A Forecasting Model for the Onset of a Major El Niño

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ABSTRACT

The feasibility of a forecasting scheme for predicting the onset of a major El Niño in the ocean is demonstrated using the linear numerical model of Busalacchi and O'Brien and the interannual components of the shipboard observed wind for 1961–82. The model upper layer thickness anomaly in the eastern Pacific, which was used as the predictand, was estimated after three months of steady wind integration. A lag time of three months is used to permit the propagation of a large El Niño-type Kelvin wave across the Pacific Ocean. If the necessary wind changes required to generate a large El Niño type Kelvin wave wave have already taken place in the western and/or central Pacific, El Niño could be predicted one to three months in advance from knowledge of the wind field alone. Starting from November 1963, three-month steady-wind integrations were performed for the wind condition of each of the seven months (November to May), for each of the 15 years extending from 1964 to 1978. This period includes four El Niño years. The probability distribution function of the three-month running mean of the upper layer thickness anomaly in the eastern Pacific was estimated separately for the El Niño and the non-El Niño groups using “bootstrap” estimates. The separation of the two probability distribution functions allows for the establishment of a criterion for forecasting El Niño. An independent wind data set for the period 1979–82, which includes the onset of the 1982/83 El Niño, was used to test the feasibility of the forecasting scheme. If the null hypothesis is that a sample year is a non-El Niño year and based on a forecast criterion of false positive error (false alarm rate) \( < 0.01 \), which corresponds to false negative error \( \geq 0.52 \sim 0.86 \) (which corresponds to a probability of detecting the occurrence of an El Niño \( < 0.14 \sim 0.48 \)), the 1982/83 El Niño would be forecast to be underway following the analysis of the April 1982 surface wind field. Since the objective is to establish a forecasting scheme for predicting the onset of a major El Niño, the forecast scheme is chosen to be one of low risk and low power in prediction performance.

1. Introduction

Predictability of large El Niño has been of considerable interest. Interaction between the atmosphere and ocean that leads to El Niño events is complex (see Julian and Chervin, 1978) and not well understood at present (Ramage and Hori, 1981; Rasmusson and Carpenter, 1982). Previous attempts to study predictability in the tropical Pacific (Quinn, 1974; Barnett, 1977, 1981; Covey and Hastenrath, 1978) have been based on statistical models. However, the oceanic response to the atmospheric variability that gives rise to the anomalously warm water in the eastern tropical Pacific is beginning to be understood due to the many recent research efforts in this field, suggesting a dynamical rather than a statistical approach.

Wyrtki (1975) attributed El Niño to the excitation of equatorial Kelvin waves due to the interannual fluctuations of the southeast trade winds over the central equatorial Pacific. Based on a statistical model, Barnett (1977) showed that interannual variations in the zonal components of the trade winds just west of the date line and just north of the equator are closely associated with changes in the basin-wide sea level field, with the wind changes leading the corresponding sea level changes by zero to two months. He also showed that the resulting changes in sea level field can be used to hindcast changes in the sea surface temperature (SST) at Talara, Peru. A recent study by Luther and Harrison (1983) shows that weakening of easterly trade winds from near-equatorial islands in the central Pacific occurred one to four months before the first SST warming at the coast of South America. The observed time lag of a few months is consistent with the eastward propagation of Kelvin waves generated in the western and/or central Pacific. Further support for the Kelvin wave mechanism comes from studies of Busalacchi and O'Brien (1981) and of Busalacchi et al. (1983). Using a numerical model forced by the shipboard observed wind, they showed that most of the observed changes in the sea level records in the equatorial and tropical Pacific Ocean are explained in terms of the oceanic response to wind forcing. The role of Kelvin waves in transmitting the wind-forced disturbance from the western and central Pacific to the eastern Pacific was clearly identified in those numerical studies.

