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The impact of sea level data assimilation on the Lamont model prediction of the 1997/98 El Niño

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Abstract. Assimilating the sea level data from tropical Pacific tide gauges greatly improved the Lamont model prediction of the 1997/98 El Niño while retaining its overall performance during the past few decades. The implication is that the Lamont forecast system is limited by the observational data used for initialization probably probably as much as by its simplified model physics. The sea level measurements in the vicinity of the equator are extremely effective in correcting the model ocean state and preconditioning it for ENSO prediction.

Introduction

For more than a decade, the Lamont model [*Cane et al.*, 1986; *Zebiak and Cane*, 1987] has played an important role in our understanding and prediction of El Niño and the Southern Oscillation (ENSO). However, the model's forecast skill has degraded in recent years, most notably in its failure to predict the large 1997/98 El Niño. This has raised some serious concerns about the Lamont model. Do recent events demonstrate that the model's obviously simplified physics are now inadequate? Is it no longer useful for experimental forecasting? Based on the results reported here, the recent misfortune of the Lamont model cannot be simply attributed to model deficiency. The model can still serve as a useful tool for ENSO prediction, but only with better data assimilation. In particular, using sea level data for model initialization makes the Lamont model performance comparable to others in predicting the recent El Niño events.

In the standard Lamont forecast system, only wind data have been used for model initialization and the sole source of data has been the monthly FSU wind analyses [*Goldenberg and O'Brien*, 1981]. Given the variety of data sets available at present, this is clearly an aspect of the system that should be updated. We could improve the situation by replacing the FSU winds with a better wind product and/or assimilating other kinds of data in addition to winds. It has been demonstrated in an accompanying work that the onset of the 1997/98 El Niño could be well predicted by the Lamont model if the NSCAT satellite derived winds were used for model initialization [*Chen et al.*, 1998]. In this study, we evaluate the impact of sea level data assimilation on the Lamont model forecasting. Strong impact is expected because of the well-known importance of sea level data, and equivalently subsurface thermal data, in diagnosing and predicting ENSO [*Wyrtki*, 1975; *Cane*, 1991; *Ji and Leetmaa*, 1997; *Rosati et al.*, 1997].

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Data Assimilation

The sea level data used in this study are from 34 tide gauge stations in the tropical Pacific. The locations of these stations and other details of the data are described in *Cane et al.* [1996]. One reason for choosing the tide gauge data is because of their relatively long records, which allows a reasonable period to evaluate forecast skill. The data assimilation procedure consists of two steps. First, we applied a reduced-space Kalman filter to assimilate the tide gauge data into a linear wind-driven ocean model, which is the dynamical ocean component of the Lamont model, to produce monthly ocean states for the 23-year period from January 1975 to January 1998. The design of this efficient Kalman filter and the quality of the resulting sea level maps are discussed in *Cane et al.* [1996]. Second, we ran the model in a coupled mode for the same period following the nudging scheme of *Chen et al.* [1995] except that, in addition to the FSU winds, the ocean states obtained from the first step were also nudged into the model.

Specifically, the additional nudging in the second step assumes the following form: $h = \alpha h_1 + (1-\alpha)h_c$, where h is the ocean state consists of the height and flow fields associated with Kelvin and Rossby waves, h_1 and h_c are the same fields from the sea-level assimilated ocean model run and the coupled model run, respectively, and the nudging parameter α is Gaussian in latitude with a maximum value of 0.8 at the equator and an e-folding scale of 2 degrees. Thus the nudging is done effectively only within the equatorial waveguide. Although this two-step procedure seems a little awkward as compared to an approach that assimilates sea level data directly into the coupled model, we choose to use it until we implement a better method to minimize the systematic differences between the model and the observational data. For convenience, we refer to this new version of the Lamont model as LDEO3. It differs from LDEO2 (the version described in *Chen et al.* [1995]) only in the addition of sea level data assimilation.

