LETTERS

Predicting Western North Pacific Ocean Climate

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30 April 2001 and 19 June 2001

ABSTRACT

It is shown that wintertime sea surface temperature anomalies in the confluence region of the Kuroshio–Oyashio Currents in the western North Pacific can be skillfully predicted at lead times of up to 3 yr. The predictions are based on the history of the wind stress over the North Pacific and oceanic Rossby wave dynamics. The predictions may be exploitable in fisheries research and other ecological applications.

1. Introduction

Predicting ocean–atmosphere climate variations has been a long-standing and elusive goal of climate scientists. Climate forecasts of the observed ocean–atmosphere system that exhibit useful skill at 3–15-month lead times for ENSO events (Latif et al. 1998) have been exploited in numerous applications. Climate variations in the midlatitude Pacific, however, such as those associated with regime shifts of the Pacific Ocean (Trenberth 1990; Miller et al. 1994; Hare and Mantua 2000), have not been demonstrated to be predictable.

A recent study of decadal variability in a full-physics coupled atmosphere–ocean model (Schneider et al. 2001, manuscript submitted to *J. Climate,* hereinafter SMP) suggests that a portion of the oceanic component of the North Pacific may be predictable several years in advance. The essence of the predictive skill is the excitation of baroclinic Rossby waves in the interior midlatitude Pacific Ocean by wind stress curl variations (see Venzke et al. 2000). The waves propagate toward the northwestern Asian coast and influence the currents and subsurface temperature of the Kuroshio–Oyashio Extension (KOE) region. During winter, deep vertical mixing and obduction (Qiu and Huang 1995) bring these temperature anomalies to the surface and generate KOE sea surface temperature (SST) anomalies.[1]

This oceanic predictability is of interest because the oceanic ecosystem in the KOE region is of vital importance in sustaining the productive oceanic fisheries industries of the northwest Pacific. The sensitivity of zooplankton and small pelagic fishes to changing ocean temperature and the reliance of phytoplankton on nutrients upwelled and mixed from the thermocline are well documented for the KOE region (Kawasaki and Omori 1995; Sugimoto and Tadokoro 1997). Predicting climate changes in the ocean and the consequent ecosystem response is a capstone of the Global Ocean Ecosystems Dynamics Program.

We establish here that the observed SST in the KOE region has a component that can be predicted years in advance as suggested by the coupled model simulation. We quantify the KOE SST forecast skill, compare it with less skillful predictors, and present experimental forecasts for the winter seasons of 2002, 2003, and 2004.

2. Data and forecast model

The forecast model is driven by North Pacific wind stress curl that we take from the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis from 1949 to May 2001.

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[1] The model atmosphere damps the SST anomalies and responds with a component of rainfall over the northeast Pacific Ocean that can be predicted from forecasts of KOE SST. We unfortunately cannot presently assess predictability of rainfall in nature because of inadequate observations and problematic analyses of rainfall.

