ENSO and ENSO-Related Predictability. Part II: Northern Hemisphere 700-mb Height Predictions Based on a Hybrid Coupled ENSO Model

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ABSTRACT

Long-range sea surface temperature forecasts from two different coupled ocean–atmosphere models of the tropical Pacific are used in conjunction with statistical models relating winter Northern Hemisphere 700-mb height and tropical SST to forecast the former field at a lead time of two seasons in advance. The forecasts show considerable skill over large areas, with a regional distribution of predictive performance that is consistent with the observed contemporaneous relation between the two fields. Comparable skills for lead time of a year or more in advance seem likely.

1. Introduction

The results from Barnett et al. (1993, Part 1) demonstrated the ability of a hybrid ocean–atmosphere model (HCM) of the tropical Pacific to forecast sea surface temperature (SST) at lead times of a year or more for large ENSO events. Similar levels of skill have been demonstrated earlier by another relatively simple coupled model described by Zebiak and Cane (1987; cf. Graham et al. 1992). It is natural to wonder if these forecasts for the Tropics can be parlayed into forecasts for midlatitude regions. The goal of this paper is to show that the tropical SST forecasts can, indeed, be used to produce successful forecasts for conditions over a significant fraction of the Northern Hemisphere (NH) during the winter season.

There are ample reasons to suspect that a good prediction of winter SST in the tropical Pacific can be used to project something about same-season pressure field over the NH. First, there is a good simultaneous relation between the two variables (e.g., Horel and Wallace 1981; Livezey and Mo 1987), and statistical models show that tropical Pacific SST anomalies explain at least 20%–30% of the variability in winter 700-mb heights over parts of the NH (Graham 1990). Second, a variety of statistical models have shown that tropical SST can be used to forecast aspects of variability in the winter circulation over the NH. For example, Barnett and Preisendorfer (1987; cf. Barnett 1981; Preisendorfer 1988; Livezey and Mo 1987) demonstrate useful skill at forecasting North American winter air temperatures at lead times of at least one season. Graham (1990) showed that statistical models using tropical Pacific SSTs from boreal summer and autumn could be used to forecast 700-mb height anomalies during the following winter over the North Pacific with considerable skill, and with generally more modest skill over portions of North America, Asia, and the Atlantic. Third, large-scale atmospheric general circulation models (AGCMs) show a reasonable ability to reproduce major Northern Hemisphere circulation patterns given only information about the wintertime tropical Pacific SST patterns (e.g., Blackmon et al., 1983; Shukla and Wallace 1983; Lau 1985; Lau and Nath 1994; Graham et al., 1994). It is against this encouraging background that we undertook the current study.

In essence, in the work described here we attempt to parlay the demonstrated predictive skill of coupled models of the tropical Pacific into forecasts of the winter circulation over the NH at lead times of 6 months. First, to provide a reference with which to compare the later results, the ability of statistical models to specify winter NH 700-mb height anomalies on the basis of contemporaneous tropical Pacific SSTs is characterized. Next, the statistical model derived from the contemporaneous relationship between those observed fields is used to make predictions of winter 700-mb height on the basis of predicted tropical Pacific SSTs forecast 6 months in advance.

The remainder of the paper is organized as follows. Section 2 briefly describes the data and methods used, section 3 presents the results, and section 4 gives a summary and conclusions.

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2. Data and procedures

The SST data used for this study are a combination of the COADS (Barbour 1986) and NMC/CAC (Reynolds 1982) products. The data are monthly values covering the tropical Pacific between 16°N and 16°S over the period 1950–90. The 700-mb height data come from the National Meteorological Center and are available monthly from 1947 to the present for the region 20–80°N. These data are on a 5° × 5° diamond grid.

