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Large-Scale Air-Sea Interactions and Short-Period Climatic Fluctuations

Jerome Namias and Daniel R. Cayan

Summary. Research during the last 15 years has shown that there is order in large-scale air-sea interactions, so that space scales of abnormalities of the lower atmosphere's circulation and the upper oceanic thermal structure are comparable. Because of this air-sea coupling, each oceanic or atmospheric pattern can be reasonably well specified by the other. Patterns of oceanic thermal anomalies are about an order of magnitude more persistent than those of atmospheric circulations, and empirical studies have had some success in using sea surface temperature patterns in long-range weather prediction. In addition to empirical studies, efforts continue in the development of numerical-dynamical models in order to understand the complex linkages of the large-scale air-sea system.

In 1965 Namias (*1*) identified some problems related to the stabilization of anomalous atmospheric circulations on seasonal and longer time scales. He hypothesized that anomalous large-scale oceanic thermal patterns might strongly influence the atmosphere. There were indications that the ocean played an important role in short-term climatic variability on a global scale and that the upper ocean and atmosphere were closely although complexly coupled over extensive areas and relatively long periods (months to a few years). However, these interconnections were based on limited observational evidence and physical insight.

Since 1965 hundreds of studies of air-sea interactions have appeared in the scientific literature. This has promoted an increased awareness of the importance of the oceans in short-term climate variability (*2–5*). The role of the oceans in the carbon dioxide problem has been treated at length (*6*). Also, use of air-sea interactions in long-range weather forecasting has been explored in a series of empirically oriented studies (*7–9*).

Our purpose in this article is to take stock of some of the research conducted over the past 15 years or so, particularly on topics germane to large-scale interactions with periods of a month to a decade. This research has yielded a much better descriptive knowledge of large-scale oceanic-atmospheric processes and in some areas has led to much improved physical explanations. Progress has been made through a broad spectrum of approaches—synoptic case studies of specific climatic events, statistical and physically motivated investigations involving various historical oceanographic and meteorological data series, new observations of key parameters for prescribed regions, and numerical experiments and theoretical studies designed to model and understand these air-sea phenomena.

Important questions still remain. The mechanisms that produce large-scale oceanic near-surface temperature anomalies are not well known, and the degree to which these anomalies then affect the atmospheric circulation is still only partially understood. The relative importance of tropical versus mid-latitudinal influences on short-term climatic variability is still being debated. In many cases we can find statistical links between different members of the macroscale ocean-atmosphere system, but we have not been able to label cause or effect.

The issue of causality has great implications for the application of oceanic or atmospheric parameters to long-range weather prediction. Experiments in which sea surface temperatures have been used as extended weather indicators have been encouraging, but these indicators are not entirely straightforward to apply, due to the seasonal and regional variations in their relation with the atmosphere and the imperfect nature of the resulting statistics.

In the following sections we first describe the nature of atmospheric and oceanic time and space scales, pointing out some areas where further research is needed. Next, we somewhat arbitrarily divide the air-sea interaction problem by first treating influences of the atmosphere on the thermal structure and currents of the surface layer of the ocean, and then discussing influences of the ocean on the atmosphere. The complex problem of coupling in real time is then addressed, largely in terms of statistical, synoptic, and modeling studies. Finally, we discuss the practical application of air-sea interaction concepts in long-range weather and climate forecasting.

Time and Space Scales

This article is concerned mainly with air-sea interactions having spatial dimensions of several hundreds of kilometers or more and time scales of a month or longer. Although it is small-scale processes that govern the details of air-sea interactions, it is certainly the large-scale phenomena that ultimately drive the temporally and spatially averaged exchanges of heat, momentum, and water vapor. An outstanding example of the

Jerome Namias is a research meteorologist and Daniel Cayan is a staff research associate with the Climate Research Group, Scripps Institution of Oceanography, La Jolla, California 92093.

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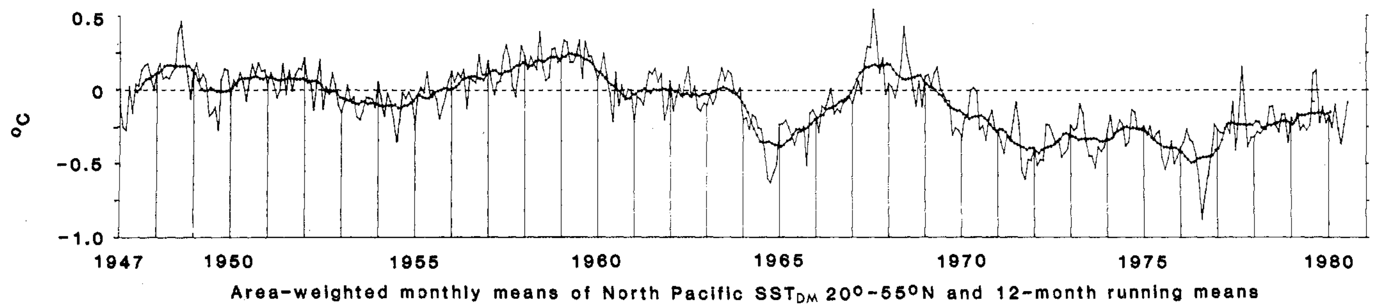

Fig. 1. Area-weighted SST average departures from the 1947–1966 mean (SST_{DM}) (dashed line) for the North Pacific in the region 15° to 60°N and 130°E to 110°W. Light lines connect monthly anomalies; the dark curve shows the 12-month centered running means.

low-frequency nature of the upper ocean's temperature field is seen in North Pacific areal average sea surface temperature (SST) anomalies for the period 1947 to 1980 (Fig. 1). Monthly values and their 12-month running means are shown. The running means exhibit a large signal, approaching 0.5°C in amplitude, with a period of several years, a fact quite impressive as they represent oscillations over the bulk of the North Pacific.

