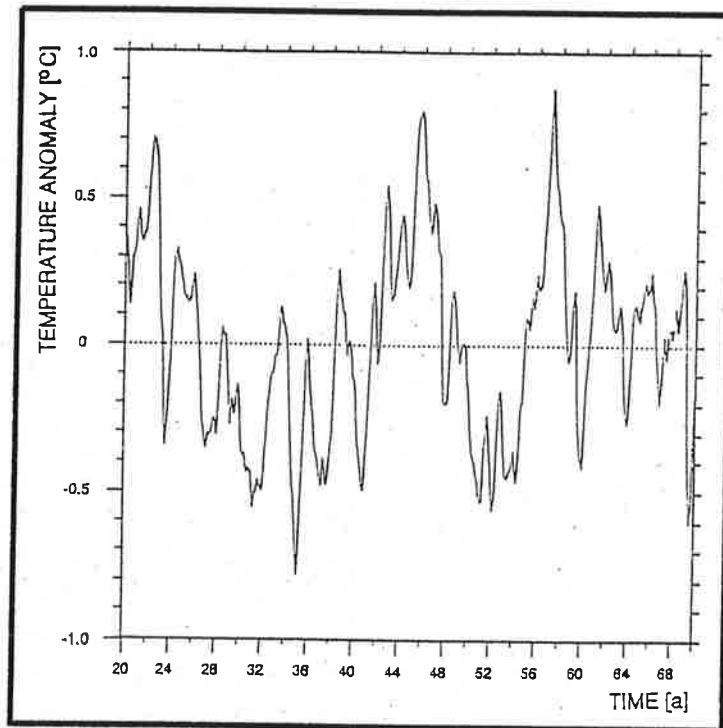




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CAUSES OF DECADEAL CLIMATE VARIABILITY OVER THE NORTH PACIFIC AND NORTH AMERICA

by

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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 and North America is investigated by analyzing data from a multi-decadal 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 and North America are uncertain. A recent example of the impact of such decadal climate variability is the multi-year drought over the southwestern United States. The decadal climate variability is characterized by anomalous surface temperatures and surface pressures over the North Pacific and North America (1-4). It has been speculated by some authors 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 more important (2, 4, 7). In this paper, 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 global coupled ocean-atmosphere general circulation model (ECHO, 8) which was forced by seasonally varying insolation and integrated 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 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 realizations of the decadal mode.

