sequence of reflection symmetry breaking in the $d_{2z}$ orbital, due to the (axial) hindrance interaction, rather than as a result of the changes in iron out-of-plane displacement that occur as the system relaxes. However, as discussed by A. M. Ahmed et al. [Chem. Phys. 185, 329 (1991)], the frequency of the Fe–His mode may well be affected by structural changes associated with the protein relaxation process.

14. The available evidence from x-ray crystallography of model compounds [W. R. Scheidt and P. Piccalo, J. Am. Chem. Soc. 84, 913 (1962)] suggests that the Fe–His bond is extended in the NO bound state, relative to the unbound species, as a result of additional electron density in the antibonding $d_{2z}$ orbital.

15. The factor $\alpha$ arises under the condition $\tau_r \ll \tau_0$, because $\tau_r (\sim 75$ fs) corresponds to one-half of the Fe–His oscillatory period ($\sim 150$ fs). A much smaller phase shift is expected for the low-frequency damping mode because $\tau_r$ is a much smaller fraction of its oscillatory period. The bound on $\tau_r$ ($\ll 75$ fs) is somewhat shorter than (but not inconsistent with) that in previous studies, where the time scale for photodissociation was given as $\sim 50$ fs [J. Petrich, C. Poyart, J. L. Martin, Biochemistry 27, 4049 (1988)], with the heme undergoing a major fraction of its initial out-of-plane displacement within the first 30 to 50 fs of photolysis [J. Petrich et al., ibid. 30, 3075 (1991)].


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Simulations of Atmospheric Variability Induced by Sea Surface Temperatures and Implications for Global Warming

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An atmospheric general circulation model was forced with observed interannual changes in the global sea surface temperatures (SSTs) for the period 1982 to 1993. The simulated seasonal surface air temperature patterns over land areas closely resemble the observed. Over most of the globe, the patterns also resemble those associated with El Niño events and are also reproduced in simulations with weak warm tropical SSTs near the date line. An exception is northern Asia, where the mechanisms for the observed warming are unclear. The results suggest that enhanced air-sea interactions resulting from recent, more persistent warm oceanic conditions in the tropics contributed to the observed global warming trend during this period.

Dominant interannual changes in the SST in the tropical Pacific Ocean are related to the quasi-periodic evolution of El Niño phenomena. These changes have an appreciable impact on the tropical and mid-latitude atmospheric temperatures (1). Although the impact of tropical SSTs on the tropical atmosphere has long been well simulated in atmospheric general circulation models (AGCMs) (2, 3), the impact on the mid-latitude atmospheric flows is only beginning to be realized (4, 5). Recent advances in the AGCMs have reached a stage where the impact of tropical SSTs on the global atmospheric flows can now be simulated.

To assess the capability of the National Meteorological Center (NMC) climate AGCM for seasonal prediction, we carried out several extended-range integrations forced with observed SSTs. This AGCM has a spectral triangular truncation at horizontal wave number 40 ($T40$) and has 18 levels in the vertical direction. The grid resolution of $T40$ is about 3° in latitude and longitude. It

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pattern for integration (iv) (Fig. 1D) with weak warming at the date line also is quite similar to that in Fig. 1C and implies that a major ocean warming in the eastern Pacific is not required to produce an atmospheric response similar to one triggered by a major El Niño.

The IPCC report also indicates that the observed warming in the recent decade was confined to the winter and spring seasons. During the fall, a cooling was observed (9). A compositing of the observations (similar to that in Fig. 1C) shows the same to be true for the observed ENSO response. Similar results are obtained in integration (iii) (Fig. 2). The remote atmospheric response in mid-latitudes results from the teleconnection response to the tropical heating anomalies forced by the tropical SST anomalies (11), and this remote response is sensitive to the atmospheric mean state (12, 13). Thus, the mid-latitude impact of a fixed tropical ENSO SST anomaly of one sign depends on the season (Fig. 2).

Global surface air temperatures since 1981 have markedly changed with a strong seasonal and regional dependence (9). These changes are very similar to the observed response of an ENSO composite (Fig. 1, A and C). The AGCM results, both for the strong ENSOs and weak warming in the vicinity of the date line, also have a global response similar to the observed ENSO composite. Since 1981, three major El Niños, as well as a persistent warming near the date line from 1990 onward, have occurred. However, only one major and one smaller cold event took place during this period. Hence, events in the tropics during this period were biased toward the production of the spatial and seasonal pattern of continental air temperature anomalies that would resemble the response of the ENSO composite. If the tropical SST warm bias was a consequence of natural variability, then most of the observed warming trend during this period could be explained as the natural variability of the ocean-atmosphere system on the decadal or longer time scale (14). The regions where this does not appear to be the case are northern Asia and the region surrounding Greenland where the trends could not be explained in terms of an ENSO-related signal.