There is a mismatch in life expectancy between large-scale atmospheric flow patterns and ocean surface temperature patterns (*10*). Figure 2 shows the persistence of North Pacific monthly average sea surface temperature patterns in contrast to sea level pressure (SLP) and contours of the 700-millibar height. The 700-mbar height is usually found at an elevation of roughly 3 km. These correlations represent autocorrelations of monthly patterns at time lags of 1 to 12 months. While the "memory" of the 700-mbar height and sea level pressure fades after 1 or 2 months, the SST anomalies persist for 6 months or more. This great SST persistence results from the large thermal capacity of the upper ocean and its relatively sluggish velocity structure. The SST anomalies represent large amounts of stored heat, since they often penetrate to depths greater than 200 meters, as seen in Fig. 3 (*11*). For this reason the SST field is a strong candidate as a long-range weather predictor, since a long-lived, large-area SST anomaly pattern could provide stabilizing boundary influences on the more turbulent overlying atmospheric flow.

In the spatial domain, the atmosphere has a considerable portion of its low-frequency energy in length scales of 1000 km or more, due largely to the dominance of long planetary waves (*12–14*). The planetary wave behavior is modulated or forced by orographic influences and seasonal heating contrasts (*15*). This large-scale coherent behavior is illustrated statistically in Fig. 4, which shows cross-correlations ("teleconnections") of winter average 700-mbar height between a point at 40°N, 170°W and points elsewhere in a 5° by 5° latitude-longitude grid in the Northern Hemisphere. The correlations exhibit strong coherence in a large region surrounding the central point and a wavelike tendency in both up- and downstream directions.

The thermal structure of the ocean also exhibits strong spatial coherence (positive correlation) over roughly comparably long length scales (*16–19*). Figure 5 shows another teleconnection map—this time for average winter SST in the North Pacific, with cross-correlations between 40°N, 170°W and all other points. The dimensions of typical SST anomalies are often somewhat smaller than those of their atmospheric counterparts, in part due to basin boundary geometry and the configuration of surface currents. Still, the warm and cold anomaly patterns can easily span half the width of the North Pacific. Doubtless, this spatial coherence owes much of its existence to the large size of the overlying anomalous atmospheric circulation, which was illustrated in the teleconnections in Fig. 4.

The tropical ocean-atmosphere system deserves special mention because of its unusually strong low-frequency, large spatial scale behavior (*20*). For much of the low latitudes, the year-to-year variability is larger than the regular seasonal variations of typical atmospheric and oceanic variables (temperature, pressure, velocity, and so on). A prominent example of low-frequency, coupled phenomena is El Niño, which affects the eastern tropical Pacific with unusually warm surface water and an altered trade wind circulation (*21*). El Niño is nonperiodic but usually recurs after an interval of 3 to 7 years. Although its strongest signal is found in the eastern tropical Pacific, El Niño is now thought to be initiated by events in the central Pacific (*22*). El Niño also has far-reaching economic consequences; for instance, the fishing and guano (fertilizer) industries of the west coast of South America are severely affected by lack of replenishment of nutrients in the upper ocean (*23*). Also, studies of large sets of historical data have linked the meteorological and oceanographic conditions in the eastern tropical Pacific to conditions throughout a large area of the tropics (*24, 25*) and even to mid-latitude atmospheric circulation patterns (*26–28*).

Influence of the Atmosphere on the Ocean

Air-sea coupling is easiest to demonstrate in the way that the atmosphere drives the ocean. The effects of these interactions appear in the ocean's thermal, velocity, and salinity fields, which are affected by the winds, temperatures, and humidities of the lower atmosphere.

An obvious example of the influence of the atmosphere on the ocean is that of wind-driven currents. The effect of large-scale winds on the gross features of the oceanic circulation was demonstrated early with wind-driven ocean circulation models (*29–31*). Recent modeling efforts have focused on smaller scale transient features, which must be included in a more complete and accurate understanding of the wind-driven circulation (*32, 33*).

The connection between the mid-latitudinal ocean and the wind is shown from the paths of satellite-tracked drift buoys deployed in the North Pacific as part of the NORPAX study (*34, 35*). The buoys were monitored between the summers of 1976 and 1977. Superposition of the mean monthly sea level pressure pattern over the buoy trajectories for winter months of that period (Fig. 6) shows the close connection between the surface water drift and the surface wind. It also indicates the large-scale nature of the atmospheric forcing and the oceanic response. Satellite-tracked drift buoys show great promise for studies of remote areas of the global oceans.

Attempts to model the large-scale ocean variability, as shown in Figs. 3 and 5, are in a very early state of development. However, recent studies show that the large-scale wind stress has a strong influence on the longitudinal variation of the surface temperature field by transporting warm water northward or cold water southward (*36, 37*). This mechanism of SST change rivals anomalous heat exchange across the sea surface (*38, 39*) and vertical mixing with colder subsurface water (*40, 41*). A recent modeling experiment (*42*) carried out to identify the mechanisms important in generating thermal anomalies in the upper layer of the central North Pacific during the winter of 1976–1977 (*43*) indicates that all the mechanisms mentioned above—horizontal advection, surface heating, and turbulent mixing—played significant roles in this case. Certainly, the intensity and relative importance of these processes vary with season and with region. Ocean models might eventually satisfy a need for synoptic, month-to-month estimates of the field of flow over the world ocean, which are currently unavailable. This information is necessary both for dynamical prognoses of the sea surface temperature field and for oceanic heat transport calculations (*44, 45*).