Statistical regression models relating the winter NH 700-mb and tropical Pacific SST fields were constructed using a variant of canonical correlation analysis (CCA). This technique is described in numerous references, and the reader interested in the approach is referred to Preisendorfer (1988), Graham et al. (1987a,b), and Barnett and Preisendorfer (1987). Useful comparisons with related methods (such as singular value decomposition) are given by Bretherton et al. (1992). For present purposes, we simply note that the method finds the optimal linear combination of the predictor (SST) data vector that will produce the highest correlation with the predictand (700mb) data vector. The true forecast skill of a CCA-derived regression model can be estimated using the cross-validation approach wherein one (or more) realization of the data is omitted from the analysis, a model estimated from the remainder of the data and then applied to "predict" the omitted data. When this is done sequentially over the entire dataset (and assuming independence between sequential realizations, a requirement met by the data used in the work described here), one can use the "predictions" so obtained to estimate the true skill of the statistical model [see Barnett and Preisendorfer (1987) and Graham et al. (1987a,b) for more details].

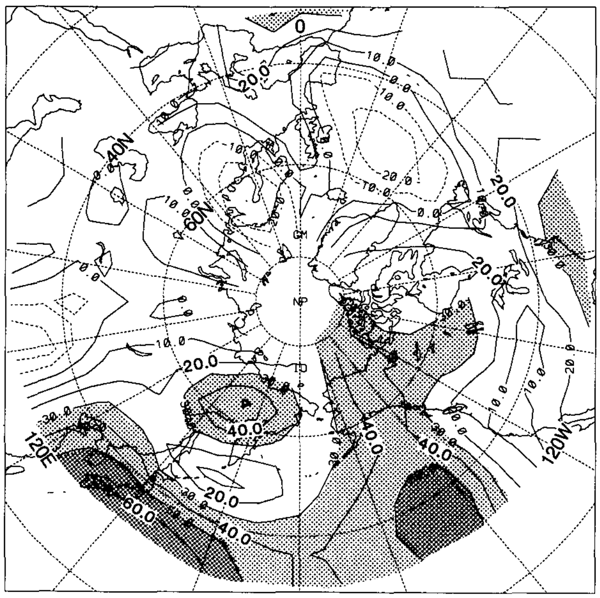

FIG. 1. Cross-validation correlations (×100) between observed winter 700-mb height anomalies and those specified by a statistical model on the basis of tropical Pacific SSTs for the period 1950–86. Light and heavy stippling denotes regions where correlations are in excess of 0.3 and 0.5, respectively; contour interval is 0.1.

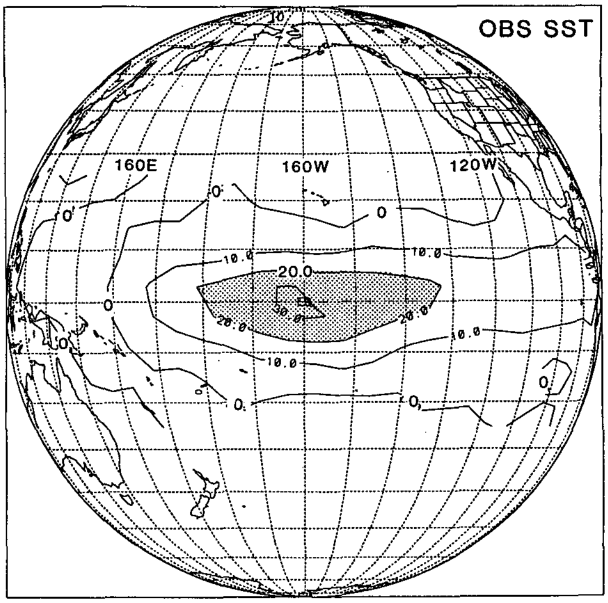

FIG. 2. Leading canonical spatial pattern relating boreal winter tropical Pacific SSTs to NH 700-mb heights; units are arbitrary, values greater than 20 are stippled.

3. Results

a. Specification skill: Winter tropical Pacific SST to NH 700-mb height

To estimate the level and spatial distribution of true skill for a regression model specifying NH 700-mb heights from contemporaneous tropical Pacific SSTs, CCA was applied to the 37-yr period 1950–86. Eight EOF modes were used to express both fields, but using fewer or more EOF modes gives similar results. The resulting cross-validation skills (expressed as correlations) are shown in Fig. 1 and indicate that there is substantial skill over much of the Pacific sector, with the maximum values over the east-central North Pacific and over eastern Siberia. Skills are also positive over most of the subtropics (including the southeastern United States), especially in the central and western Pacific. There is also some suggesting of modest skill over portions of western Canada and Alaska. Little skill is indicated over the North Atlantic, Europe, and most of Asia.

