Forecasts of tropical Pacific SST and sea level using a Markov model

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Abstract. A seasonally varying Markov model is constructed in a multivariate EOF space of observed SST and sea level analysis for 1981-98. The hindcast skill of SST and sea level is estimated with a cross-validation scheme. For SST, the correlation skill is highest in the central-eastern equatorial Pacific at about 0.5 at 9 month lead. The Markov model has a marginal SST forecast skill at 3 month lead (> 0.4) in the north-western Pacific (NWP) around 10^oN. For sea level, the correlation skill is highest in the central equatorial Pacific and the NWP around 10^oN at above 0.5 at 9 month lead. In the western Pacific, sea level anomalies are generally more predictable than SST anomalies. The real time forecast of sea level by the Markov model is available at the official web site of the Climate Prediction Center, NOAA (http://www.cpc.ncep.noaa.gov/pacdir).

Introduction

The forecasting of the El Nino-Southern Oscillation (ENSO) phenomenon has focused mainly on forecasting sea surface temperature (SST) anomalies in the central and eastern equatorial Pacific (see "Experimental Long Lead Forecast Bulletin" issued quarterly by the Center for Ocean-Land-Atmosphere Studies). Associated with the SST anomalies are substantial sea level anomalies within the tropical Pacific which have significant impacts on the socio-economic conditions on many Pacific islands, and inquires about sea-level forecasts have been received by the Climate Prediction Center (CPC), NOAA. The purpose of this study is to investigate the predictability of sea level and construct a statistical model for an operational forecast of sea level at CPC.

Above normal sea level in the western equatorial Pacific (WEP) has been suggested as being a precursor for ENSO [*Wyrtki*, 1985; *Zebiak*, 1989]. Recently, *Xue et al.* [2000] constructed a linear Markov model based on sea level, SST and wind stress data to forecast the tropical Pacific SST. They found that the forecast skill of the Markov model is largely attributable to sea level data. This study suggests that sea level contains the essential information for ENSO evolution. In this study, we constructed a linear Markov model based on SST and sea level data using the method of *Xue et al.* [2000]. We will show that the Markov model has a moderate forecast skill for both SST and sea level up to 9 month lead. The hindcast skill of SST and sea level for 1981-98 are discussed.

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Paper number 1999GL011107.
0094-8276/00/1999GL011107$05.00

Markov Model

The SST data are from the SST analysis by *Reynolds and Smith* [1994], and the sea level data are from the ocean analysis at the National Centers for Environmental Prediction (NCEP) [*Behringer et al.*, 1998]. All the data are monthly values averaged in grid boxes of 6 degrees in longitude and 2 degrees in latitude, and cover the tropical Pacific region within 19 degrees of the equator. The Markov model is built using three multivariate EOFs (MEOFs) of the anomalous fields of SST and sea level from 1981-98. In the MEOF calculation, the anomalous SST and sea level fields are first each normalized by the square root of the total variance in the study region, and then are combined to construct the covariance matrix. The Markov model contains 12 regression matrices, each of which describes evolution from month to month (refer to *Xue et al.* [2000] for details).

Hindcast Skill

The hindcast skill of the Markov model for 1981-98 is estimated using a cross-validation scheme [*Barnston and Ropelewski*, 1992]. In a cross-validation scenario, one year of data is removed, and a Markov model is trained upon the remaining years (17 years) and verified using the removed year. The one year window is moved forward month by month until the end of the time series is reached. So there are in total 216 multiple analyses with different 12-month periods removed.

Fig. 1 shows the correlation skill of SST anomalies in the tropical Pacific at different lead times. Note that 0 month lead refers to the initial conditions from which the Markov model starts, and the lead is the number of months from the initial times. It is seen in Fig. 1 that the correlation skill in the western equatorial Pacific (WEP) is around 0.4 at 0 month lead, and is less than 0.3 at 3 month lead, indicating that the Markov model has no usable skill in that region. It is interesting that the Markov model has a marginal SST forecast skill at 3 month lead (> 0.4) in the north-western Pacific (NWP) around 10^oN. For SST, the most predictable region is the central-eastern equatorial Pacific where the correlation skill at 9 month lead is above 0.5.