In this paper, forecasting of El Niño is studied using the numerical model of Busalacchi and O'Brien
and Busalacchi et al. (1983). In those studies, it was shown that the model response to the monthly wind stress input reproduces broad features of the seasonal variability of the equatorial current regime (Busalacchi and O'Brien, 1980), and also the interannual variability (including El Niño events) of the equatorial Pacific during the 1960s (Busalacchi and O'Brien, 1981) and the 1970s (Busalacchi et al., 1983). Those studies show that the onset of El Niño events in the 1960s and 1970s was due to the anomalous relaxation of the easterlies in the central and western Pacific exciting a large downwelling Kelvin wave pulse, which traveled along the equator and arrived at the eastern boundary one to three months later. Impingement of the Kelvin wave upon the eastern boundary produces a deeper pycnocline in the eastern Pacific, which corresponds to a thicker upper layer. The positive sea level anomaly in the eastern Pacific, a characteristic of the El Niño events, compares well with positive upper layer thickness anomaly (ULTA) (equivalent to negative pycnocline height anomaly, PHA) in the eastern Pacific (Busalacchi and O'Brien, 1981; Busalacchi et al., 1983).

The success in reproducing broad features of the El Niño events in the 1960s and 1970s points to the feasibility of establishing a dynamical-statistical forecast scheme for predicting El Niño one to three months in advance, provided timely wind data are available. In this study, the interannual components of the monthly wind stress for 1961–78 are used as a dependent data set to force the model. The model ULTA in the eastern Pacific is used as the predictand, and criteria for predicting the occurrence of El Niño are presented. Then, independent forecasts are carried out for the period 1979–82, which includes the onset of the 1982/83 El Niño.

It should be noted that a similar study based on a dependent data set with an independent test, but using a statistical model rather than a dynamical-statistical approach adopted in this study, was carried out by Barnett (1981). Using the linear prediction theory, he was able to show that SST anomalies off Peru are predictable one year in advance for the period 1976–79. Hasselman and Barnett (1981) improved forecasting skills of the linear prediction model. Recently, Barnett (1984) applied his linear prediction model to the 1982/83 El Niño. Using anomalous components of the zonal and meridional wind field in the near equatorial region as predictors and observed SST off South America as predictand, he showed that the warming off South America during 1982–83 could have been predicted four to five months in advance. We consider this study to be complementary to the work of Barnett (1984).

2. The ocean model and the wind data

The ocean model is a one-layer reduced-gravity, linear transport model on an equatorial β-plane. The model domain extends from 126°E to 79°W and from 18°N to 12°S, representing the tropical Pacific Ocean with idealized boundaries. Open boundary conditions are used along the northern and southern boundaries. A detailed discussion of the model was presented by Busalacchi and O'Brien (1980). The phase speed of the internal mode is taken to be $2.45 \text{ m s}^{-1}$, which is considered to be the phase speed of the equivalent first baroclinic mode in the real continuously stratified ocean.

The wind stress data used in this study come from ship wind observations for each month spanning from 1961 to 1978. The original data set had been grouped into monthly values and subjectively analyzed onto a 2° by 2° mesh. Details of the wind stress data for 1961–70 were discussed by Goldenberg and O'Brien (1981).

Due to the linearity of the model, the interannual variability (including El Niño events) of the model ocean response is examined by analyzing the model response to the interannual components of the monthly winds. Interannual components in the zonal and meridional wind stress components at each grid point were computed by subtracting from each monthly winds the 18-year mean for that month at the grid point.