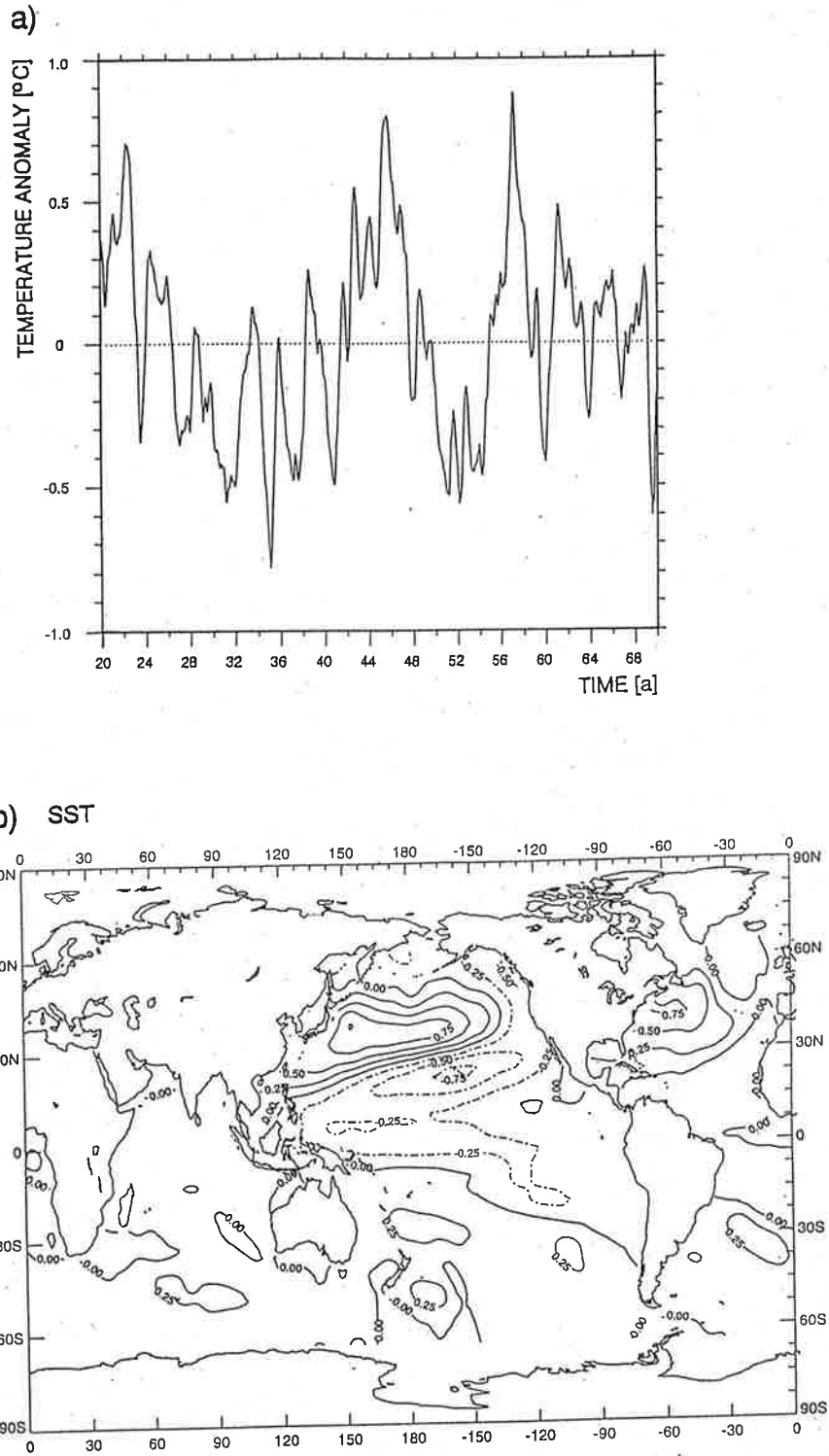


Fig. 1: (a) Time series of the coupled model's anomalous SST ($^{\circ}\text{C}$) averaged over the region 150°E - 180° and 25°N - 35°N . The time series was smoothed with a nine months running mean filter. (b) Spatial distribution of linear regression coefficients between the index time series shown in (a) and SST. The pattern was scaled such that the maximum SST anomalies were to 1°C .

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 across almost 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 to 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 (not shown). The spatial structure of the SST anomalies affects the meridional temperature gradient in the Pacific, and this has important consequences for the atmospheric circulation, as discussed below.

To elucidate the mechanism producing the SST pattern, we investigated the characteristic evolution of upper ocean heat content anomalies, as defined by the vertically averaged temperatures over the upper 500 meters of the water column via a complex empirical orthogonal function (CEOF) analysis (10). Before the CEOF analysis, the heat content data were smoothed with a low-pass filter that retained variability at time scales longer than 3 years. The leading CEOF mode, accounting for about one third of the variance in the filtered heat content data, has a period of about 20 years. Anomalies in upper ocean heat content reconstructed from this leading CEOF mode (Fig. 2) are displayed at intervals of about two and a half years. When the SST anomalies are fully developed and in a stage corresponding to that shown in Figure 1b ($\Theta=0$) the main heat content anomaly is positive and covers the majority of the western and central Pacific. A negative anomaly extends

