic, the more general cause may have been due to large-scale interactions over the North Pacific Ocean. A large positive sea temperature anomaly appeared in the eastern Pacific in late 1957 and persisted throughout 1958 (Sette and Isaacs 1960) (Eber 1971). Namias (1959) explains that the contrast of anomalous warm ocean temperatures to the east of cold ocean temperatures, which was the situation in 1957 in the eastern Pacific, provided abnormal feedback in heat exchange processes to the atmosphere which provided the additional baroclinicity upon which cyclones could feed. This cyclogenesis helped maintain the deep Pacific trough south of Kodiak Island which was abnormally intense by the late fall of 1957. Downstream from this area of activity, a responsive ridge developed in the western United States (evident from Figure 1) and a deep trough along the Atlantic seaboard. This distribution is also consistent with the statistical findings of O'Connor (1969) who noted that when an anomalously deep trough forms in the 700-mb circulation in the east central Pacific, the chances for a trough off the eastern seaboard are high.

Air-Sea Interactions in Other Years

It is tempting to argue that events such as the 1957-58 occurrence described above occur so seldom that it is not worth the effort to study them and their effects on fisheries. Study of years when extreme conditions prevail, however, provides hints of the processes that are occurring in the natural system in other years. Definitive findings through study of more normal years are often difficult to obtain because processes involved may be obscured by the subtle interactions of a number of factors.

The interaction of the type described above may not be as infrequent as one might believe. A situation similar to the winter of 1957-58 seems to have occurred in the winter of 1939-40. O'Connor (1958) noted very cold air temperatures along the eastern seaboard in the winter of 1939-40 which were as intense as those in 1957-58. Although sea temperature records are sparse for winter months (December through February) of 1939-40, what data are available show an extremely cold and widespread anomaly in the Gulf of Mexico (Figure 5) and along the eastern seaboard where temperature anomalies of 5° and 6°C below normal were observed in February 1940.

Further analysis of these large-scale air-sea interactions suggest a possible relation between equatorial Pacific Ocean temperatures and those in the Gulf of Mexico. Bjerknes (1969) has shown that in the winters 1957-58, 1963-64, and 1965-66 high sea-surface temperatures prevailed in the eastern tropical Pacific Ocean. This is characteristic of El Niño years which are best known for the invasion of warm water off the Peruvian coast and effects on the anchoveta populations there. It is known also that in the winter of 1939-40 a severe El Niño was present in the eastern Pacific. In all of these winters cold sea-surface temperature anomalies prevailed in the Gulf of Mexico (Figure 5). There appears, then, to be a relation between sea temperature anomalies in the equatorial Pacific and anomalies in the Gulf of Mexico, that is, negative sea-surface temperature anomalies in the Gulf and western Atlantic in some situations may be related to positive sea temperature anomalies in the eastern equatorial Pacific through processes described by various authors mentioned previously and those described in this paper.