The model was started from rest, and the starting point was the middle of January 1961. The original monthly wind was assigned to the middle of the month. A time step of two hours is used for numerical integration. The wind stress at any particular time step is computed by linear interpolation between the observed wind data for midmonth before and after the input. Since the model was started from rest and the model domain extends from 18°N to 12°S, the first three years (1961–63) are considered to be a spinup period. The model ULTA variability in the eastern equatorial Pacific is represented by the mean ULTA averaged over a region extending from 10°S to 10°N and 80 to 100°W. The large area average for ULTA is necessary for achieving a high confidence level for the representativeness of the predictand for El Niño. This is in accordance with a definition usually used which refers to El Niño as anomalous warming of SST in the general area of the eastern equatorial Pacific (e.g., Barnett, 1977). The model response (ULTA in the eastern Pacific) to the interannual components of the 18-year wind is shown in Fig. 1. Due to the dominance of the interannual variability in the equatorial Pacific Ocean, the model ULTA variability shown in Fig. 1 is similar to the model PHA variability at the Galápagos Islands, presented by Busalacchi and O'Brien (1981) and Busalacchi et al. (1983) who used the observed wind stress rather than its interannual components. In Fig. 1, the four El Niño events (1965, 1969, 1972 and 1976) observed during 1964–78 are characterized by large positive peaks. Therefore, positive anomalies of
and the non-El Niño years are shown in Fig. 2. The distributions of D for the two groups (El Niño and non-El Niño) have similar standard deviations (19.4 m for the El Niño group and 18.8 m for the non-El Niño group). However, the means are noticeably different, with 10.0 m for the El Niño group and 

-6.0 m for the non-El Niño group. The existence of two preferred climate states is not limited to the eastern Pacific alone and is also found in oceanic parameters in the central and western Pacific (Hickey, 1975; Meyers, 1982). This bimodality in the tropical Pacific Ocean is in response to the bimodality found in atmospheric forcing (Pazan and Meyers, 1982; Barnett, 1983). The change from one mode to the other is associated with changes from easterlies to westerlies in the equatorial Pacific. This transition from easterlies to westerlies appears to be an anomalous amplification of the annual cycle (Horel, 1982).

the mean ULTA in the eastern Pacific (averaged over 10°S–10°N and 80–100°W) are used as an index of El Niño.

3. Forecast simulation

Rasmusson and Carpenter (1982) examined six significant El Niño events that occurred between 1949 and 1976, and showed that the dramatic switch from easterly to westerly wind anomalies west of the date line took place after October of the year preceding El Niño. Previous studies (Busalacchi and O'Brien, 1981; Busalacchi et al., 1983), using the same numerical model used in this study, showed that the anomalous relaxation of the easterlies that led to the onset of the El Niño events in the 1960s and 1970s took place between November of the year preceding El Niño and April of the El Niño year.

The forecast simulation study of El Niño was performed as follows: For each month starting from the middle of November 1963, three-month steady-wind integrations were performed for the wind condition of the middle of that month. This steady wind integration was performed for the wind condition of each of the seven months from November to May, for each of the 15 years extending from 1964 to 1978. It should be noted that holding the wind steady does not result in further generation of Kelvin waves. If the necessary wind changes required to generate a large El Niño type Kelvin wave have already taken place in the western and/or central Pacific, El Niño could be predicted one to three months in advance from knowledge of the wind field alone. A lag time of three months is used to permit the propagation of the Kelvin wave across the Pacific.

Based on three months of steady wind integration, the ULTA in the eastern Pacific, D, was computed (see the Appendix); histograms for the El Niño years and the non-El Niño years are shown in Fig. 2. The distributions of D for the two groups (El Niño and non-El Niño) have similar standard deviations (19.4 m for the El Niño group and 18.8 m for the non-El Niño group). However, the means are noticeably different, with 10.0 m for the El Niño group and 

-6.0 m for the non-El Niño group. The existence of two preferred climate states is not limited to the eastern Pacific alone and is also found in oceanic parameters in the central and western Pacific (Hickey, 1975; Meyers, 1982). This bimodality in the tropical Pacific Ocean is in response to the bimodality found in atmospheric forcing (Pazan and Meyers, 1982; Barnett, 1983). The change from one mode to the other is associated with changes from easterlies to westerlies in the equatorial Pacific. This transition from easterlies to westerlies appears to be an anomalous amplification of the annual cycle (Horel, 1982).