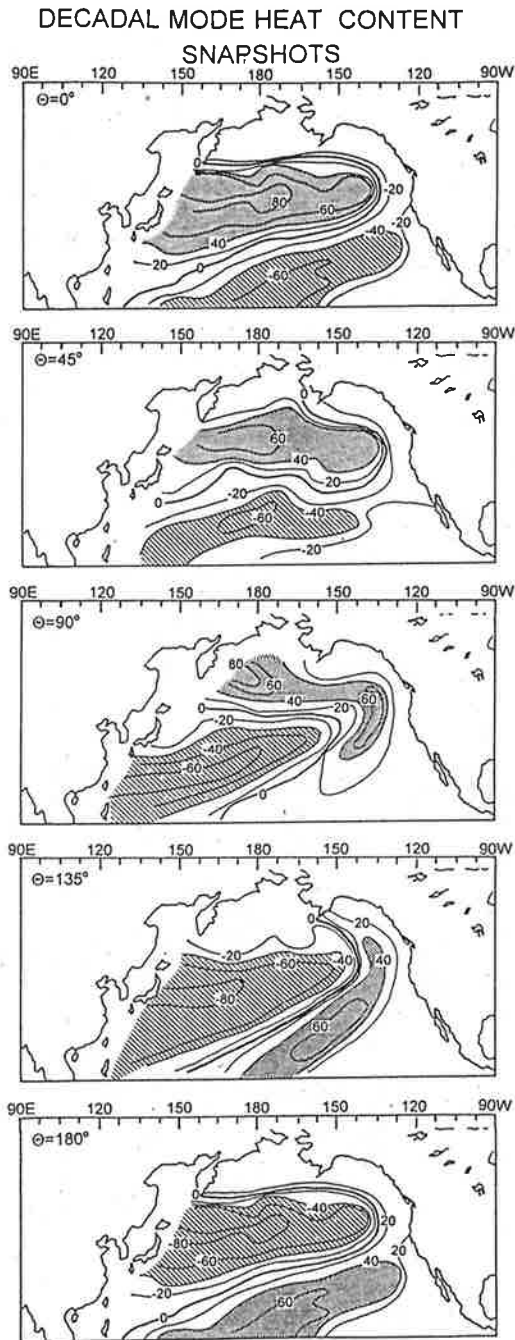


Fig. 2: Reconstruction of anomalous heat content ($^\circ\text{Cm}$) from the leading CEOF mode. The individual panels show the heat content anomalies at different stages of the decadal cycle, approximately 2.5 years apart from each other.

southwesterly from North America and increases in area and strength as it approaches the tropics. With time, through one-half of a cycle, the large anomalies rotate around the Pacific in a clockwise fashion reminiscent of the general gyral circulation. Thereafter, the whole sequence of events is repeated, but with reversed signs, and that completes one full cycle.

This evolution is characteristic of the transient response of a midlatitude ocean to a variable wind stress, as described in many theoretical and modeling papers (for example, 11-13). The response is mostly baroclinic at climate time scales longer than several months and involves the propagation of long, relatively fast planetary waves with westward group velocity and their reflection into short, relatively slow planetary waves with eastward group velocity. However, the mean horizontal currents will affect the wave propagation. The net effect of this wave propagation is to modify the strength of the subtropical gyre circulation (13). In particular, resultant fluctuations in poleward transport of warm tropical waters by the western boundary current lead to the generation of SST anomalies along the path of the Kuroshio and its extension. The spin-up time of the subtropical gyre, of which the changes in the western boundary current are a part, is several years to a decade or more, which accounts for the decadal time scale of the mode under discussion.

The remaining task is to explain the oscillatory nature of this mode. Our hypothesis is that it arises from an instability of the coupled ocean-atmosphere system in the North Pacific. The characteristic SST anomaly pattern exhibits a strong meridional gradient which either reduces or enhances the meridional SST gradient normally found in the central Pacific.

Suppose the coupled system is in its reduced meridional SST gradient state shown in Fig. 1b. It has been suggested (14) that such a distribution of SST would result in a northward shift of the baroclinic eddy activity in the atmosphere, leading to a weakened Aleutian Low, and subsequently reduced westerly winds over the midlatitudes ocean. Indeed, the model results show that a reduced meridional SST gradient goes along with anomalous high pressure over the entire North Pacific (not shown).

To further investigate the nature of the atmospheric response to the anomalous SST pattern, we forced the atmospheric component of our coupled model in a stand-alone integration by the SST pattern shown in Fig. 1b. The integration was done in a perpetual January mode and an ensemble of 12 January integrations was performed. The atmospheric response is highly significant and shows the expected result: anomalous high pressure over the North Pacific (Fig. 3a, 15). The response pattern is the weak-Aleutian Low-extreme of the 'Pacific North American' (PNA) mode, which is one of the most prominent eigenmodes of the atmospheric circulation and also excited during extremes of the ENSO cycle (16). Note, however, that the response shown in Fig. 3 arose from an atmospheric model simulation in which tropical SSTs were near their climatological norms, that is the tropics played a minor role in the result. This was confirmed by an additional integration in which SST anomalies south of 25°N were entirely neglected.