Fig. 2 shows the correlation skill of sea level anomalies. A comparison of Fig. 1a and 2a indicates that in the WEP sea level anomalies are much better described by the first three MEOFs than SST anomalies are. At 3 month lead, the correlation skill of sea level is high (> 0.7) in most of the tropical Pacific. At 6 month lead, the correlation skill is moderate (> 0.6) in the WEP, the central equatorial Pacific

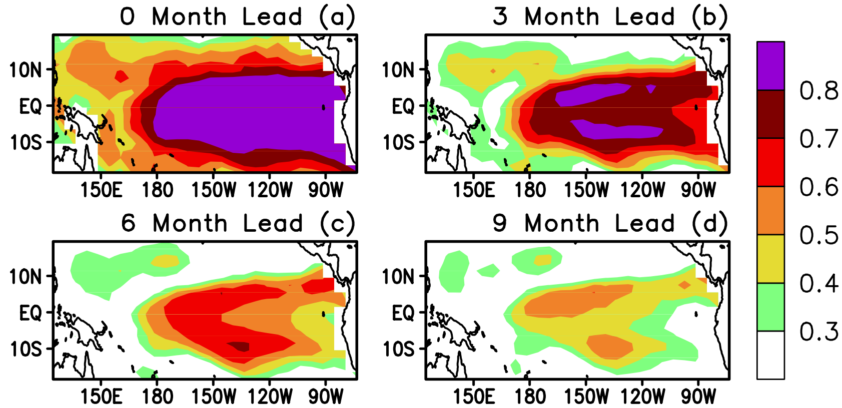

Figure 1. Correlation skill of SST anomalies for all the forecasts initiated from 1981 to 1997 at (a) 0, (b) 3, (c) 6 and (d) 9 month leads.

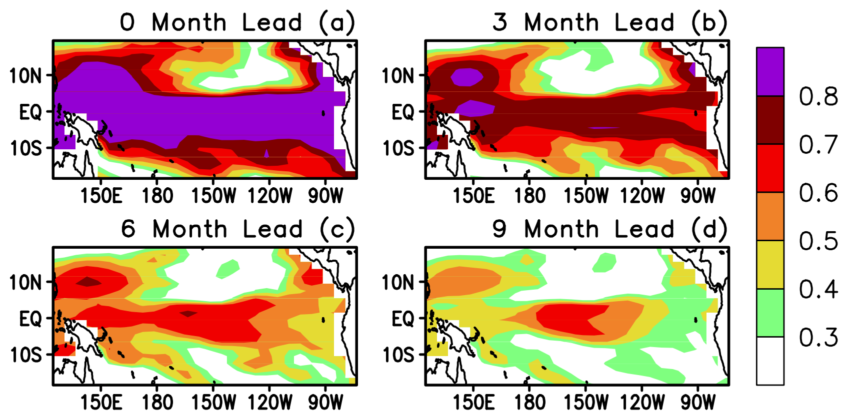

Figure 2. Same as Fig. 1 except for sea level anomalies.

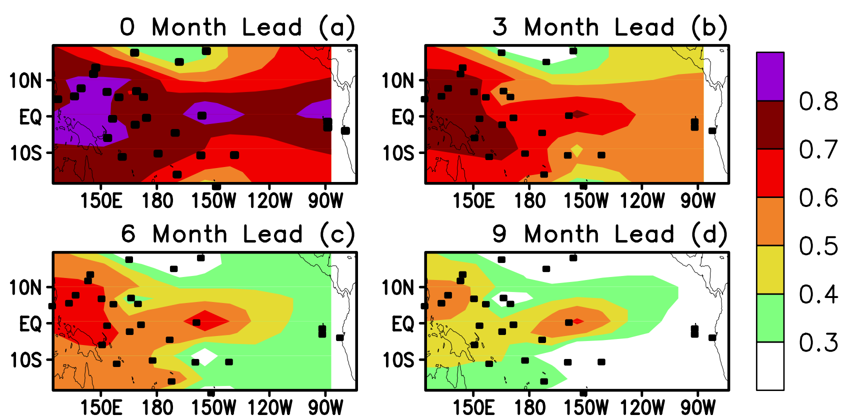

Figure 3. Correlation skill of sea level anomalies against 25 tide gauge observations for all the forecasts initiated from 1981 to 1997 at (a) 0, (b) 3, (c) 6 and (d) 9 month leads.