More is known about thermal variations of the upper ocean than about variations in velocity, since temperature is more easily measured than currents. A number of field programs devoted to elucidating the dynamics of large-scale ocean temperature variability have taken frequent and dense samples to provide temperature records in selected oceanic regions (*46–48*). Because efforts requiring research vessels are expensive, oceanographers have found other means of measuring the temperature field. For decades, routine merchant ship reports of engine intake water temperatures have been used to construct the sea surface temperature field over much of the world's oceans. Maps are made up from tens of thousands of such reports per month. Remote sensing of SST by satellite with infrared and microwave imagery has been the subject of intense development (*49*), although it has been hampered by cloud cover as well as by difficulties in making the satellite SST data compatible with conventional ship reports (*50*). A recent innovative approach to economically measure the temperature field of the entire upper layer has been to enlist the services of merchant "ships of opportunity," from which regularly spaced expendable bathythermograph (XBT) recordings are taken along North Pacific shipping lanes over an extended period (*47*). The XBT's record the temperature of the upper 300 to 700 m of water. Expendable bathythermographs dropped from aircraft have also been employed along meridional sections in the tropical Pacific (*51*). The temperature of the entire column of the upper layer of the ocean is believed to be superior to the SST because it represents the heat storage of the upper ocean.

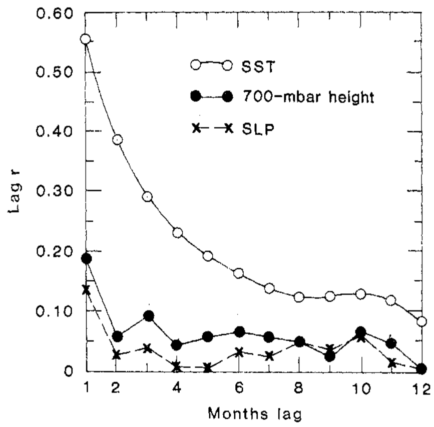

Fig. 2. Autocorrelations of standardized values for monthly mean patterns of SST, 700-mbar height, and sea level pressure (SLP) from a 5° grid of points covering the North Pacific (north of 20°N), based on the 20-year period 1947 to 1966; *r*, correlation coefficient.

On a dismal note, we must report that most of the ocean weather stations have been discontinued as cost-cutting measures. For years these station positions were occupied by government oceanographic vessels, and they provided the most complete long-term climatic records of the open ocean. We are thus faced with a sample set that is long enough to provide tantalizing clues about climatic fluctuations but too short to attach statistical significance to the variability.

Turning from measurements and physical modeling studies, there has been a host of empirical studies linking the large-scale ocean temperature patterns to the overlying atmospheric circulation patterns (*7, 52*). Contemporaneously, SST patterns are well correlated to atmospheric patterns so that, especially in the North Pacific, knowledge of one of these fields allows reasonably accurate specification of the other, accounting for about 60 percent of the variance. In addition, atmospheric conditions for a month or a season have been used to predict the future season's SST pattern, owing to the low-frequency response and persistent nature of the upper ocean on seasonal average time scales. An important issue for long-range weather prediction is whether the SST field is useful in predicting subsequent atmospheric states; this question is taken up in the following sections.

Effect of the Ocean on the Atmosphere

We have described studies that convincingly demonstrate effects of the atmosphere on the thermal characteristics of the upper layer of the ocean. Despite the apparent logic of the thesis that the sea also influences the atmosphere, this thesis is difficult to prove, particularly the influence of SST anomalies on the contemporary or future atmospheric state. It seems to us that since the oceans play an important role in long-period atmospheric climate, as can now be demonstrated by physical numerical simulations (*53*), there must be some effect of SST anomalies on the overlying atmosphere in the short term. However, attempts to demonstrate this quantitatively through dynamical models or empirical techniques have not yielded entirely conclusive results—a circumstance not uncommon with complex, coupled systems.

Ultimately, the best laboratory for testing the influence of ocean temperature variability on the atmospheric circulation will be provided by atmospheric general circulation models that include the coupled air-sea system. These models allow controlled numerical simulations of the atmosphere based on computer integrations of the governing hydrodynamic and thermodynamic equations. Because they directly incorporate the physics involved, general circulation models are an attractive means of understanding the physical processes of air-sea interactions as manifested in observations and empirical findings.

The results of general circulation model testing of atmospheric sensitivity to prescribed mid-latitudinal SST anomalies have not been conclusive (*54, 55*). In most cases the model showed a response localized in the atmosphere directly overlying the anomaly, but significant downstream effects were not unequivocally shown. The responses found were generally small except when unrealistically large SST anomalies were imposed. To determine the statistical significance of model results it is necessary to establish the level of model variability, and this is generally difficult because it requires a great deal of expensive computer time. The ability of general circulation models to simulate the atmosphere realistically is also an important issue, because responses may be strongly model-dependent. Another important issue is the effect of allowing the SST to vary rather than fixing it as a boundary condition; there are indications that these alternatives may profoundly influence a model's results (*56*). Coupled ocean-atmosphere models have mainly been concerned with simulating the long-term climatology of the atmosphere and ocean (*53, 57*) and have not yet addressed the important problem of year-to-year variability.

In the meantime, there have been some simplified or idealized models that have shown downstream effects of midlatitudinal SST anomalies (*58, 59*). These simple models indicate that certain wavelengths in the atmosphere may be excited preferentially by heating or cooling, which then can produce perturbations in the atmospheric flow in areas remote from the imposed SST anomaly pattern.