Model Results

Figure 1 compares the hindcasts of the equatorial thermocline depth anomalies made by LDEO2 and LDEO3 for the 1975-97 period. These represent the initial ocean conditions from which forecasts will be made. Both LDEO2 and LDEO3 give large interannual thermocline depth fluctuations associated with ENSO, and the timing and magnitude of these fluctuations in the two cases are quite similar during the 1970s and 1980s, but rather different in the 1990s. Thus assimilating sea level data has a stronger impact in the recent years, when the model had difficulty simulating the real climate change using only wind data. For example, LDEO2 missed the thermocline deepening associated with

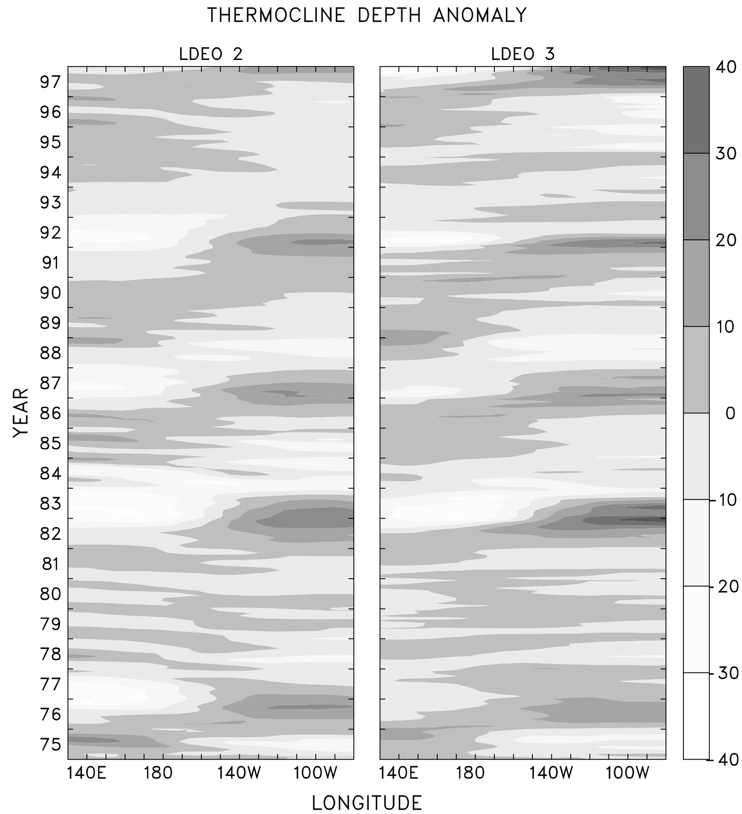

Figure 1. Time-longitude plots of the equatorial thermocline depth anomalies from the Lamont model with (right) or without (left) sea level data assimilation.

the short warm events in the spring of 1993 and at the end of 1994, and largely underestimated the rapid thermocline deepening associated with the 1997/98 El Niño. But with sea level data assimilated, these thermocline variations were well simulated in LDEO3. The corresponding sea surface temperature (SST) anomalies are shown in Figure 2 for the

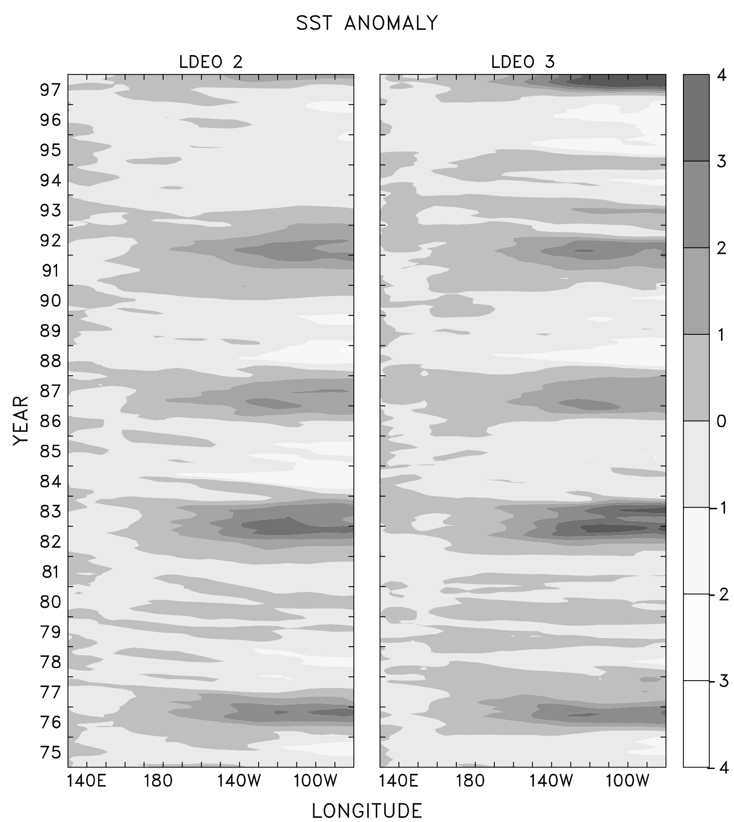

Figure 2. Same as Figure 1 except for sea surface temperature anomalies.