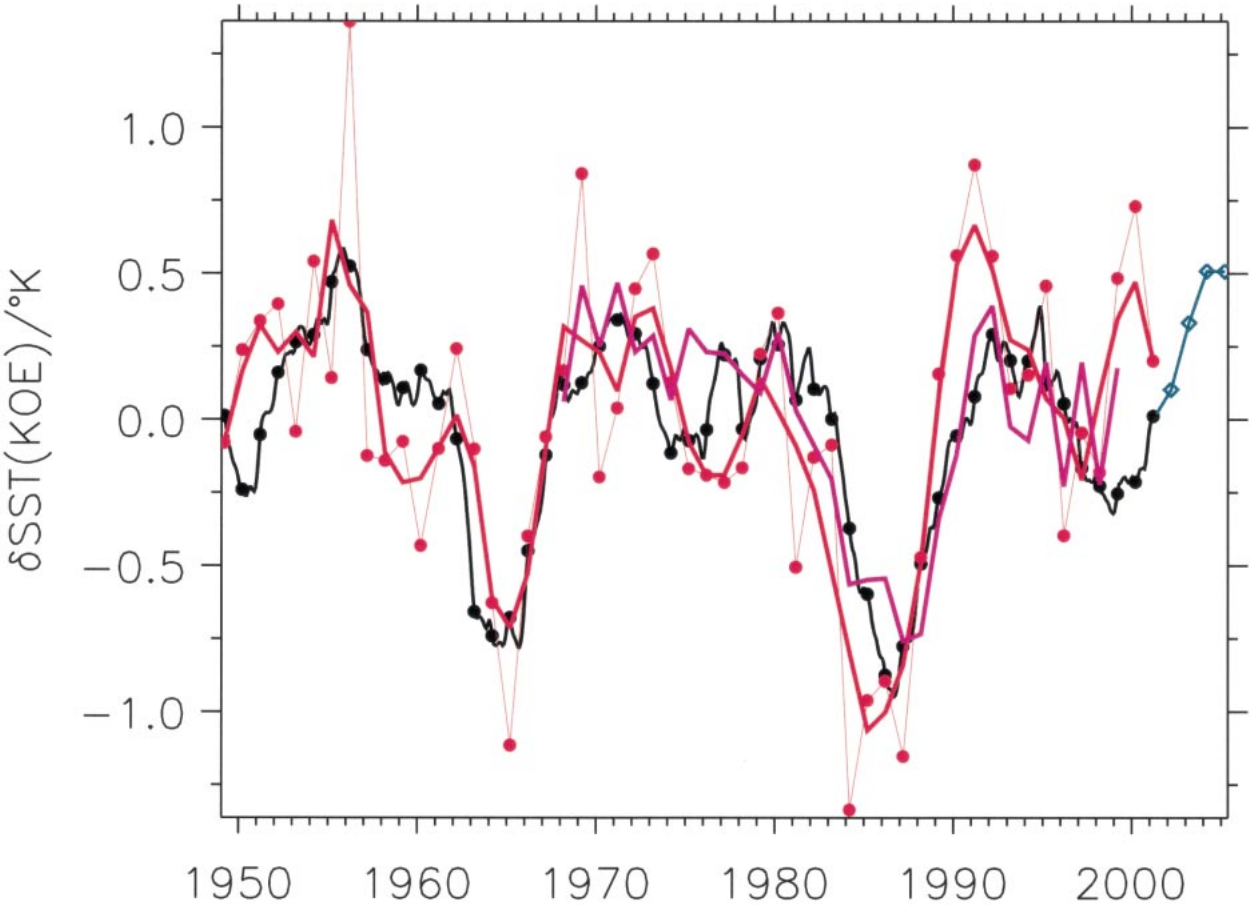

FIG. 1. Time series of FMA SST anomalies in the KOE along 40°N, 140°–170°E. Connected red dots are observations from the reanalysis; thick red line is the 3-yr average. Solid black line is the hindcast of SST anomalies from Eq. (1). Purple line is observed (White 1995) 100–400-m temperature, a proxy for thermocline depth. Blue diamonds are the forecast for FMA of 2002, 2003, 2004, and 2005 obtained from reanalysis winds up to May 2001.

SST is also taken from this source for skill verification. After removal of local, linear trends (-0.01 K yr^{-1} for KOE SST and typically -2.6×10^{-10} N m^{-3} yr^{-1} for wind stress curl between 35° and 40°N) monthly-mean anomalies are computed. Wintertime SST anomalies in the KOE region (40°N, 140°–170°E) exhibit distinct low-frequency variations (Fig. 1) that are strongly correlated with observed subsurface temperature anomalies (Deser et al. 1996, 1999; Miller et al. 1998), which are a proxy for oceanic pressure in the KOE region.