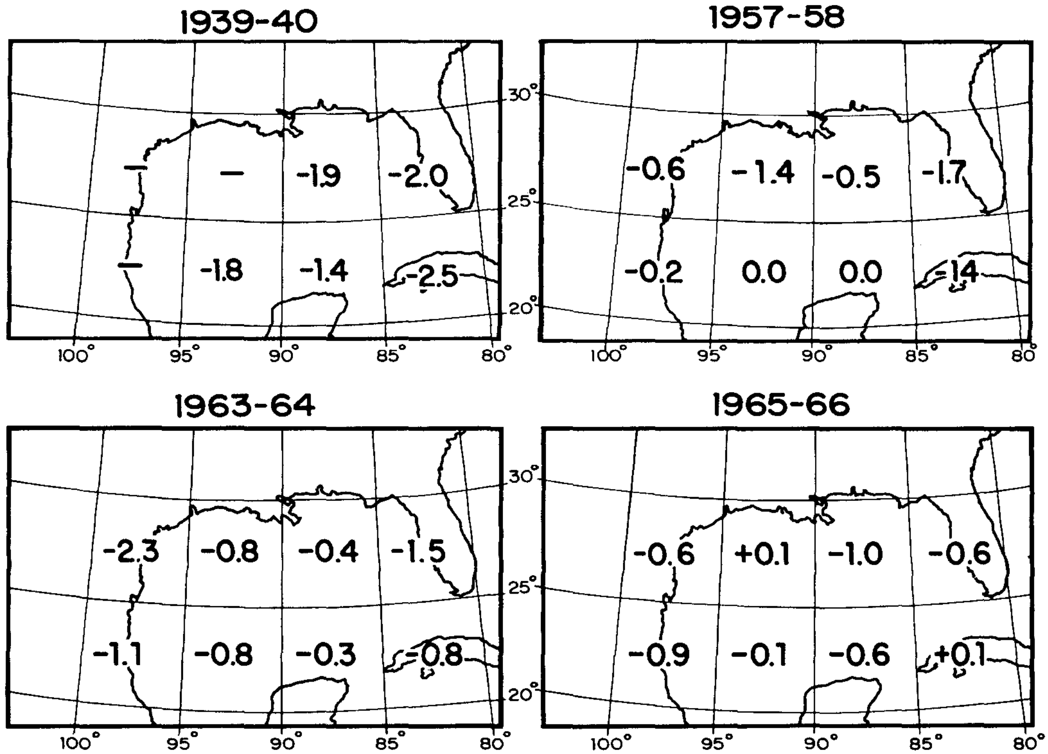

FIGURE 5.—Sea-surface temperature anomalies (°C) in the Gulf of Mexico for selected winters.

During the recent 1972-73 El Niño, however, a situation occurred where this relation did not exist. A trough did not develop off the eastern seaboard until late winter and was short-lived in nature. During most of the winter it was situated over the central United States. Consequently, the flow of cold, continental air over the Gulf of Mexico, especially in the eastern Gulf, was not as intense as in previous El Niño years, and thus not as much cooling of surface waters occurred in the Gulf of Mexico.

A situation opposite to the cold winters along the eastern seaboard described above occurred in the winter 1948-49. Very little cooling occurred in the waters of the Gulf, and the net heat exchange at the air-sea interface likewise was small (Figure 4). The sea-surface temperature anomaly patterns in the winter of 1948-49 compared to the winter 1957-58 are remarkably opposite in sign and magnitude (Figure 6). Whereas, cold sea temperature anomalies prevailed in the latter winter off the southeastern United States, widespread warm anomalies were present in the winter 1948-49. In this winter a distinct ridge developed over the eastern United States in the 700-mb heights, a trough over the western U.S., and another ridge in the northeast Pacific (Figure 7) which is consistent with the hypothesis given by Quinn (1972) and by the findings of Namias.

Namias (1972) suggested that the 1957-58 winter marked the beginning of a new climatic regime in the northern hemisphere. He shows, for example, that the winter mean air temperature at Atlanta, Ga. for the decade 1948-57 was about 5°F higher than the following decade. A trend is also noted in decadal differences of sea temperatures in the Gulf of Mexico. The 1948-57 decade average of February sea temperature was about 1.0°C higher than the 1958-67 February average. Somewhat lower sea temperatures generally prevailed along the entire eastern seaboard in the 1958-67 decade compared to the one preceding.

Sea temperatures and circulation off the U.S. west coast also showed a climatic change. Huang (1972) calculated that southward transport in the general area of the California Current from San Diego to long. 150°W in the period 1958-69 was less than in the previous decade. He showed further that the California Current annual sea temperatures were as much as 1.4°C above normal in the