Sensitivity studies of the effects of tropical SST anomaly patterns on the atmosphere have been more convincing. Tropical effects may be easier to detect in models because of the strong, built-in coupling of sea-to-air heat transfer, which modulates cumulus convection with resulting release of latent heat of condensation aloft; this then alters the large-scale air circulation elsewhere as well as in the variable SST area (*25, 60, 61*). These ideas are in agreement with the empirically based theories of Bjerknes (*62*), which we discuss later. Also, the level of natural variability in the tropical models is lower, which probably makes the SST forced signal more detectable.

Considering the mixed results of numerical experiments, the thesis of sea-to-air influence seems to rest mainly on empirical studies, which provide a large body of circumstantial evidence. Many of these are case studies involving a combination of synoptic, statistical, and conceptual physical reasoning. Case studies suffer from the malady common to many investigations of climatic variability—there are usually too few realizations to attach statistical reliability to the calculations. Also, these articles require perusal of many maps and charts and sometimes tedious descriptive prose, and their impact on the overburdened community of meteorologists and oceanographers is often not overwhelming. The transition from descriptive procedures to desired objectivity is bound to be difficult.

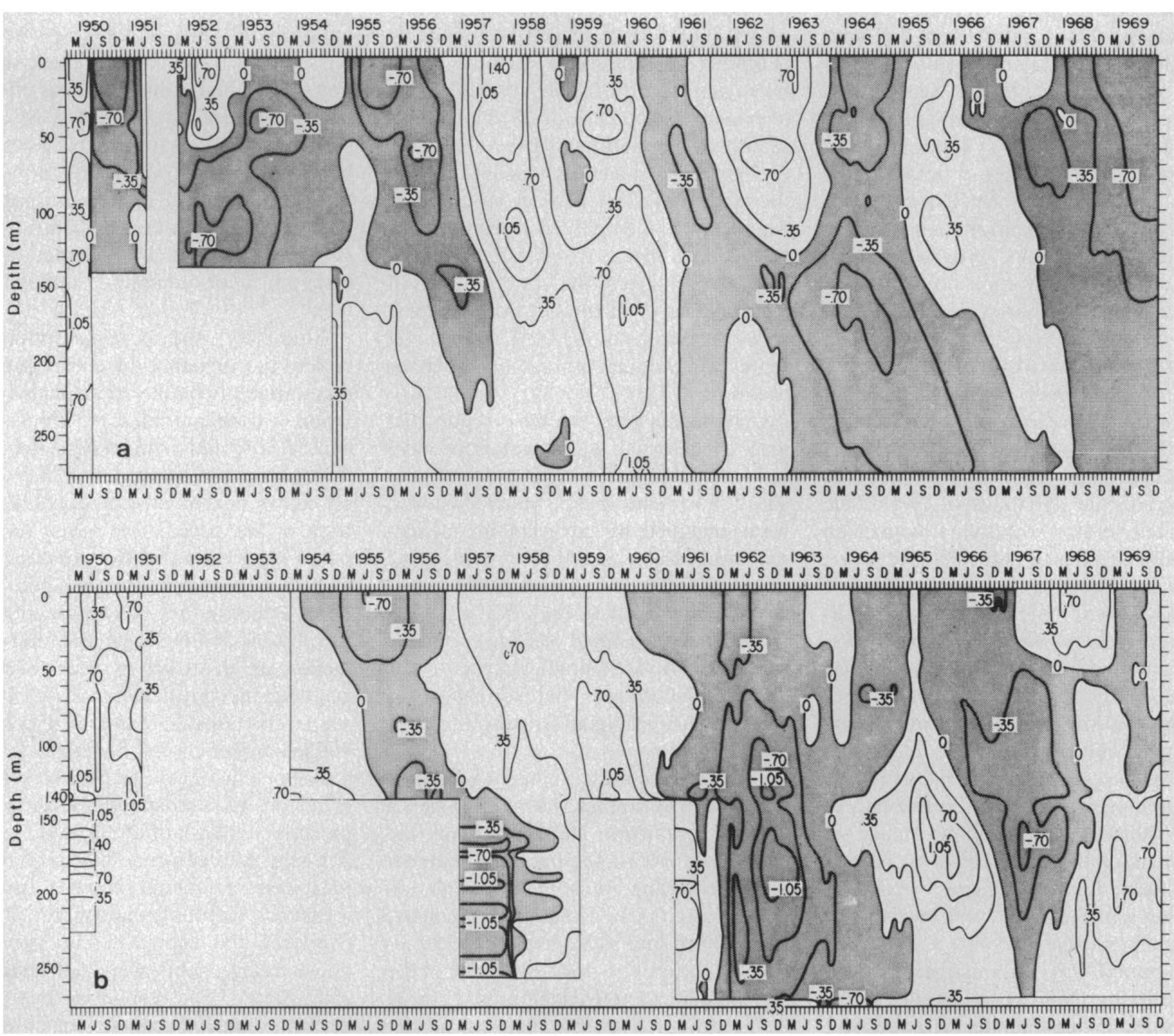

Fig. 3. Water temperature anomalies (degrees Celsius) as a function of depth at ocean weather stations (a) PAPA (50°N, 145°W) and (b) NOVEMBER (30°N, 140°W). The original monthly data have been smoothed with a 12-month running mean. Areas where data are missing are left blank. Shaded areas denote below-normal temperature for the period of the data.

Many of the empirical studies are designed to determine whether the rapidly changing atmosphere, through its own internal dynamics, can force persistently recurrent weather phenomena and result in the large anomalous circulations observed on monthly, seasonal, or even annual mean charts. It is possible that abnormal surface conditions stabilize anomalous atmospheric flow patterns, as do fixed features such as mountains and coastlines. Among the prime candidates for exerting these stabilizing forces are anomalous conditions in the oceans, the cryosphere, and the soil moisture of land surfaces. Since thermal structure of the ocean's upper layer is influenced by the atmosphere on both a contemporary and an antecedent basis, it is difficult to prove that the ocean is not simply a slave to the atmosphere.