A linear, forced Rossby wave equation, motivated by physical process studies (SMP), is used as the forecast model:

$$\partial_t p - c_0 \partial_x p = F, \qquad (1)$$

where p is the oceanic pressure anomaly due to changes of the thermocline depth and F is Ekman pumping. Friction is not included given that these pressure perturbations are considered to be part of the inviscid interior flows. Wintertime KOE SST anomalies are linearly related to thermocline depth undulations (Fig. 1) via $\mathrm{SST}|_{\mathrm{KOE}} = \alpha p|_{\mathrm{KOE}}$, where α is a regression coefficient that relates the amplitude of SST and Ekman pumping anomalies. The speed c_0 was set to 2.5 cm s^{-1}, which closely corresponds to a best fit of this model to independent coupled model results.[2] The parameter α was estimated from observations of $\mathrm{SST}|_{\mathrm{KOE}}$ and hindcasts of $p|_{\mathrm{KOE}}$.

3. Hindcast skill

Hindcast skill is assessed by integrating Eq. (1) from 1949 to the present. The meridional domain covers the Pacific Ocean from 150°E to 125°W, averaged over 35°–40°N, with $p = 0$ on the eastern boundary. At speed c_0, Rossby waves traverse the entire basin in approximately 10 yr, which is the memory of wind forcing in Eq. (1). The hindcast pressure matches observed changes of thermocline depth very well (Fig. 1), confirming that Eq. (1) successfully describes low-

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[2] These speeds are faster than expected for first baroclinic Rossby waves but are consistent with thermocline observations (Miller et al. 1997) and theoretical considerations (Liu 1999).