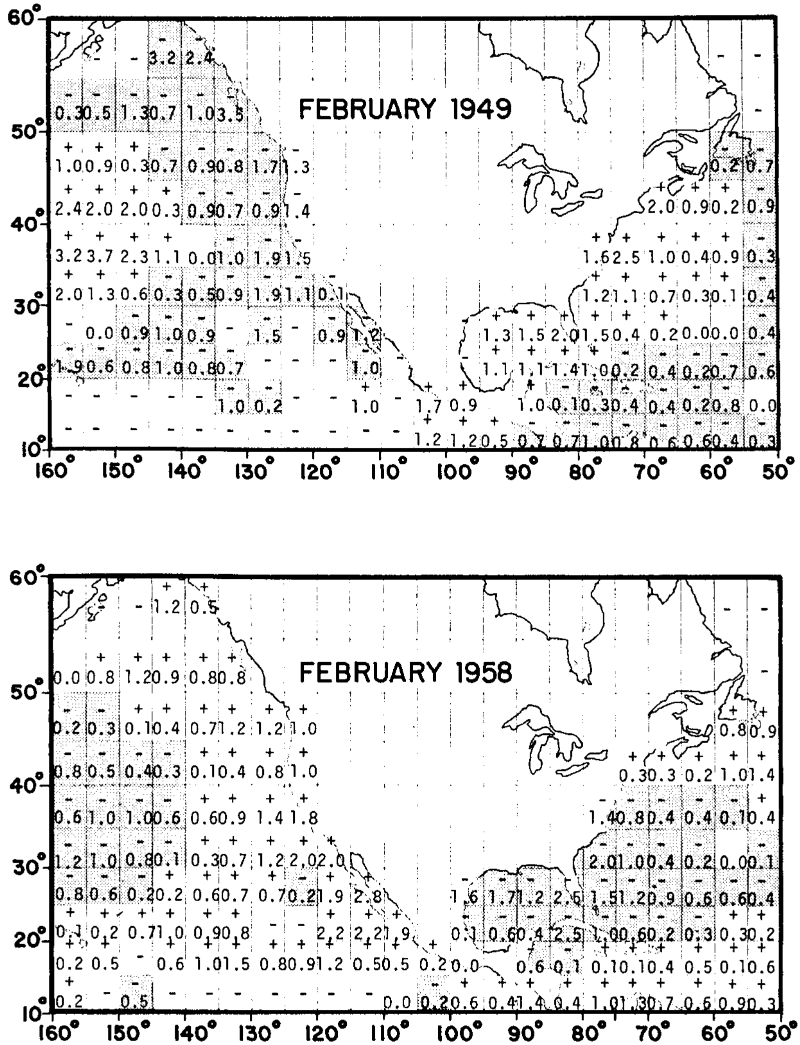

FIGURE 6.—Sea-surface temperature anomalies (°C) February 1949 and February 1958 in eastern Pacific and western Atlantic oceans. Shaded areas colder than 20-yr (1948-67) mean.

1958-69 period and the seasonal temperature departure in winter was greater than 2°C in some places. Apparently, this was caused by less advection of cold subarctic water southward.

DISCUSSION

The authors have attempted to show that development of sea-surface temperature anomalies in the Gulf of Mexico and along the U.S. eastern seaboard in wintertime may be related to the origin of the overlying air masses. In situations where trough development occurs in the upper air circulation over the eastern United States, cold continental air from North America is likely to flow over the Gulf and waters off the eastern seaboard causing excessive loss of heat through evaporation and conduction of sensible heat. Conversely, in situations where a ridge develops, warm air masses predominate, and loss of heat from the ocean is retarded. In fact, as Figure 4 indicates, the water in some winters may cool very little. Furthermore, an attempt has been made to show that the development of these