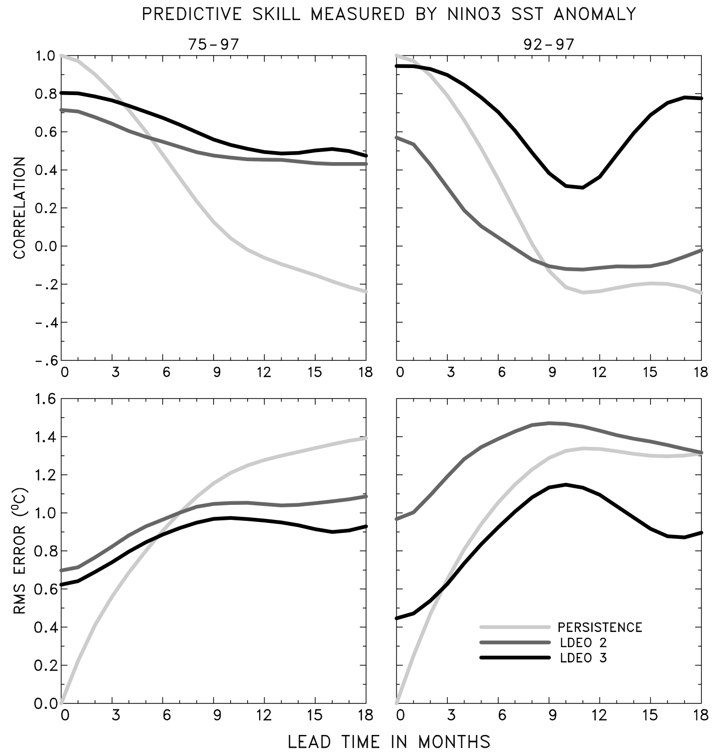

Figure 3. Correlations and rms errors between model forecast and observed NINO3 index for the 1975-97 period and the 1992-97 sub-period. The light thick curve is persistent forecast, and the two darker curves are the model forecast initialized with (thick) or without (thin) sea level data assimilation.

two cases. Again, the positive impact of sea level data assimilation is most pronounced in the 1990s, especially for the three warm events mentioned above.

The same conclusion can be extended to model forecasts. Figure 3 compares the predictive skills of LDEO2 and LDEO3 for lead times up to 18 months. The skills are measured by the correlation and the root-mean-square (rms) error between monthly model forecast and observed NINO3 (SST anomaly averaged over $90^o - 150^oW$ and $5^oS - 5^oN$). For the whole 23 year period from 1975 to 1997, LDEO3 gives a higher correlation and lower rms error at all lead times as compared to LDEO2. Yet this improvement is mostly derived from the better performance of LDEO3 in the recent years, as indicated by the large differences in correlation and rms error between the two cases for the 1992-97 period. While LDEO3 has a predictive skill comparable to