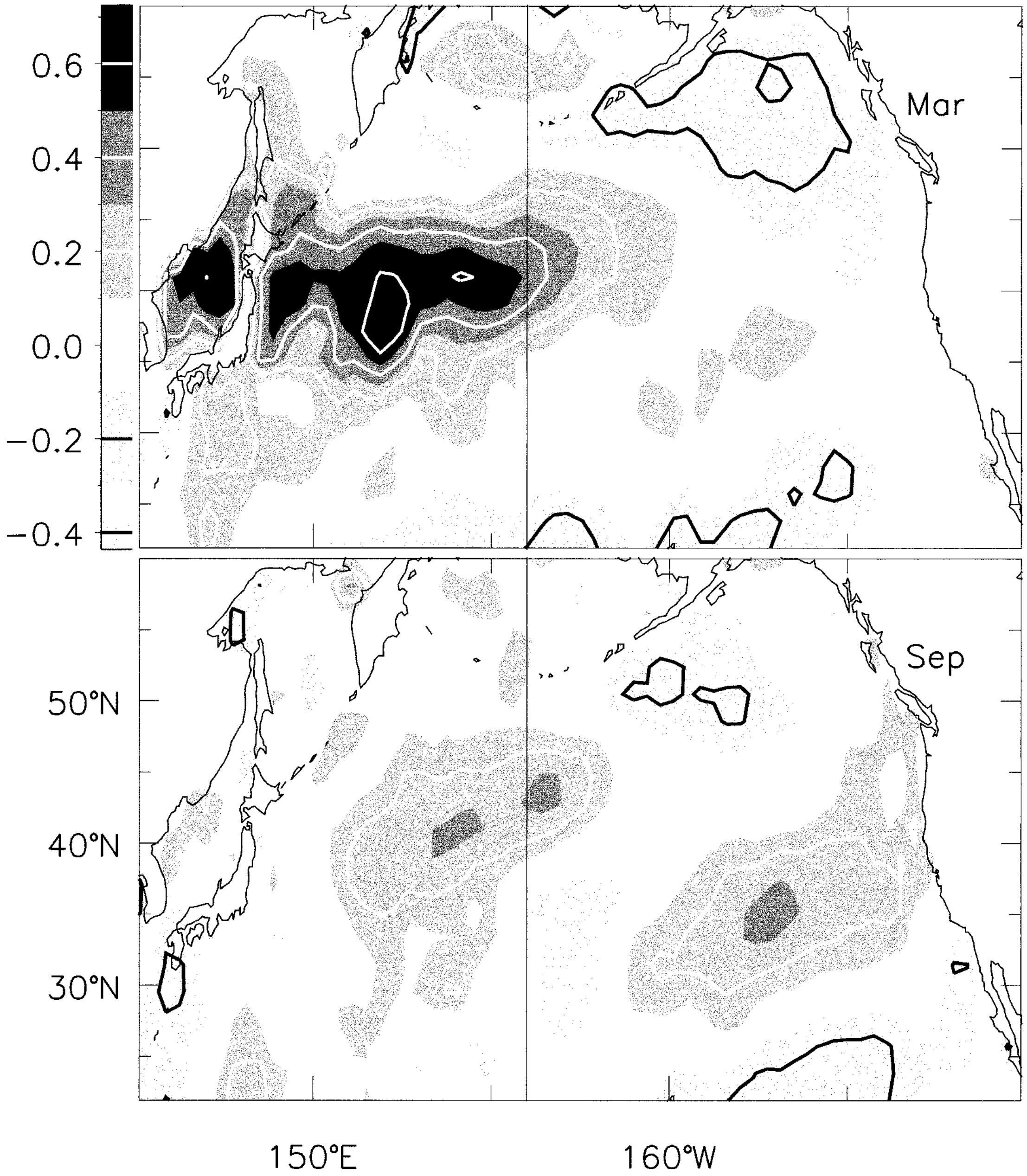

FIG. 2. Correlation of observed SST with hindcast oceanic pressure using Eq. (1) driven by 1948–2000 reanalysis wind stress curl. The correlation is for (top) Feb–Mar–Apr and (bottom) Aug–Sep–Oct averages.

frequency thermocline variability in the subarctic North Pacific as in the subtropical North Atlantic (Sturges and Hong 1995).

Significant correlations between simulated KOE pressure and observed SST occur only in the KOE region (Fig. 2). The correlation is largest in winter, for seasonal (3 month) averages centered on February and March. In contrast, no significant correlation is found in the summer (Fig. 2). This dramatic seasonal dependence reflects the effect of deep wintertime mixing that brings (predictable) anomalies of the thermocline to the surface layer. During summer, the seasonal thermocline decouples the surface waters from below.

The correlation of February–March–April (FMA) anomalies of hindcast pressure with observed KOE temperature anomalies is 0.62, increasing to 0.71 for 3-yr averages. This increase of skill for lower frequencies is consistent with the underlying physical hypothesis: anomalies of KOE SST result both from contemporaneous and unpredictable atmospheric air–sea fluxes of heat and momentum with a white frequency spectrum (Cayan 1992) and from predictable anomalies of the