The spatial pattern of tropical Pacific SSTs that provides most of the regression model's predictive skill is shown in Fig. 2 (after Graham et al. 1994). From the perspective of variability in the NH winter circulation, the region of principal importance is seen to be the

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central equatorial Pacific. This distribution apparently reflects the fact that it is in this region where interannual variability in SSTs tends to cause total temperatures to cross the approximate 28°C threshold required for the maintenance of organized convection (Graham and Barnett 1987; Livezey and Mo 1987; Waliser et al. 1993). AGCMs have also been shown to have similar sensitivity to changes in SST (and diabatic heating) in the west-central equatorial Pacific (e.g., Geisler et al., 1985; Blackmon et al., 1983; Graham 1994). Fortunately, it is also the region where the hybrid coupled model (HCM) used to provide the forecast SST fields is most skillful (see Part 1, Figs. 8–13).

In summary, the statistical model shows some ability to specify major features of the midlatitude winter 700-mb field in the region from the east coast of Asia to the west coast of North America. Outside of this region the specification model shows little skill.

b. Forecast skill: Predicted SST to winter NH 700-mb height

1) Extreme event forecasts

This section repeats the procedures of section 2 but explores the use of SSTs forecast to occur during the winter, rather than the observed winter SST, to predict winter 700-mb height. As an initial investigation, we used the SST forecast by the HCM for three large cold events (1970–71, 1973–74, 1988–89) and three large warm events (1982–83, 1986–87, 1991–92), thus providing a total of six forecasts. The statistical model used to convert the SST forecasts to 700-mb height forecasts was constructed over the period 1970–88. The SST forecasts used were those from integrations of the HCM initialized at the end of May and validating in the following December, January, and February (i.e., lead times of 6–8 months). The predicted winter SST anomaly, calculated as the average of the predicted values for those months, was then processed through the statistical model to provide the associated forecast 700-mb height field.

The correlations between the six observed and forecast 700-mb height fields are shown in Fig. 3. The results show large regions of skill over the midlatitude Pacific and the subtropical regions of the Atlantic and Pacific Oceans. A secondary skill region located over the Great Lakes and eastern Canada reflects the wavelike response of the circulation to SST anomalies in the central equatorial Pacific. Other regions of apparent skill appear over Asia but we shall see that these are most likely spurious. Maximum correlations in the midlatitude Pacific exceed .80, as do those over Canada and the Tropics. These values are high, but it should be remembered that only six forecasts were evaluated and they were all associated with large events selected a posteriori. Because such a procedure produces a sample in which the signal-to-noise ratio has been considerably boosted, the correlations so obtained may be higher than would be achieved in an operational setting.

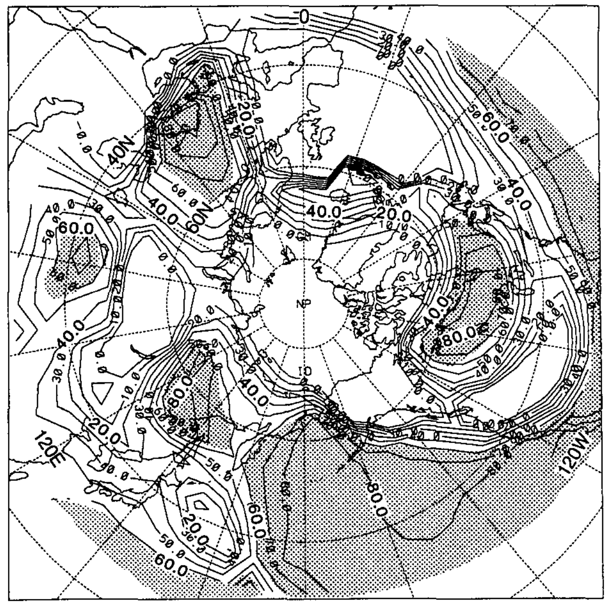

FIG. 3. Correlations (×100) between observed winter 700-mb heights and those predicted using the 6-month lead SST forecasts from the HCM; here for the six winters 1970–71, 1973–74, 1982–83, 1986–87, 1988–89, and 1991–92 using a statistical model based on observations for the period 1970–88. Contour interval is 0.1; only positive values are shown, stippling indicates regions where Monte Carlo tests indicate the correlations are significant at the 90% level.