There are indications that strong, large-scale gradients of anomalous SST influence the anomalous overlying atmospheric flow. In the North Pacific, case studies [for instance (*43*)] and a recent statistical investigation (*63*) have suggested that anomalous SST gradients encourage atmospheric flow contrasts through differential heat fluxes.

Aside from the large number of detailed case studies and several statistical investigations implying oceanic control, some complications have arisen. Davis (*17*) found that when all months are lumped together, North Pacific SST patterns tend to follow atmospheric sea level pressure patterns by a month or so. On the other hand, Namias (*64*) found that the Aleutian low-pressure system in fall was modified in strength by antecedent SST conditions south of the Aleutians and in the Gulf of Alaska, as indicated by lag-correlations of summer SST to fall SLP (Fig. 7). This promoted a statistical study of seasonally stratified data by Davis (*52*), which confirmed Namias's results and also showed a significant relation between summer SST and fall SLP. In addition, Davis found that antecedent SLP was an equally good predictor of the fall and winter SLP field, which at first glance seems to complicate the simple interpretation of the ocean driving the atmosphere. However, it can be argued that both SST and SLP would have to be precursors because of their interdependence during the antecedent season. In any event, few oceanographers or meteorologists dispute the coupled nature of air-sea systems. What causes what and exactly how changes are brought about are unsolved problems that await further efforts of both meteorologists and oceanographers.

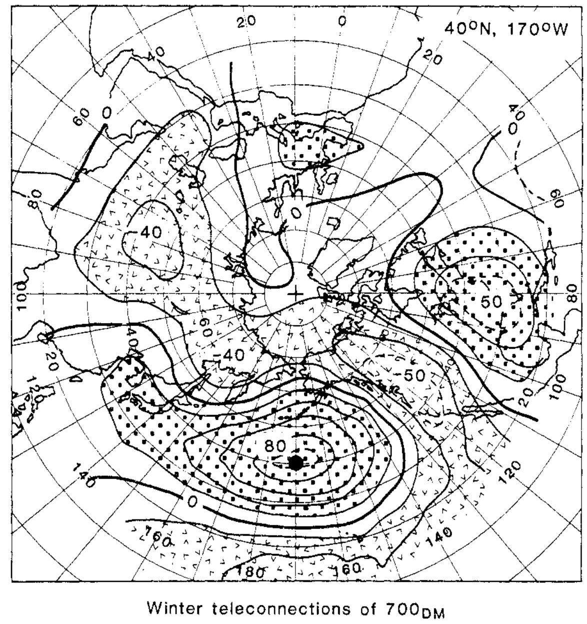

Fig. 4. Cross-correlations (teleconnections) of winter mean 700-mbar height at the point 40°N, 170°W (●) with other values of the 700 mbar height around the Northern Hemisphere, based on winter months (December to February) over the period 1947 to 1972. Negative and positive correlations exceeding the 95 percent confidence limit are indicated by patterns of small v's and small squares, respectively.

In the next section, we take up some concepts that have been sufficiently researched to be useful in long-range weather and climate forecasting. These sea-air methods are often used in combination with atmospheric internal mechanisms.

Air-Sea Interaction in Long-Range Forecasting

In contrast to day-to-day weather forecasting, where the present atmospheric state and the governing hydrodynamic equations constitute an initial-value problem, the application of air-sea interactions in long-range forecasting is more akin to a boundary-value problem. The SST anomalies can be considered a boundary condition, since they change slowly relative to the overlying atmospheric circulation and thus influence subsequent monthly or seasonal mean atmospheric conditions.

At present, "long-range" forecasting is mostly confined to 1 month or one or two seasons in advance. Mean temperatures and total precipitation for a month or a season are generally predicted, often in terms of equally probable classes such as terciles (for instance, above normal, normal, and below normal). A "broad brush" approach is generally used for the forecast patterns, with emphasis on large-scale features. The level of skill achieved is quite modest, with average skill scores for the coterminous United States of about 0.10, where skill is estimated as (percent of area correct − percent correct expected by chance)/(100 percent − percent correct expected by chance).

Although skill levels are low, the so-

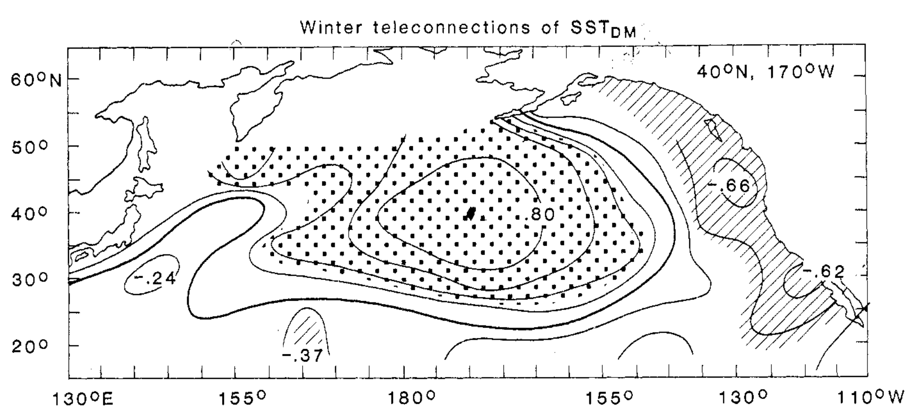

Fig. 5. Cross-correlations (teleconnections) of winter SST at the point 40°N, 170°W (◆) with all other gridded values of SST across the extratropical North Pacific. Negative and positive correlations exceeding the 95 percent confidence limit are indicated by patterns of hatching and small squares, respectively.

cial and economic benefits that would result from improved long-range forecasts have motivated considerable activity during the past decade (*65, 66*). A novel approach has been the use of SST patterns as atmospheric predictors.