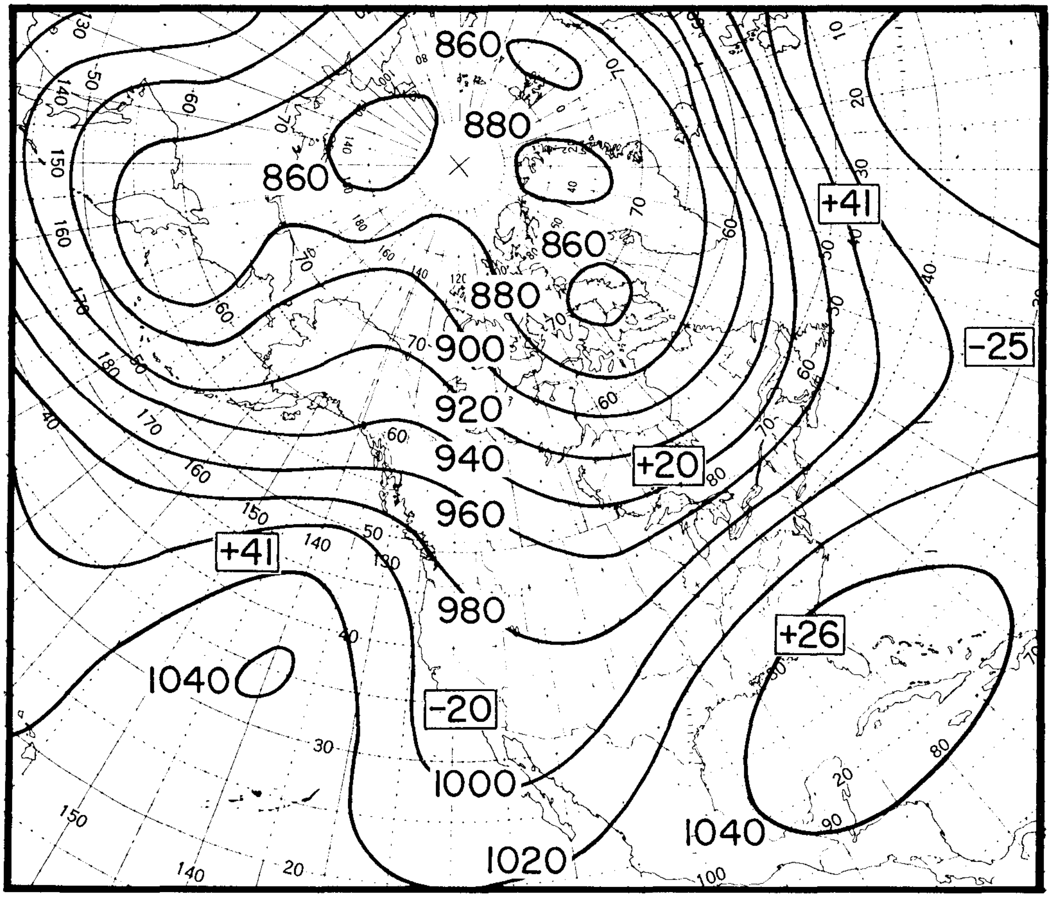

FIGURE 7.–700-mb heights and departures from normal, tens of feet, January 1949. Major departures are enclosed in boxes.

troughs and ridges in the upper air circulation may have been related to air-sea interaction processes in the Pacific Ocean.

It is interesting to speculate on the physical consequences following the development of a large-scale cold sea-surface temperature anomaly in the winter of 1957-58 in the Gulf of Mexico and western Atlantic. It is quite possible that further investigation will show differences of flow in the Gulf Stream. The fact that the anomaly developed in winter suggests that the water to the depth of the thermocline may be affected. A large cold mass of water of this type alters the density distribution over a large area and thus alters the surface circulation. The authors have noted an apparent drift of the anomaly away from the U.S. east coast northeastward until the early summer of 1958 when the surface anomalies were obscured, although it may be quite possible and even likely that the deeper waters were still colder than usual. The effects on Europe of this cold water mass after a period of eastward drift can only be speculated at this time. The fact that the anomaly could be traced for a time following its formation suggests an interesting possibility for further research.

The biological consequences of such large-scale air-sea interactions are even more complex. The effect of the warm sea temperature pool in the eastern Pacific in 1957 and 1958 on fish populations is well documented by Radovich (1961). Southern species were found much farther north than normal in the temperate northeastern Pacific apparently in response to the warm sea temperatures. In the western Atlantic and Gulf the effects of the cold anomaly were less evident although there is a suggestion from the work of Williams (1969) that the shrimp populations were affected.

Williams believes that catches of penaeid shrimp in the southeastern United States fluctuate in such a way as to suggest dependence on coastal temperatures. His studies show an apparent association of good catches with warm years and poor catches with cold years. The shrimp season following the cold winter of 1957-58 was particularly poor in several areas. His indices of cold and warm years are derived from coastal air temperatures which probably are a reasonable indicator of sea temperature variation in estuarine and coastal waters. Williams believes it might be possible to use winter coastal air temperatures as predictors for the succeeding year's catch when better definition and measure of fishing effort are available.

These hints of biological consequences of large-scale air-sea interactions point out possibilities for future research. Clearly, investigations of this nature will require a cooperative effort among meteorologists, oceanographers, and fishery biologists.

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