2) Statistical significance and robustness of the results

To assess the statistical significance and robustness of the forecast skills implied by Fig. 3, we tested the results using three approaches, all of which give broadly consistent results. These tests, described below, included Monte Carlo trials, the development of an independent statistical model, and application of our forecast procedure using SST predictions from a different coupled model.

Monte Carlo simulations provide a means of estimating the probability of obtaining correlations above a given value from unrelated data. To obtain these estimates we applied a resampling procedure similar to that used by Graham et al. (1994) in which pointwise correlations between random permutations of the observed (1950–92) and forecast 700-mb height fields were calculated repeatedly (500 times), with the constraint that the observations and forecasts not be for the same winter. The resulting significance estimates, indicated in Fig. 3, show that correlations significant at the 0.10 level (corresponding to a value of about 0.6) cover most of the North Pacific and Western Hemisphere subtropics. Some features in Fig. 3 can be related to those seen in Fig. 1 such as the band of rel-

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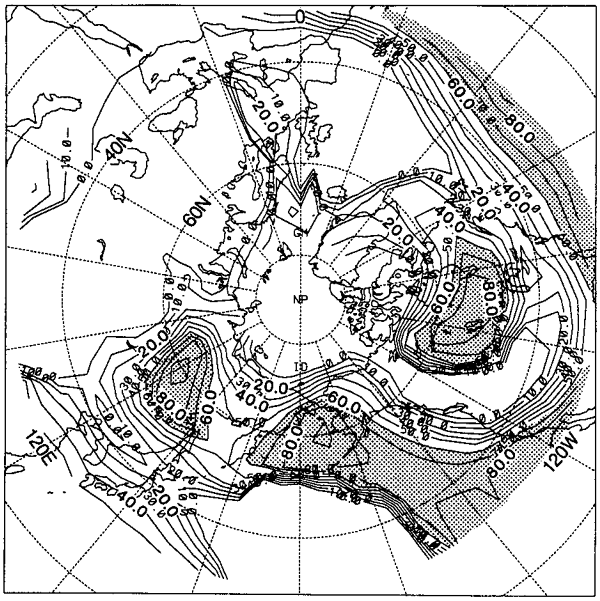

FIG. 4. As in Fig. 3 but using a statistical model based on observations for the period 1950–69.

atively high skill stretching across the North Pacific south of 40°N and the suggestion of some skill in the southeastern United States.

An alternative method of assessing the stability of the results shown in Fig. 3 is to construct a statistical model using data from a temporally independent period and then apply this model to make the 700-mb height forecasts. If the relationships responsible for the predictive skill are robust, then the resulting correlation patterns should be similar to those seen in Fig. 3. To make this test, a statistical model was constructed relating SST and 700 data over the period 1950–1969. This model was then used in the forecast operation as described above. Thus, the statistical model and the HCM are completely independent of each other. The patterns of correlations and significance levels calculated using this statistical model and the six SST forecasts used to construct Fig. 3 are shown in Fig. 4. The spatial distribution of skill from the two models shows a number of similarities and also a major difference. Among the major features reproduced by the independent model are the regions relatively high skill over the eastern Pacific, central Canada, eastern Siberia, and in the subtropical Atlantic and western Pacific. The major difference between Figs. 3 and 4 is the lack of skill over the central Pacific in the latter (1950–69 model). Why this is the case has not been investigated. One possibility is that changes in the relationships between tropical SSTs and the NH circulation are due to changes in the background climate state. In such a case the skills of ordinary statistical models would be transitory. Another possibility is that the character of the data has changed. For example, inspection of SST anomaly fields in the 1950s appears to show much less of the organized structure related to equatorial ocean dynamics than do the maps in the later part of the record. Changes of this type would also produce transitory performance in a statistical (or dynamical) model. Finally, it is possible that the differences between Figs. 3 and 4 are due simply to sampling variability.