The associated changes in the net surface heat flux (Fig. 3b) are such that they tend to reinforce the SST anomalies over most of the North Pacific. Heat is anomalously pumped into the ocean in most of the region where it is already warm and vice versa (compare Fig. 1b with Fig. 3b). Changes in the

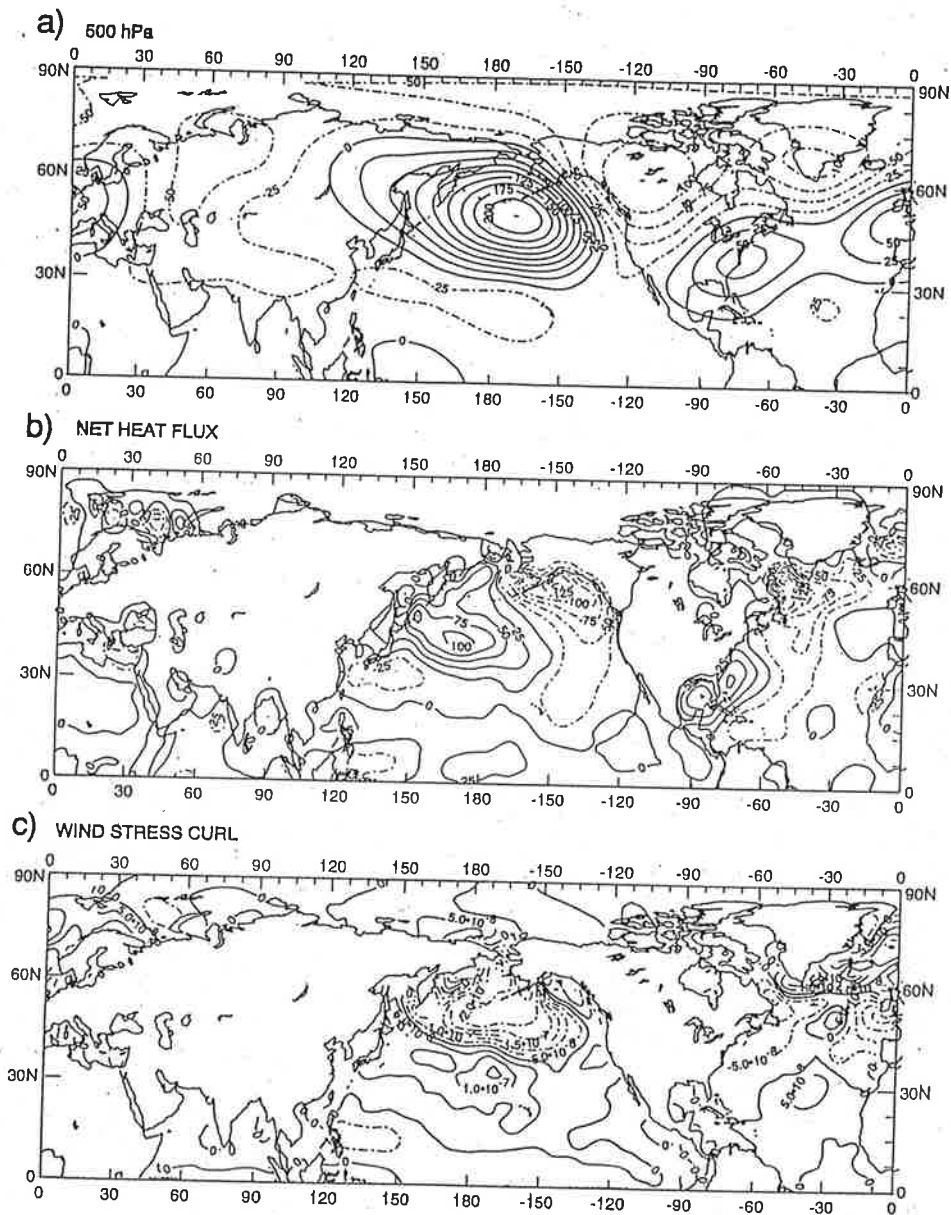


Fig. 3: Atmospheric response to the SST anomaly shown in Fig. 1b. The upper panel shows the response in the 500 hPa field (gpm), the middle panel shows that of the net surface heat flux (W/m^2), while the lower panel shows that of the wind stress curl (Pa/m). The mean fields shown in the panels were obtained by averaging the results of a 12 member ensemble of 30-day perpetual January integrations using the same SST forcing.

latent and sensible heat flux contribute most to the net surface heat flux anomaly. Furthermore, because the westerlies are weakened over the warm SST anomaly, the mean wind speed is reduced, leading to reduced mixing in the ocean, which tends also to strengthen the initial SST anomaly (3). Thus, ocean and atmosphere form a positive feedback system capable of amplifying an initial disturbance, giving rise to instability of the coupled system. The growth is eventually equilibrated by nonlinear processes and the phase switching mechanism described below.