The application of air-sea interaction relations to long-range prediction schemes is not straightforward. Relations between the SST and the overlying atmosphere vary with season and location. From a synoptic point of view, the seasonal weather pattern is influenced by a number of factors, of which the ocean is only one, and their relative importance changes with each case. At present, there is no proven dynamical forecast model that incorporates the proper physics of mean states and accounts for these seasonal and synoptic variations. Therefore, work toward improving the present empirical approach continues. We now present a brief description of techniques and principles, with emphasis on a physically motivated synoptic approach developed by J.N.

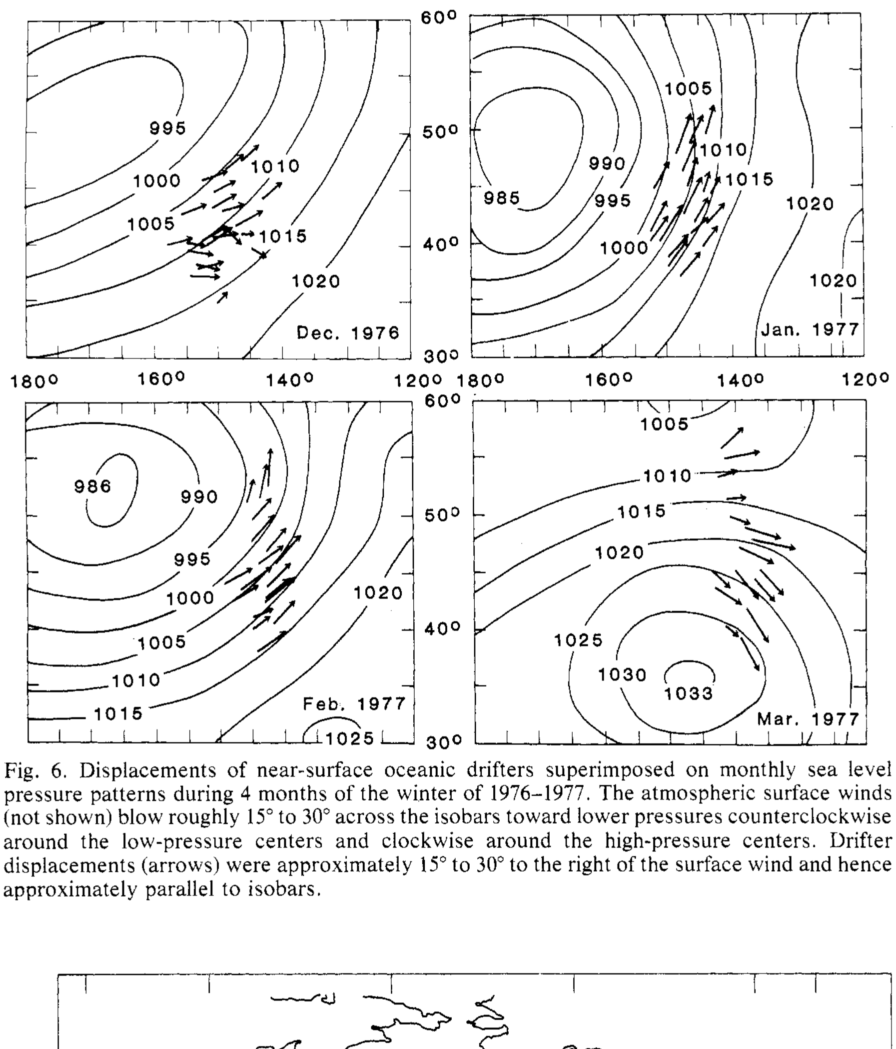

Fig. 6. Displacements of near-surface oceanic drifters superimposed on monthly sea level pressure patterns during 4 months of the winter of 1976–1977. The atmospheric surface winds (not shown) blow roughly 15° to 30° across the isobars toward lower pressures counterclockwise around the low-pressure centers and clockwise around the high-pressure centers. Drifter displacements (arrows) were approximately 15° to 30° to the right of the surface wind and hence approximately parallel to isobars.

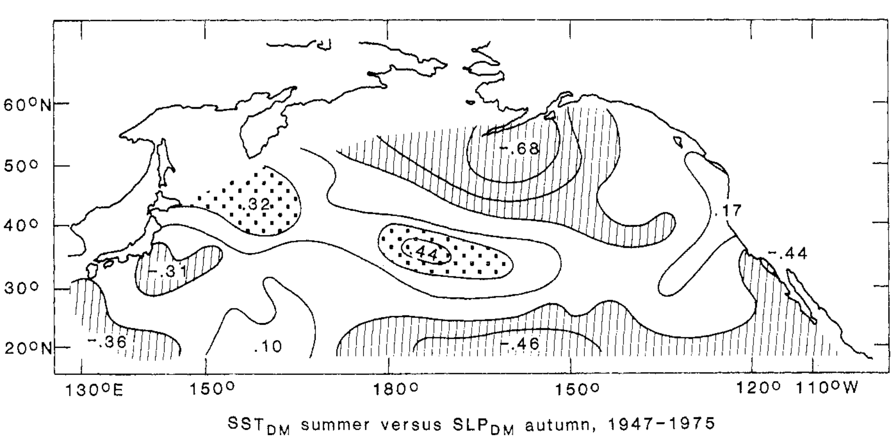

Fig. 7. Isopleths of point correlations between the number SST anomaly and the autumn SLP anomaly for seasons of 1948 to 1975. Negative correlations below −0.20 and positive correlations exceeding 0.20 are indicated by patterns of hatching and small squares, respectively. Numbers denote centers of maximum correlation.