![Fig. 1. Model upper layer thickness anomaly (ULTA) in the eastern Pacific Ocean averaged over 10°S–10°N and 100–80°W for the period 1961–78. Model is forced by interannual components of the wind stress.](image-url)
Following Barnett (1977), the hindcast skill ($S$) to be used in this study is defined as

$$S = \left[1 - \frac{\sum_{n=1}^{N} (\hat{D}_n - D_n)^2}{\text{Var}\hat{D}}\right] \times 100\%,$$

where $\hat{D}$ is the value of the ULTA in the eastern Pacific for the observed continuous wind case, $N$ is the sample number and Var$\hat{D}$ is the variance of $\hat{D}$. This measure is the percent of variance accounted for by the hindcast model.

It turned out that the month-to-month correspondence between $\hat{D}$ and $D$ is not good. However, a high hindcast skill can be achieved for time scales longer than two to three months, suggesting a good forecastability of slowly varying events. This seems to indicate that keeping the wind constant for three months deprives correct hindcast of wind with time scales less than two to three months. It should be noted also that El Niño is usually defined as some type of persistent feature lasting longer than two to three months. For example, at the fifth meeting of SLOCOR (Scientific Committee on Oceanic Research) Working Group 55 held in Miami in the fall of 1982, El Niño was referred to as the appearance of anomalously warm water along the coast of Ecuador and Peru defined by a normalized sea surface temperature anomaly exceeding one standard deviation for at least four consecutive months at three out of five coastal stations (International Council of Scientific Unions, 1983). The hindcast skill for $D_3$, the three-month running mean of $D$, is 71% (see Fig. 3), which is considered to be an acceptable value; the skill can be improved to 77% for the five-month running mean. However, a three-month running mean is chosen for the predictand because the loss of one month in forecast lead time does not appear to be offset by the improvement in hindcast skill.

With shorter lead time (i.e., steady wind integrations are performed for a period shorter than three months), higher hindcast skills are expected (in the limit of zero lead time, the model would be the actual continuous wind case). For example, the skill for the three-month running mean increases to 91% for two-month lead time and to 98% for one-month lead time. On the other hand, lead times of longer than three months should be accompanied by more rapid decrease in the skill, due to the fact that the eastern Pacific should start feeling the effect of the disturbances generated by the subsequent wind changes in the western and central Pacific. The choice of a three-month lead time attempts to achieve maximum lead time with reasonable forecastability.

4. Forecast criteria

The observed separation between the two distributions of $D$, with one distribution corresponding to an El Niño state and the other to a non-El Niño state, are used to classify any sample year either as an El Niño or a non-El Niño year. The objective was to establish some type of statistical procedure that would provide information regarding relative location of any observed point with respect to the two distributions. In order to establish a reference distribution, one must address the serious problem of small sample size. This is particularly acute because of the use of a three-month running mean for the predictand. It appears that there is noticeable intermonth variability. If we assume different distributions for different months, for example, the sample size is only four for the El Niño group for any of the five months (December through April). Hence, we cannot rely on any classical continuous probability density function (PDF). Rather than consider a parametric approach, we regard all the data points on hand as correct and representative of the real world, and choose to approach the small sample problem using a nonparametric procedure. Specifically, the bootstrap technique (Efron, 1982; Diaconis and Efron, 1983) is applied. To our knowledge it has not been used in meteorology or oceanography previously.

In comparison to other nonparametric methods such as the jackknife, the cross-validation and the permutation technique, the bootstrap technique is relatively new [introduced by Efron in 1977 (see Diaconis and Efron, 1983)]. Efron (1982) gives detailed discussion on the jackknife, the cross-validation and the bootstrap, and Hollander and Wolfe (1973) present some examples of the permutation technique. In general, nonparametric methods have not been used extensively for meteorological or oceanographic