The changes in the wind stress curl (Fig. 3c) force characteristic changes in the ocean, eventually reducing the strength of the gyre circulation and enhancing meridional SST gradients. The ocean has a memory to past changes in the wind stress and is not in equilibrium with the atmosphere. It is this transient response of the ocean to imposed wind stress, expressed in terms of planetary wave propagation illustrated in Fig. 2, that provides a switch to change from one phase of the decadal mode to another and, hence, enables the coupled system to oscillate. The oscillation can become easily irregular in the presence of high frequency weather fluctuations. Elements of these ideas were put forward over 20 years ago (5, 6).

The model results are observable in the real world. For instance, SST patterns and their associated atmospheric patterns from observations (1, 2, 4) are close to those from our simulation. Further, projecting the last 45 years of observed SST fields onto the leading EOF of the anomalous SST field from the model yielded a principal component whose amplitude and characteristic time scale closely resembles the model principal component (not shown). More critical, the relation between atmospheric response and

ocean transport indices were the same in both the model and observations (17): Gyre strength and atmospheric pressure vary in phase on decadal time scales (Fig. 4).

Interestingly, North Atlantic SST variability exhibits pronounced energy at time scales of about ten years (18). This is consistent with our scenario, because the zonal width of the North Atlantic is only about half that of the North Pacific. Moreover, the spatial patterns of the decadal variability observed in the North Atlantic region agree with those we found in the North Pacific region: Anomalously warm SSTs go along with anomalously high pressure and vice versa, and the associated changes in the surface heat flux and oceanic mixing tend to reinforce the SST anomalies (18).

Both model and observations show a strong, simultaneous wintertime relation between low-pass filtered anomalies of atmospheric pressure in the heart of the main atmospheric response region south of the Aleutians (Fig. 3) and air temperature over North America (Fig. 5, 1, 4, 19). The remarkable skill of the model in reproducing the dipole correlation over North America suggests that it can be used to numerically forecasting decadal climate change over North America (20). At a minimum, knowledge of the present phase of the Pacific mode obtained from current observational programs would allow a 'nowcast' (21) of expected climate 'bias' associated with this decadal climate change, which is equivalent to a climate forecast several years ahead.