Fig. 1. (A) Geographical distribution of observed surface air temperature anomalies (in kelvin) for the period 1980 to 1993 relative to 1950 to 1980. (B) Surface air temperature anomalies for the AGCM forced with the observed SSTs of 1982 to 1993 relative to the climatological SST integration. (C) Surface temperature anomaly for ENSO composite relative to 1950 to 1980. The nine warm events are 1958, 1966, 1970, 1973, 1977, 1978, 1983, 1987, and 1992, and the nine cold events are 1950, 1951, 1955, 1956, 1971, 1974, 1976, 1985, and 1989. (D) Same as (B) but for AGCM integration with the mean of January, February, and March 1991 SSTs reduced uniformly in amplitude by a factor of 2 and superimposed on the climatological seasonal cycle. The anomalies are averages for December to March. The contour interval is 0.5 K.

Fig. 2. Seasonal dependence of the surface air temperatures anomalies (in kelvin) for AGCM integration with January 1992 SST anomaly superimposed on the climatological seasonal cycle. Anomalies are averages for (A) January and February and (B) October. The contour interval is 1.0 K.
alone. However, all of the model simulations, which used global SST anomalies, did produce these (Fig. 1, B and D). It is likely that the model responses in these regions are the result of extratropical anomalies. Results from a subsequent suite of numerical experiments performed to separate the effects of various tropical and extratropical SST anomalies also suggest this connection.

This investigation does not preclude the possibility that the observed warming of the tropical oceans is the end result of global warming itself. If so, our results imply that the spatial and temporal characteristics of the global warming trends are manifested as a bias in the frequency of occurrence of one of the modes of the natural variability of the ocean-atmosphere system, that is, ENSO. As a corollary, the AGCMs that do not simulate these modes of natural variability for the present climate may also misrepresent the spatial and temporal characteristics of predicted global warming.

REFERENCES AND NOTES

8. For the source of observed surface temperature data, see C. F. Ropelewski, J. E. Janowiak, M. S. Halpert, Mon. Weather Rev. 113, 1101 (1985).
10. The model error for the ENSO composite in the tropical eastern hemisphere can also be seen in the comparison of Fig. 1, A and B.
14. Conclusions similar to this have been obtained in an observational study by K. E. Trenberth and J. W. Hurrell (Clim. Dyn. 9, 325 (1994)).
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Causes of Decadal Climate Variability over the North Pacific and North America

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The cause of decadal climate variability over the North Pacific Ocean and North America is investigated by the analysis of data from a multidecadal integration with a state-of-the-art coupled ocean-atmosphere model and observations. About one-third of the low-frequency climate variability in the region of interest can be attributed to a cycle involving unstable air-sea interactions between the subtropical gyre circulation in the North Pacific and the Aleutian low-pressure system. The existence of this cycle provides a basis for long-range climate forecasting over the western United States at decadal time scales.

The origins of decadal climate variability over the North Pacific Ocean and North America, characterized by anomalous surface temperatures and surface pressures (1–4), are uncertain. A recent example of the impact of such decadal climate variability is the multiyear drought over the southwestern United States. It has been speculated by some researchers that unstable air-sea interactions over the North Pacific and changes in the large-scale ocean circulation might force the decadal climate variability (5, 6), while other studies suggest that tropical forcing is a stronger influence (2, 4, 7). In this report, we develop a consistent physical picture of how decadal climate variability over the North Pacific and North America may be generated.

To study the decadal climate variability, we used a state-of-the-art coupled model of global ocean-atmosphere general circulation (ECHO) (8), which was forced by seasonally varying insolation and integrating for 70 years. The coupled model simulates well the mean climate and observed short-term interannual variability. In particular, it simulates realistically the El Niño–Southern Oscillation (ENSO) phenomenon. An earlier version of this model was also applied successfully to predict the behavior of ENSO (9). The coupled model simulates pronounced decadal variability over the North Pacific and North America during the course of the 70-year integration. One example (Fig. 1A) of such variability is the anomalous sea surface temperature (SST) in the western Pacific in the region of the Kuroshio extension. Simulated SSTs in this region exhibit a distinct irregular oscillatory behavior on a decadal time scale with maximum anomalies of slightly less than 1°C. There are three manifestations of the decadal mode.

To determine the spatial coherence of the decadal-scale SST variability, we computed the associated SST regression pattern (Fig. 1B). It is dominated by a large-scale positive SST anomaly centered near 35°N and extending from the Asian coast almost across the entire Pacific. The orientation of this positive anomaly coincides approximately with the position of the model Kuroshio current and its eastward extension. The positive SST anomaly is surrounded by negative anomalies, most prominently in the south. The space-time structure of the SST anomalies can be represented as a combination of a standing wave pattern and a propagating pattern, with the latter component dominating in the region of the Kuroshio and its extension. The spatial structure of the SST anomalies affects the meridional temperature gradient in the Pacific, which has important consequences for

![Fig. 1](image)

Fig. 1. (A) Time series of the coupled model’s anomalous SST (°C) averaged over the region from 150°E to 180°E and 25°N to 35°N. The time series was smoothed with a 9-months running mean filter. (B) Spatial distribution of linear regression coefficients between the index time series shown in (A) and SST values. The pattern was scaled so that the maximum SST anomalies were to 1°C.