![Fig. 3: Hindcast of the model upper layer thickness anomaly (ULTA) in the eastern Pacific. The crosses are hindcast values using three-month steady-wind integrations, and solid lines are for observed continuous wind. The values for observed continuous wind are as in Fig. 1 but filtered with a three-month running mean.](image-url)
applications. Recently some applications of nonparametric methods in meteorology or oceanography were made by Mielke et al., (1981) and by Preisendorfer and Barnett (1983) who used the permutation technique. For some practical problems, different nonparametric methods would give the same results. As will be discussed later, for this particular problem, MRPP (multi-response permutation procedure) (Mielke et al., 1981) would give exactly the same result. However, because of the potential wider applications, the method, which will be described in the following section, will be referred to as the bootstrap method.

a. Example of bootstrap

The general idea behind the bootstrap can best be illustrated by an example representative of the problem under consideration. Readers are referred to the aforementioned references for other applications.

We suppose there are $n$ subgroups (for example, four El Niño years), and there are three responses (for example, $D$ values for January, February and March) obtained in $n$ subgroups. The statistic under consideration is the mean ($D_3$ values) for each group. If it can be assumed that the data consist of three independent random samples,

$$X_1, X_2, \ldots, X_n \sim F,$$

$$Y_1, Y_2, \ldots, Y_n \sim G,$$

$$Z_1, Z_2, \ldots, Z_n \sim H,$$

where $F$, $G$ and $H$ are three possibly different distributions (for example, each corresponding to $D$ values for January, February and March, i.e., assuming that for each of the months, $D$ values for all the El Niño years can be considered as coming from the same population). Having observed that $X_1 = x_1$, $X_2 = x_2$, $\ldots$, $X_n = x_n$, $Y_1 = y_1$, $Y_2 = y_2$, $\ldots$, $Y_n = y_n$ and $Z_1 = z_1$, $Z_2 = z_2$, $\ldots$, $Z_n = z_n$, the statistic of interest is the mean of the three corresponding samples $\bar{F} = (x_1 + y_1 + z_1)/3$, $\bar{G} = (x_2 + y_2 + z_2)/3$, $\ldots$, $\bar{H} = (x_n + y_n + z_n)/3$.

The bootstrap idea is comprised of the following steps:

i) $F$, $G$ and $H$ are not known, but we can estimate them by the empirical probability distributions $\hat{F}$, $\hat{G}$ and $\hat{H}$ by weighting with probability mass $1/n$ for each observed data point $x_i$, $y_i$ and $z_i$ ($i = 1, 2, \ldots, n$).

ii) A bootstrap sample consists of a random sample $X^* \sim \hat{F}$ drawn from $\hat{F}$ (drawn independently with replacement and with equal probability for the set $(x_1, x_2, \ldots, x_n)$), $Y^* \sim \hat{G}$ drawn from $\hat{G}$ (for the set $(y_1, y_2, \ldots, y_n)$) and $Z^* \sim \hat{H}$ drawn from $\hat{H}$ (for the set $(z_1, z_2, \ldots, z_n)$).

In the present problem under consideration, a typical bootstrap sample might consist of $D$ value for January 1965, $D$ value for February 1969 and $D$ value for March 1972. We then compute the bootstrap replication $Q^* = (X^* + Y^* + Z^*)/3$, the value of the mean evaluated for the bootstrap sample.

iii) Repeat step (ii) some large number ($M$) of times obtaining independent bootstrap replications $Q^{*,1}$, $Q^{*,2}$, $\ldots$, $Q^{*,M}$. In this case, there are precisely $M = n^3$ ways to compute bootstrap replications. For large numbers of $M$, bootstrap replications are evaluated by the Monte Carlo technique.