As discussed earlier, the atmospheric pressure distribution contains an appreciable large-scale signal, even when averaged over a month or a season. The mean pressure distribution and departures from normal can be used to infer the ensemble of weather events that characterize the period, including prevailing air masses and storm tracks. From the mean flow pattern, determined by the pressure distribution, an estimate of the oceanic thermal response can be obtained. Anomalous winds produce anomalous responses in the ocean through horizontal transports, fluxes of heat through the air-sea interface, upwelling and downwelling, and internal mixing. These can all come into play, often synergistically, as discussed above. It follows that warmer than normal surface water is usually found to the east of low-pressure anomaly centers due to horizontal transport of warm surface waters, reduced latent and sensible heat loss by the ocean, and frequently a decrease in vertical mixing of the upper ocean. Downwelling, through the convergence of surface waters in the center of atmospheric high-pressure anomaly areas, also leads to warmer than normal temperatures. Similar reasoning shows that there is cool water to the west of low-pressure centers. These phenomena are well illustrated in the North Pacific atmospheric circulation and SST patterns observed during the winter of 1980–1981 (Fig. 8).

In view of these considerations and the long time constant of the ocean temperature field, one can estimate the SST pattern from known mean pressure and SST distributions. We have done this for the North Pacific by statistical techniques such as stepwise multiple regression. Formulas based on 30 years of monthly or seasonal mean data allow specification of the SST field from the sea level pressure or 700-mbar height field.

Similar concepts provide a basis for predicting the sea surface temperature a month or a season in advance. Again, purely statistical methods can be employed with reasonable success (*52, 67*). In addition, some first approximations are now being made by computing the transport of water around the North Pacific gyre, assuming that (i) the speed of surface currents is given by the climatological annual mean values and (ii) the SST anomalies are conserved in transit—two great oversimplifications.

Once the future SST field has been predicted, the compatible atmospheric pressure field is specified. The influence of the North Pacific pressure fields on

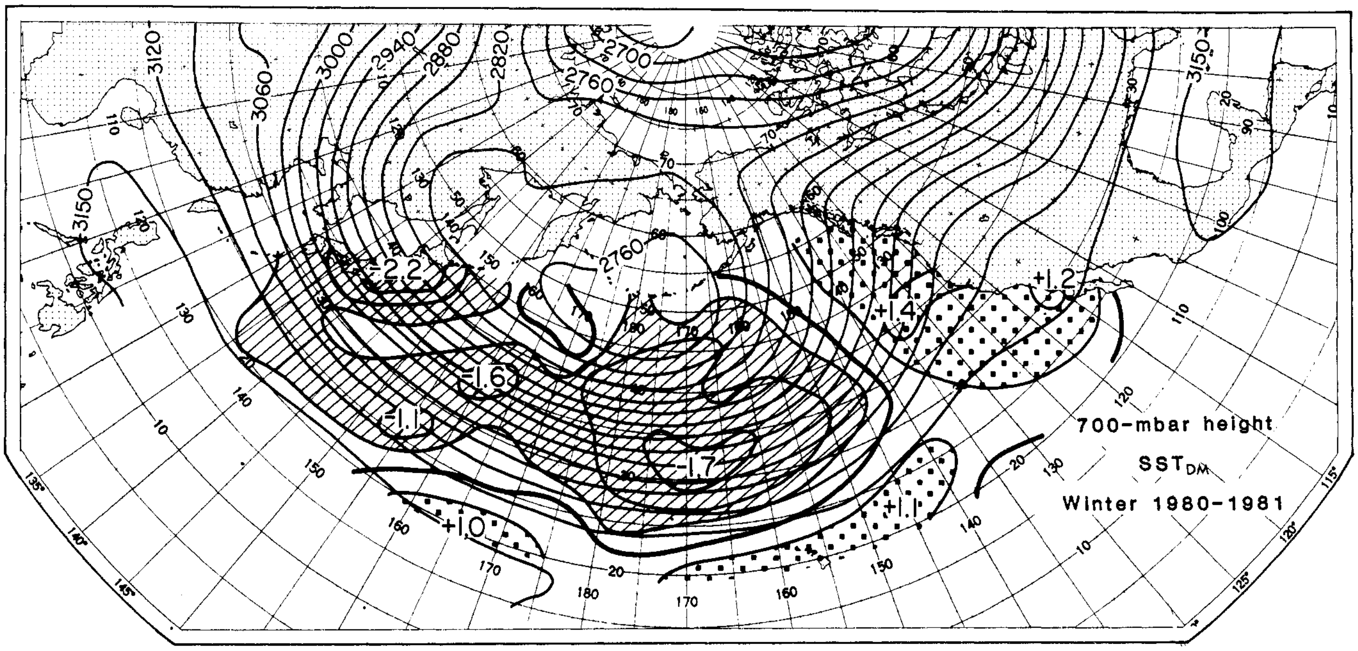

Fig. 8. Sea surface temperature anomalies (degrees Celsius) and 700-mbar contours (meters) for the winter of 1980–1981. Positive and negative SST anomalies are indicated by patterns of hatching and small squares, respectively. Note strong SST gradient at about 145°N, where the cyclonic curvature of the 700-mbar height contours implies frequent storminess.

North America is then determined by teleconnection charts, as described earlier and illustrated by Fig. 4. This finally leads to a forecast of seasonal mean temperature and precipitation from synoptic and statistical considerations (*68*).