A third way to test the robustness of the skill of this forecast technique is to use predicted SSTs from a different coupled model, in this case the "LAMONT" model described by Zebiak and Cane (1987). First, we used the SST forecasts for the same six winters described above and calculated correlations analogous to those in Fig. 3. The results for the LAMONT model, shown in Fig. 5, are similar in many respects to the corresponding distribution for the HCM (Fig. 3), although the LAMONT results tend to be somewhat higher in many areas. A notable exception is the lack of skill of the LAMONT model in the western subtropical Pacific. The poor performance in this region may reflect the fact that the LAMONT model tends to underestimate the amplitude of SST anomalies in the central equatorial Pacific (e.g., Miller et al. 1993).

As noted earlier, the use of three predicted cold events and three predicted warm events in the statistical approach used to this point effectively reduces the "noise" in the signal, thereby increasing model performance. Such procedures can also be applied in an operational setting when there are means of making an a priori assessment of the probability that a particular forecast is a good one [e.g., experience (S. Zebiak, personal communication) has shown that when the

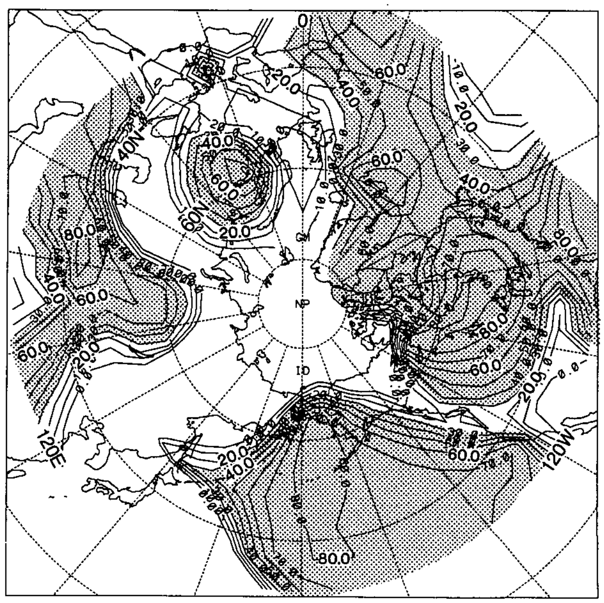

FIG. 5. As in Fig. 3 but using SSTs forecast by the Lamont model for the six extreme winters.

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forecasts for a particular season (but from different initial times) agree closely, the probability of a good forecast is increased. However, just what performance would be achieved using such an a priori approach is not clear, and it seems likely that the correlations seen in Figs. 3 and 5 are overestimates of the values that would be achieved in an operational setting.

An alternative approach to using a few selected episodes when assessing forecast skill is to use all of the years for which forecasts are available. As in the case for the cross-validated correlations shown in Fig. 1, it is implicit in this approach that no a priori judgment is made concerning whether or not a particular forecast likely is a good one. Though it seems unlikely that the forecast method would be applied operationally, correlations calculated using all years set the most conservative estimate of what sort of performance might be expected. We have conducted this analysis using the LAMONT model for predictions of the 23 winters 1969–70 through 1991–92. The correlations for the forecast 700-mb height forecasts are displayed in Fig. 6. As might be expected, the distribution of correlations is a much-muted version of that seen in the Figs. 3 and 5. For example, the maximum correlation in the northeast Pacific is approximately 0.60, down from 0.80 in the extreme event forecasts. The North American high skill region is shifted westward with a maximum correlation of 0.4, and the tropical Atlantic region now shows no significant skill. The correlations over the southeastern region of the United States are also considerably reduced (now near 0.3), but nevertheless are significant at the 0.10 level. An interesting point is that east of the date line the pattern in Fig. 6 agrees qualitatively with the cross-validated correlations for the contemporaneous observations (Fig. 1). The results of these tests suggest that the forecast technique is robust and can provide useful guidance as an adjoint to other much more complex techniques.