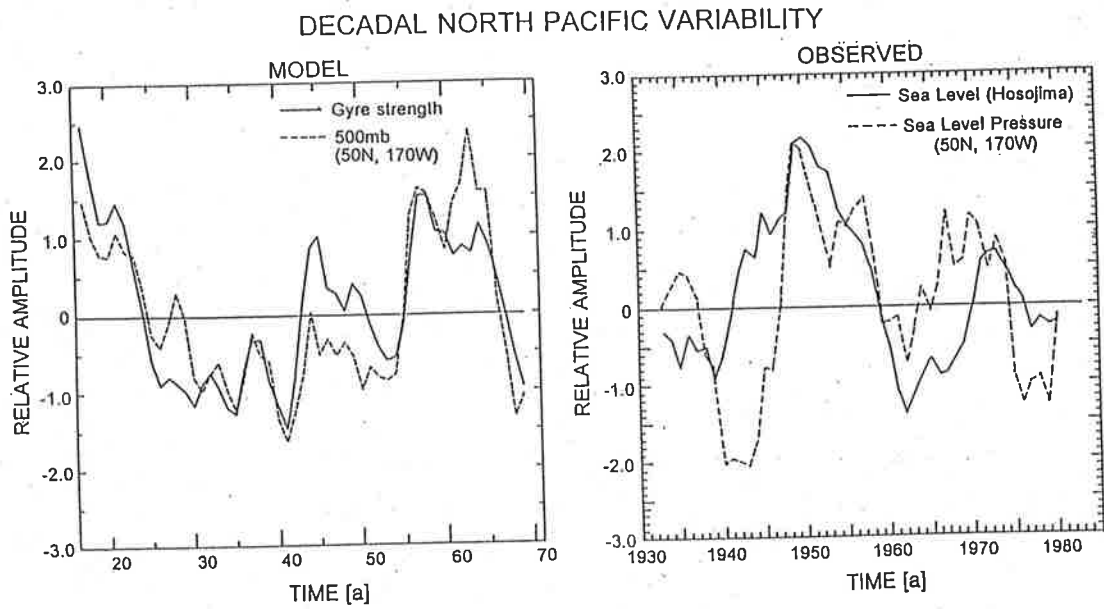


Fig. 4: Comparison of 500 hPa height anomaly near the Aleutian Islands and transport of subtropical gyre (17) from the coupled model between years 18-68 (left) and observed sea level pressure near the Aleutians and sea level at Hosojima, Kyusu, the latter being a surrogate of subtropical gyre strength, between 1935-1990 (right). All data were smoothed with a 3 year running mean filter and are shown in relative units.

**CORRELATION:
ALEUTIAN ATMOSPHERIC PRESSURE
vs.
WINTER SURFACE AIR TEMPERATURE**

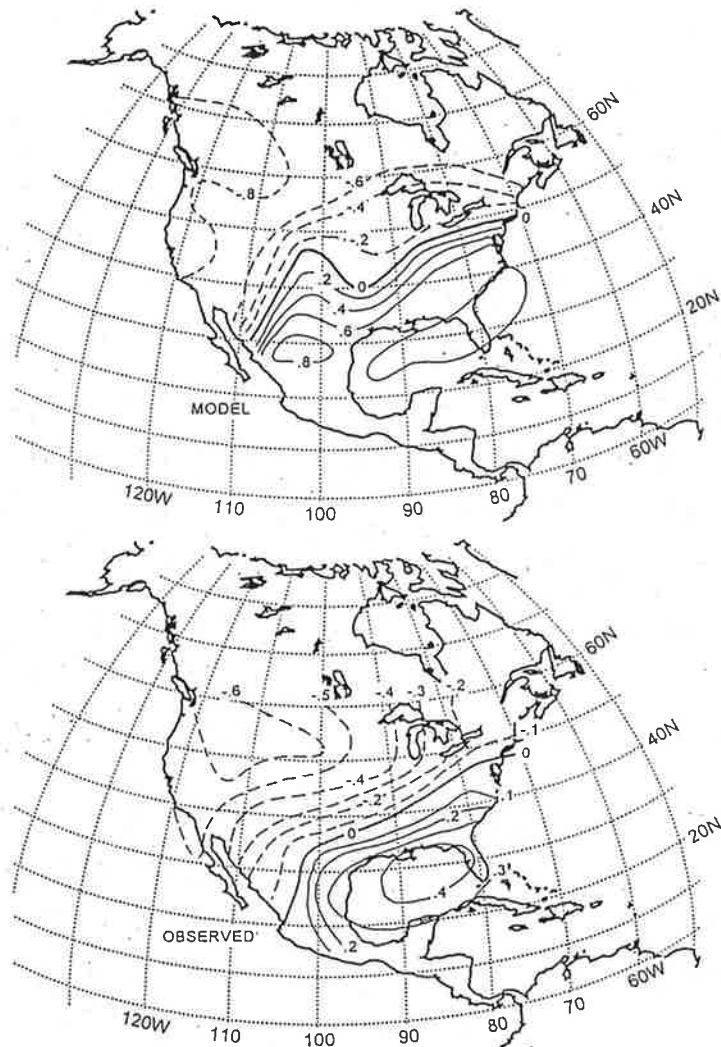


Fig. 5: Correlation between (upper) coupled model 500 hPa height anomaly near the Aleutians and model 2m air temperature over North America in winter over years 18-68 and (lower) a similar correlation from sea level pressure and surface temperature observations over the period 1935-90 (adapted from (4)). The data were smoothed with a 3 year running mean filter before calculation. Note the different contour intervals on the two panels.

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15. Typical decadal-scale 500 hPa height anomalies over the North Pacific simulated by the coupled model are of the order of about 10 gpm.
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20. The long (decadal) range forecasts would require that the ocean component of the coupled model be initialized with (at least) the observed thermal structure of upper 500m of the Pacific over a region extending from the Aleutians to 20°N and from Asia to North America. Existing expendable bathythermograph and buoy programs are currently close to being able to provide the required information.

21. This phrase was coined by J. J. O'Brien (Florida State University).

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