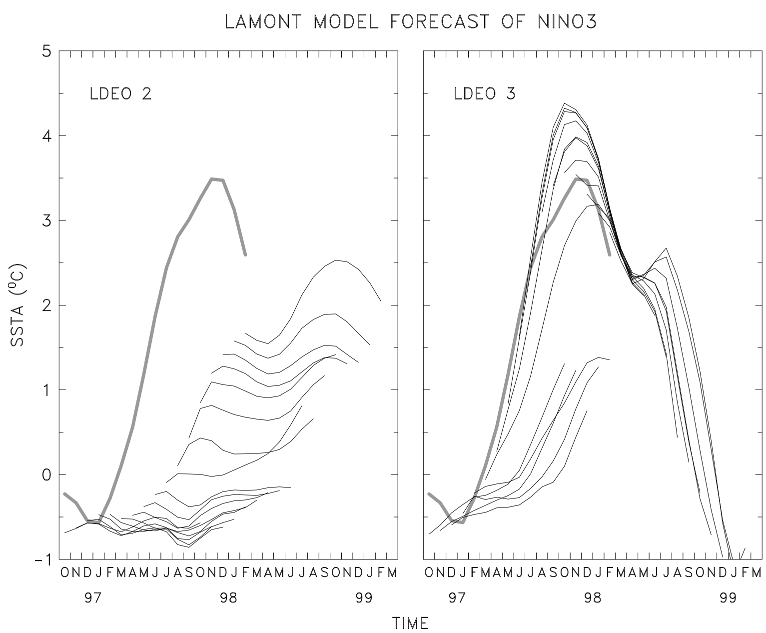

Figure 4. Lamont model forecasts of the 1997/98 El Niño with (right) or without (left) sea level data assimilation. The thick curve is observed NINO3 SST anomaly. Each thin curve is the trajectory of a 12 month forecast starting from the middle of each month.

LDEO2 during 1970s and 1980s, it scores much higher in the 1990s, when LDEO2 has little skill after the 1991-92 El Niño.

The most striking difference between LDEO3 and LDEO2 is in their forecasts of the 1997/98 El Niño, as shown in Figure 4. LDEO2 totally missed the onset of this big event, and even the initial conditions (the start point of each thin curve) were way off the mark. In the case with LDEO3, however, the situation is much improved. First of all, initial SST anomalies followed observations closely. The model predicted a warming in 1997 at times when NINO3 was still on the negative side. Starting from March 1997, the forecasts became quite consistent and captured the rapid growth of the El Niño toward the end of the year and its decay afterwards. Although the model overshot the maximum warming at the end of 1997 and its prediction for the rest of 1998 still remains to be verified, the positive impact of the sea level data assimilation is unquestionable.

Summary and Discussion

We have resurrected the Lamont ENSO forecast system from its recent failure by assimilating the sea level data from tropical Pacific tide gauges. This implies that the system is limited by the observational data used for initialization probably as much as by its simplified model physics. A major drawback of the previous system is its sole dependence on the FSU wind analyses for information about the real world. With the help of better and/or more data, the model can continue to produce useful forecasts, at least for simple indices such as NINO3. The procedure described here forms the basis for a new version of the Lamont forecast system, LDEO3, which will replace LDEO2 to provide routine experimental ENSO forecasts to the community.

A question that remains unclear is why the Lamont model worked so well in the past with only the FSU wind data, but desperately needs additional data at present. It is not reasonable to assume that the FSU analyses are generally getting worse, though there is evidence that this product gave too strong easterly winds in the eastern tropical Pacific before the arrival of the 1997/98 El Niño, which made the SST there too cold and the thermocline too shallow to allow the rapid onset of this warm event [*Chen et al.*, 1998]. A more probable explanation is that there is a decadal or longer term climate change which is neither captured by the model nor by the FSU winds. Yet the change is well contained in the sea level data. In any case, it is advisable to assimilate multiple data sets so that they can complement one another.

Given the sparsity of the tide gauge stations [*Cane et al.*, 1996] and the fact that we essentially only used the data within the equatorial waveguide, it seems amazing that the model hindcasts and forecasts could be improved at such a magnitude. This suggests that assimilating the sea level measurements in the vicinity of the equator, or equivalently the observations of the equatorial thermocline, are extremely effective in correcting the model ocean state and preconditioning it for ENSO prediction. Thus the data from an equatorial mooring array such as TOGA-TAO may prove to be invaluable. We are currently working on a systematic procedure that will incorporate sea level and thermocline data from all sources, including TOPEX/POSEIDON, TOGA-TAO, and XBTs (Expendable Bathythermographs) as well as tide gauges.

Finally, we should point out that data assimilation is not the ultimate solution to our problems, and the improved model forecasts reported here is no proof that the model itself is trouble free. In fact, it is because of the large mismatch between the model and the reality that data assimilation is so much needed. For example, with a prescribed mean state, the Lamont model by design is not capable of producing long-term climate variabilities. If there has been a mean state shift in recent years due to decadal or longer term climate changes, the model is bound to fail without being corrected by data assimilation. Our intention here is not to defend the simplified physics of the Lamont model, whose limitations and advantages are well known, but to explore the possibility of making optimal use of data assimilation in such a simple forecast system.

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