(CEP) and the NWP. At 9 month lead, the correlation skill is highest in the CEP and NWP at above 0.5. A comparison of Fig. 1 and 2 indicates that in the western Pacific in general sea level anomalies are more predictable than SST anomalies.

Tide Gauge Verification

The correlation skill shown in Fig. 2 is verified against the sea level analysis used to construct the Markov model. Since the sea level analysis contains model errors and data errors, it does not agree with tide gauge observations completely [*Behringer et al.*, 1998]. Tide gauge observations are not used in the sea level analysis, so they represent an independent data set. We reevaluated the skill of the Markov model against 25 tide gauge observations in the study region (Fig. 3). The tide gauge observations are obtained from the Sea Level Center at the University of Hawaii. In the calculation of the correlation skill, the missing values in tide gauge observations are simply ignored. It is seen that the correlation skill in Fig. 3 is generally lower than that in Fig. 2. This is understandable since the tide gauge observations are an independent data set which may contain variations not well simulated by the sea level analysis. However, Fig. 3 confirms that the most predictable regions for sea level are the CEP and NWP.

To better understand the correlation skill in Fig. 3, the time series of sea level at Christmas Island (157^oW, 2^oS) and Koror (135^oE, 7^oN) are shown in Figs. 4 and 5. It is seen in Fig. 4 that at 0 month lead the sea level anomalies at Christmas Island during the 1982-83, 1997-98 warm and 1988-89 cold events are underestimated. These errors are mostly from the sea level analysis rather than from MEOF truncations (not shown). The correlation skill at Christmas Island is moderate (0.6) up to 9 month lead. It is seen that most of the skill comes from the hindcasts of the 1984-85 and 1998-99 cold events. In contrast, the amplitudes of the 1982-83, 1997-98 warm and 1988-89 cold events are severely underestimated (Fig. 4d). For Koror in the Republic of Palau, the sea level anomalies at 0 month lead are hindcast well except that the very large amplitude of the 1988-89 cold event is severely underestimated (Fig. 5). As at Christmas Island, most of the correlation skill at Koror is due to the hindcasts of the 1984-85 and 1998-99 cold events. In addition, the hindcast of the 1991-92 warm event also contributes positively to the correlation skill (Fig. 5d).

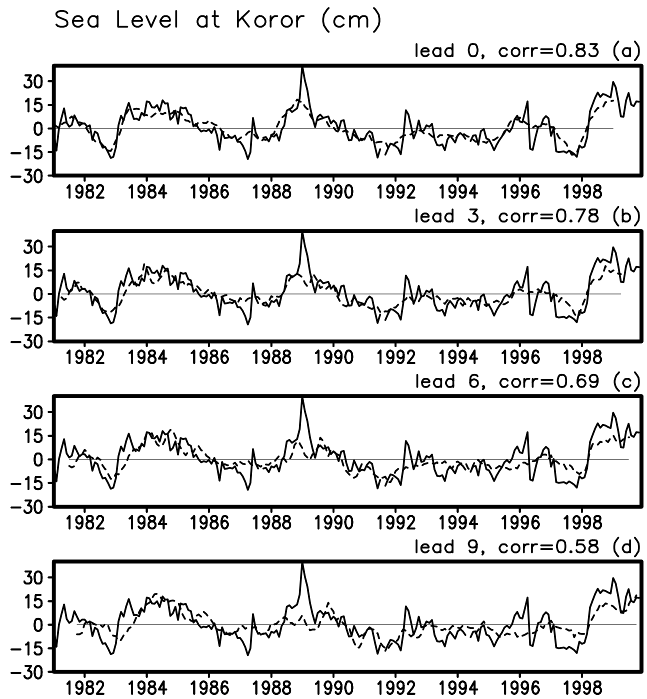

Figure 5. Same as Fig. 4 except for Koror.

Summary and Discussions

A seasonally varying Markov model is constructed in a multivariate EOF space of the SST and sea level analysis at NCEP for 1981-98. The hindcast skill of SST and sea level is estimated with a cross-validation scheme. For SST, the correlation skill is highest in the central-eastern equatorial Pacific at about 0.5 at 9 month lead (Fig. 1). The Markov model has no usable SST forecast skill in the WEP, but has a marginal skill at 3 month lead (> 0.4) in the NWP around 10^oN. For sea level, the correlation skill at 3 month lead is high (> 0.7) in most of the equatorial Pacific (Fig. 2b). The correlation skill at 9 month lead is highest in the CEP and NWP at above 0.5 (Fig. 2d). In the western Pacific, SST anomalies are generally less predictable than sea level anomalies. This is because SST anomalies in the western Pacific are smaller than those in the eastern Pacific, whereas sea level anomalies are comparable in the east and west. *Mayer and Weisberg* [1998], and *Wang et al.* [1999b] discussed the asymmetry between the eastern and western Pacific in more detail, and gave an explanation of why sea level pressure anomalies in the west are as large as those in the east despite smaller SST anomalies.