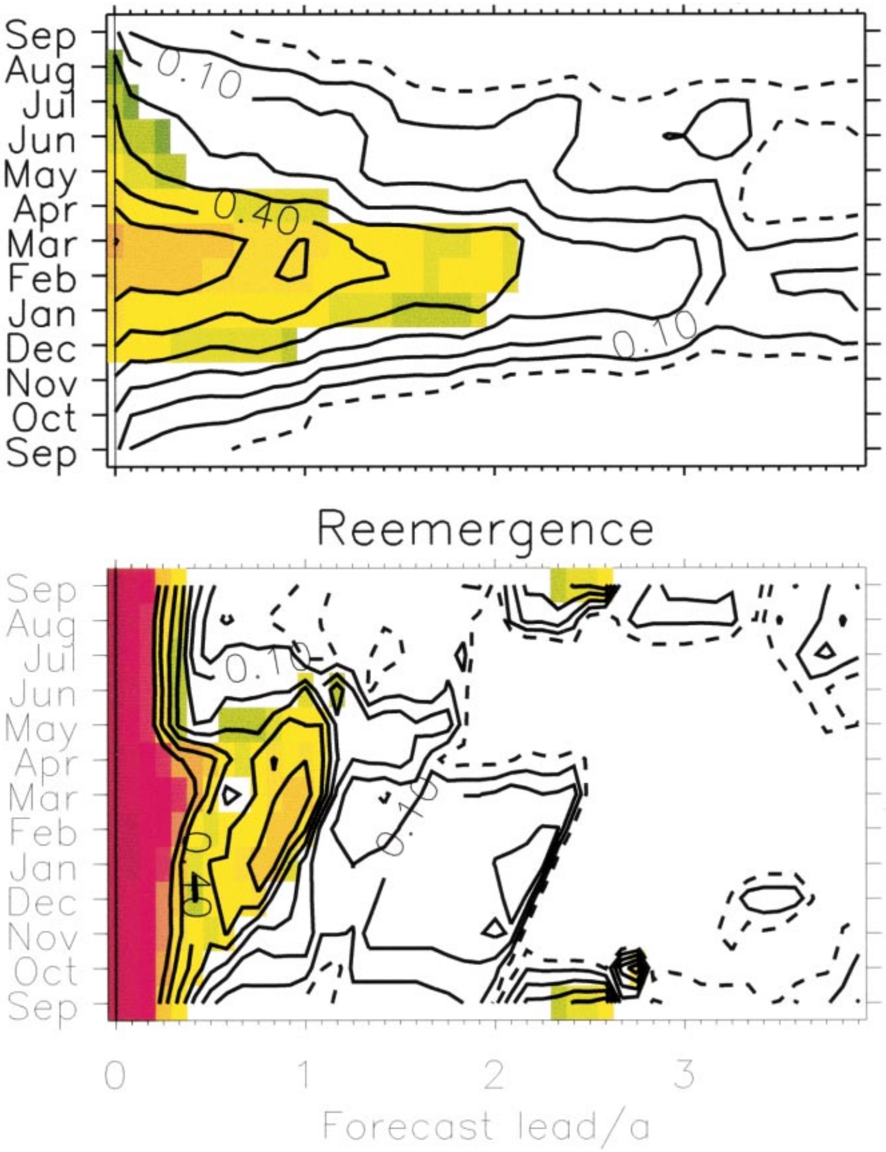

FIG. 3. Skill (correlation) of retrospective forecasts obtained (top) from Eq. (1) and (bottom) from the reemergence mechanism as a function of forecast lead in years, and of the center month of the 3-month forecast interval. Contour interval is 0.1, in the range −0.1 to 0.6, with negative contours dashed. Color indicates relative significance at the 10% level (see Table 1).

ocean thermocline with a red spectrum (Frankignoul et al. 1997). Low-frequency KOE SST anomalies are therefore more strongly affected by thermocline changes (Xie et al. 2000; Seager et al. 2001).

The Pacific decadal oscillation (PDO) index, defined as the leading EOF of monthly SST in the Pacific north of 20°N (Mantua et al. 1997), accounts for part of the winter KOE SST anomaly variance (correlation coefficient $r = -0.63$). However, the KOE SST anomaly hindcast is virtually independent of the PDO index ($r = -0.16$), even though the hindcast is correlated to observed SST ($r = 0.62$) at the same level as the PDO. This is because SST variance in the KOE region consists of (at least) two components: 1) the direct atmospheric forcing by variability associated with the PDO and 2) the primarily low-frequency oceanic forcing associated with the arrival of Rossby waves excited by the past PDO forcing as shown by a hindcast of Eq. (1) with PDO-correlated winds. In contrast, ENSO and the KOE SST anomalies hindcast are largely independent: correlation of the hindcast with the winter Niño-3.4 (5°S–5°N, 180°–140°W) SST index and with a hindcast of Eq. (1) with ENSO-correlated winds are both small.

Table 1. Skill scores for prediction of Jan–Feb–Mar KOE SST anomalies. Skill is measured by the correlation C of anomalies observed x_i and forecast z_i, and by the score $S = 1.0 - \Sigma_i(x_i - z_i)^2/\Sigma_i x_i^2$. A perfect forecast yields $S = 1$, guessing the climatological mean ($z_i = 0$) yields $S = 0$. Skills are shown for the Rossby wave model [RWM, Eq. (1)] and the reemergence mechanism (REM), for lags of 0–3 yr. Significance has been assessed as the 90% values of skill scores of a large number of red-noise time series with the same variance and spectral characteristics of the Rossby wave hindcast. The significance levels were estimated for calendar months separately to account for the different characteristics of winter and summer KOE temperatures.