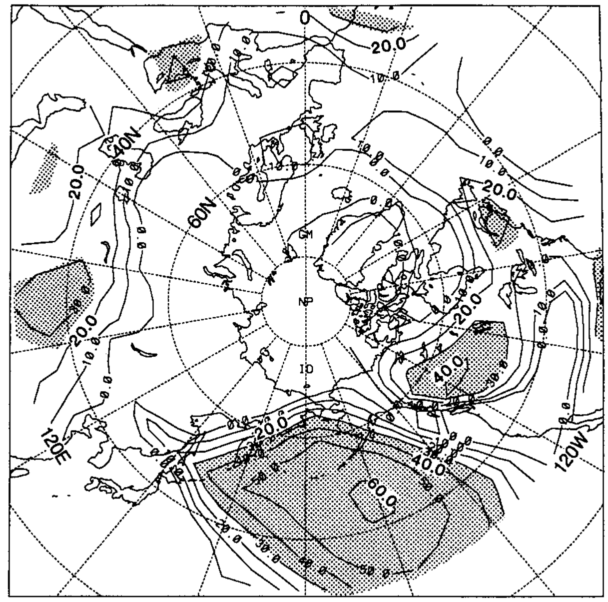

FIG. 6. As in Fig. 3 but using SSTs forecast by the Lamont model for the 23 winters 1970–92.

4. Conclusions

The contemporaneous connection between tropical Pacific SST variability and the boreal winter circulation over the Northern Hemisphere (particularly over the North Pacific and less so over North America) has been demonstrated repeatedly in analyses of observations and numerical model simulations (e.g., Horel and Wallace 1981; Graham 1990; Lau 1985; Graham et al. 1994; Fig. 1 in this paper). Though by no means one-to-one, the relation is the strongest tropical–extratropical teleconnection seen in present-day interannual climate variability. It has also been shown that relatively simple (in comparison with full-scale general circulation models) coupled models can predict tropical Pacific SSTs with considerable skill at lead times of 6–12 months (Cane and Zebiak 1985; Part 1, Graham et al. 1992).

We describe a forecast methodology that takes advantage of these two facts to allow predictions of winter Northern Hemisphere 700-mb height anomalies at lead times of 6 months. First, a statistical model for specifying Northern Hemisphere winter 700-mb heights using contemporaneous tropical Pacific SSTs was calculated. This model was then used to provide forecasts of winter 700-mb heights using forecasts of tropical Pacific SSTs from the hybrid coupled model described in Part 1 and the LAMONT coupled model (Zebiak and Cane 1987). When applied to six extreme ENSO episodes, the forecast 700-mb heights were highly correlated with observations over the North Pacific and portions of North America and eastern Asia, and over the Western Hemisphere subtropics, much as suggested by the analyses of the SST-circulation link referenced above.

Tests were conducted to estimate the statistical significance of the results and the robustness of the methodology. A separate statistical model of the contemporaneous relation between tropical SST and Northern Hemisphere 700-mb heights was calculated using the period 1950–69. When the forecast technique was applied using that model, the performance was essentially unchanged in the eastern Pacific, eastern Asia, North America, and the subtropical Atlantic. However, performance over the central Pacific equatorward of 45°N. (which was relatively good with the original statistical model) was poor. Other analyses showed that that although the forecast technique worked best for extreme warm and cold episodes (an expected result), substantial skill was also found when a block of 23 consecutive winter predictions from the LAMONT model were scored. Thus, depending on our ability to make an a priori assessment of whether a prediction of an extreme

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warm or cool episode is correct (skill in this regard has been clearly demonstrated), operational forecast performance levels are expected to be at least as good as in Fig. 6, and possibly as good as those than depicted in Figs. 3 and 5.

The methodology described here represents a new approach to long-range climate prediction that can provide practically useful forecasts of the winter Northern Hemisphere circulation. The predictive skill of this technique provides a useful reference with which to compare the performance of the much more sophisticated climate forecast systems currently under development.

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