A number of other investigators have experimented with SST predictors in seasonal forecasting models (*8, 9, 69–71*). A variety of empirical methods have been employed, including synoptic, semiobjective techniques outlined earlier, regression or similar linear techniques (*9*), and analog methods (*8*). In comparison to many atmospheric circulation parameters, the SST predictors have been relatively skillful (*9, 70, 71*). Although forecast methods vary in principle and in content, it is probably fair to say that the SST field has now been established as a useful long-range weather and climate predictor.

One question related to the practical use of SST is: Which oceanic regions are most important in contributing to atmospheric predictability? Several studies have indicated that certain key regions or patterns of SST are best related to a given atmospheric predictand. The SST regions vary considerably with the domain of the forecast (*9, 64, 69, 70, 72, 73*). For most of the coterminous United States, the evidence thus far seems to indicate that the North Pacific SST overshadows the Atlantic SST as a predictor, except perhaps in the eastern United States, which is sensitive to the Bermuda high. Farther east, the SST in a broad area of the North Atlantic south of Newfoundland is well related to downstream circulation patterns over the eastern Atlantic and western Europe (*69*). An important aspect of this question concerns the influence of the tropics relative to the mid-latitudes as the primary seat of influence for North American weather. Arguments can be made for each region. Both synoptic case studies and forecast experiments (*7–9, 69, 73*) have shown significant predictive relations between mid-latitudinal SST and subsequent overlying or downstream atmospheric weather patterns. There is considerable evidence that this predictability depends on season and on the particular case at hand (*66*). As for the influence of tropical SST on the atmospheric circulation in mid-latitudes, Bjerknes (*62*) proposed that warming in the tropical Pacific would stimulate direct thermal (Hadley) circulation in lower latitudes, which would speed up the zonal westerly winds in the mid-latitude Pacific by transporting angular momentum poleward. One could then argue that North American weather patterns would be affected by downstream responses. Bjerknes had only limited data to support his hypothesis, but later studies (*25, 26, 70*) have substantiated it, although local interactions between the ocean and atmosphere

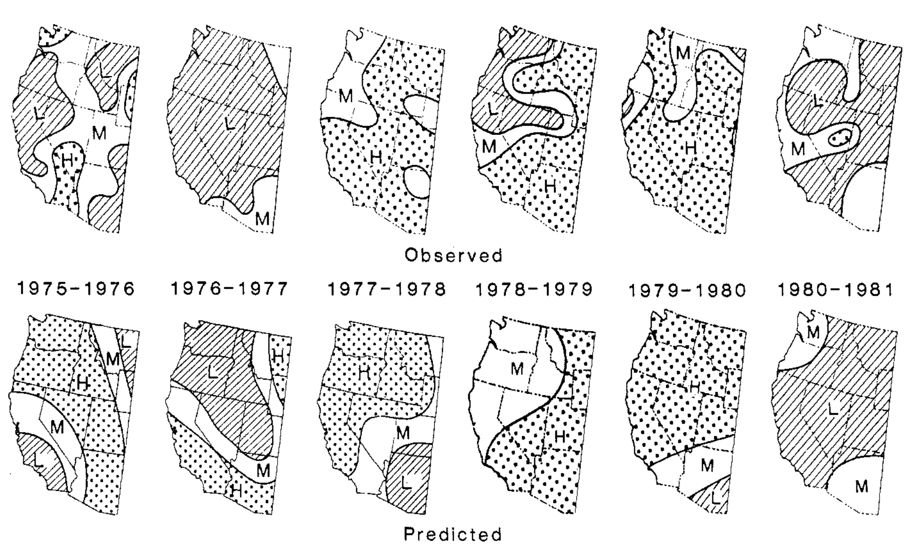

Fig. 9. Observed and predicted winter patterns of precipitation for the western third of the United States expressed in three equally probable categories: *L*, light; *M*, moderate; and *H*, heavy.

may vary considerably (*74, 75*). In experiments with a statistical linear prediction scheme, Barnett (*70*) suggests that tropical Pacific SST predictors of U.S. temperatures are more skillful than midlatitudinal Pacific SST's.

Another important issue is the regional limits of predictability from SST. What continental areas can and cannot be reliably predicted from SST fields? One statistical study of natural climatic noise (the random, unpredictable part of the data) indicates that for the coterminous United States, the potential long-range predictability of temperature is highest for littoral areas and decays to a minimum in the western plains region (*76*). This is consistent with much of the empirical long-range forecasting verifications for the United States. Linear predictability and association studies also suggest something of this nature (*70, 73*). A possible example of this higher skill is seen in predictions made by J.N. for winter precipitation over the western third of the coterminous United States for the last 6 years (Fig. 9). The predicted anomaly patterns, although not perfect, are generally good considering the present state of the art, and are better than forecasts for other areas of the country made by J.N. A rigorous statistical verification of these western forecasts shows high skill levels. Temperature forecasts for this area (not shown) also show relatively high skill. Based largely but not entirely on SST, these forecasts seem to indicate the influence of the upstream North Pacific SST on weather in the western United States.

Conclusions

It should be clear that while substantial progress has been made in studying large-scale air-sea interactions, our understanding is woefully inadequate to achieve reliability in prediction. The major advances have been in describing phenomena, illuminating time and space scales, and specifying the thermal anomalies of the ocean by the atmosphere and vice versa. The precise dependence of one medium on the other—an issue that includes response time, physical mechanisms, and prediction—has eluded both empiricists and theoreticians. Even with this unsatisfactory state of understanding, some success has been attained in specifying and predicting on seasonal time scales, and thus some sense has been made of hitherto perplexing climatic fluctuations. Although numerical-dynamical models for the coupled air-sea system are still under development, the present rapid pace of research implies that much better understanding will be achieved in the years to come.

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