While not shown here, it is found that the hindcast skill of SST has a strong seasonal dependency, often referred to as "spring barrier". The seasonal dependency of the skill of sea level is not as strong as that of SST. At 6 month lead, the hindcast skills of SST and sea level are highest for summer starts, and are lowest for later winter and early spring starts.

The fact that the correlation skill of sea level in the NWP is moderate (> 0.6) up to 9 month lead suggests that sea level variability in the NWP is closely related to ENSO. This is consistent with the sea level patterns of the first two MEOFs which have large amplitudes in the NWP [*Xue et al.*, 2000]. *Wang et al.* [1999a] suggested that sea level variability in the NWP is mainly forced by local wind stress curl, and the wind circulations there are considerably influenced by East Asian monsoon and midlatitude variations. However, *Mayer and Weisberg* [1998], and *Wang et al.* [1999b] proposed that in the western Pacific the ocean and atmosphere are coupled and these coupled interactions are important for ENSO. It appears that the physical mechanisms

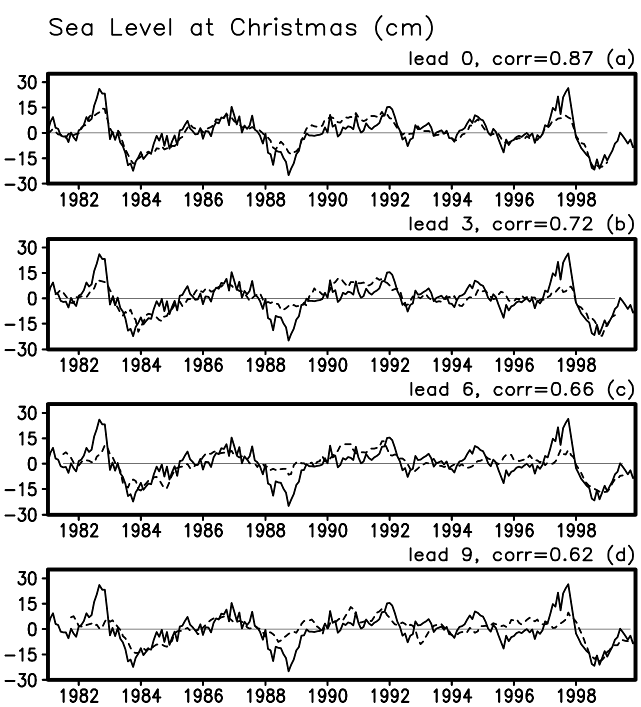

Figure 4. Comparison of tide gauge observation at Christmas Island (solid) and sea level forecast (dash) at (a) 0, (b) 3, (c) 6 and (d) 9 month leads.

for the air-sea interactions in the NWP are yet to be fully understood.

A problem with the Markov model is that the 1982-83, 1997-98 warm and 1988-89 cold events are seriously underestimated. *Barnston et al.* [1999] showed that this problem is common among ENSO forecast models in the prediction of the 1997-98 warm event. It has been suggested that atmospheric high frequency variabilities, e. g. westerly wind bursts and Madden-Julian Oscillations, played critical roles in the timing and strength of the 1997-98 warm event [*Yu and Rienecker*, 1998]. We suspect that atmospheric high frequency variabilities played important roles in the timing and strength of the 1982-83 warm and 1988-89 cold events as well.

The real time forecast of sea level anomalies by the Markov model has been published at the official web site of the Climate Prediction Center, NOAA. We are also experimenting with the Canonical Correlation Analysis method for forecasting sea level anomalies. Eventually, we intend to replace the statistical models with the dynamical forecast system at NCEP for an operational forecast of sea level.

Acknowledgments. The authors thank Tony Barnston for helpful discussions..

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(Received October 6, 1999; revised January 13, 2000; accepted May 3, 2000.)