	C		S	
	RWM	REM	RWM	REM
0 yr	0.55	1.0	0.32	1.0
1 yr	0.50	0.41	0.26	0.17
2 yr	0.39	0.19	0.14	0.03
3 yr	0.27	−0.16	0.05	−0.06
90%	0.29		−0.59	

4. Forecast skill

Forecast skill is evaluated retrospectively by integrating Eq. (1) using observed wind stress curl until the retrospective forecast is initiated. Thereafter, the anomalous wind stress curl is set to zero, and the forecasts are executed for up to 4-yr lead time. Observations during the forecast interval were withheld from the calculation of regression coefficients α that relate KOE SST and pressure anomalies. Retrospective forecasts starting at every month from January 1958 to May 2001 were compared with observed KOE SST anomalies. As expected, summertime anomalies are not predictable from this physics. However, cold-season KOE SST anomalies can be predicted up to 3 yr in advance (Fig. 3). The skill is significant for lead times up to 2 yr and is at the edge of significance at a lead of 3 yr (Table 1). These cross-validated forecasts account for 26%, 14%, and 5% of the KOE winter SST variance at 1-, 2-, and 3-yr leads, respectively. The cross-validated skill level at 1-yr lead is comparable to ENSO forecasting skill levels.

An alternative hypothesis for the year-to-year predictability of SST anomalies is the reemergence mechanism (Alexander et al. 1999). In this process, temperature anomalies of deep winter mixed layers result from anomalous atmospheric forcing and persist beneath the thin summer mixed layer. During the cold season of the following year(s), anomalies are reentrained into the mixed layer and imply a (damped) persistence of wintertime SST anomalies from one year to the next. Although the Rossby wave model similarly relies on the wintertime entrainment, it determines the subsurface temperature evolution from the arrival of Rossby waves.

The skill of reemergence was evaluated as an alternative forecast benchmark. Excluding data from the forecast interval, the best linear predictor for SST at each lead and calendar month was determined among the monthly values in the year preceding the forecast. Retrospective forecasts were obtained and were compared with observations. Reemergence forecasts have significant skill in predicting winter SST anomalies at a lead of up to a year but have no significance for longer leads (Fig. 3; Table 1).

The KOE SST forecast model [Eq. (1)] is therefore capable of predicting a significant fraction of the KOE SST anomaly variance above the skill levels associated with the best forecast contender (reemergence). The remaining fraction of KOE SST anomaly variance can likely be explained by contemporaneous forcing by the atmosphere (Cayan 1992).

5. Concluding remarks

We executed experimental forecasts of the KOE SST anomaly field for the winter seasons of 2002, 2003, and 2004 (Fig. 1) using Eq. (1) with observed winds through May of 2001. The forecasts show a trend to above-normal conditions. The associated oceanic high pressure signals were generated east of the date line during the previous three winters (1998/99, 1999/2000, 2000/01). Ocean ecosystem biologists and fisheries managers may be able to exploit these and future KOE SST predictions for anticipating changes in regional primary and secondary productivity and the direct influence of ocean temperature on small pelagic fish populations.

Although indications of PDO phase shifts have occurred (Schwing and Moore 2000; Minobe 2000), our forecasts cannot indicate the future fate of the PDO. Decadal-timescale SST variations in the North Pacific have two dominant patterns (Nakamura et al. 1997; Miller and Schneider 2000). One pattern with anomalies bearing opposing signs in the central and eastern North Pacific is in phase with the changing North Pacific atmospheric pressure system. The other SST pattern is in the KOE region and lags the central North Pacific SST (and forcing) by several years. It is the latter pattern that we predict, based on past atmospheric variability with a PDO-related component. The remaining fraction of KOE SST anomaly variance likely results from unpredictable atmospheric forcing or from ocean dynamics that have not been shown to be predictable.

Acknowledgments. The authors thank Drs. M. A. Alexander, B. D. Cornuelle, D. W. Pierce, and T. Barnett for helpful discussions. This paper is funded by the National Science Foundation (OCE97-11265 and OCE00-82543), the Department of Energy (DE-FG03-98ER62605), and the National Oceanic and Atmospheric Administration, U.S. Department of Commerce, under Grants NA77RJ0453 and NA47GP0188. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies.

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