It should be noted that in this particular application, this result can also be obtained via multi-response permutation procedures (MRPP) (Mielke et al., 1981) (for further applications of permutation procedures, see Preisendorfer and Barnett, 1983). However, if the problem required that more than one observation be drawn from the same empirical distribution, results of the bootstrap analysis would be different from that of MRPP, which does not sample with replacement.

b. Implementation of bootstrap

It was found that temporal correlation is weak for the data set under consideration. Therefore, for each group, all the $D$ values falling within the same month are regarded as coming from the same population (i.e., quasi-stationarity for each month of the year is assumed). However, there is reason to assume different distributions for different months. First, a bootstrap sample is drawn by independent random sampling for each month. Then, a three-month running mean is computed for the bootstrap samples. In this case, bootstrap estimates can be made for all the possible sample configurations, namely $64 (=M = 4^3)$ for the El Niño group and 1331 ($=M = 11^3$) for the non-El Niño group. Histograms of $D_3$ for the two groups based on the bootstrap samples are presented in Fig. 4 for each month extending from December to April. Note that, for example, the histogram for December is based on $D_3$ using $D$ values for November, December and January (i.e., it is necessary to know wind variability through January). The more rugged shape of the histograms for the El Niño group is due to the smaller number of samples.

It is interesting to note discernible intermonth variability in the shape of the histograms shown in Fig. 4, probably reflecting some seasonal signals remaining in the wind input. This could be caused by possible amplitude modulation of the seasonal signal, similar to the amplitude modulation of the annual cycle observed in the sea level records at Truk Island (Meyers, 1982) and in the atmospheric parameters (Horel, 1982). Despite the intermonth variability observed in the shape of the histograms, the separation between the two histograms measured by the distance between the means is noticeable for any of the months considered, and it increases as the year pro-
Here, the null hypothesis is that a sample year is a non-El Niño year, while the alternative hypothesis is that a sample year is an El Niño year. Referring to Fig. 5, based on the non-El Niño histograms, a probability of false rejection of $\alpha$ (Type I or false positive error) is decided on first, one for each month. This would fix a critical value $C$ of the variable $D3$. Since the relative locations of both types of histograms (El Niño and non-El Niño) are determined by the data, this choice of $\alpha$ also fixes a probability of false acceptance of $\beta$ (Type II or false negative error). At this stage of the model construction it is permissible to juggle $\alpha$ and $\beta$ values for each month by varying $C$ value. Once $\alpha$ is chosen, and $\beta$ accepted, they are fixed for subsequent testing purposes. Those $D3$ values exceeding $C$ will produce an El Niño warning. In practical forecasting, it might be advantageous to make $\alpha$ small to avoid issuing wrong warnings. In contrast, if the null hypothesis is false and we accept the hypothesis, no great harm has been done since we can always wait for the next year. Consequently, $\beta$ can be relatively large. It should also be noted that we are interested in developing a forecasting scheme for predicting the onset of a major El Niño. If one has chosen $\alpha = 0.01$, then the probability of not having an El Niño when one is forecast (namely $\alpha = 0.01$) will indicate the false alarm rate (risk of prediction failure) of using the model. For $\alpha = 0.01$, the critical value ($C$) would be in the range of 10.3–18.9 m, while $\beta$ would be in the range of 0.52–0.86 (see Fig. 6). Another type of probability of interest is the model’s power ($1 - \beta$), i.e., the probability of detecting the occurrence of an El Niño. Quantities $\alpha$ and $1 - \beta$ are called the model risk and power, respectively. It should be noted that larger separation between the two PDFs would result in less risk (smaller $\alpha$) and more power (larger $1 - \beta$).

A crucial assumption made in estimating PDFs for the two groups is quasi-stationarity for each month of the year. There appears to be a long-term trend present in the forecast values, as is evident in Fig. 3. The effect of that assumption should result in underestimating the spread of the PDFs. Therefore, it is important to make $\alpha$ small to be conservative. One way to improve our estimates of the PDFs would be to use an autoregressive model (Box and

The histograms in Fig. 4 are used as estimates of the true PDFs. When a decision is made to accept or reject a hypothesis based on the results of an experiment, it is possible to make one of two types of errors. These errors are called: 1) Type I error, rejection of a null hypothesis that is true, or 2) Type II error, acceptance of a null hypothesis that is false.
were performed for each month, for each of the four years from 1979 to 1982. Figure 7 shows $D_3$ values together with the three-month running means for the observed continuous wind. The observed continuous wind case is well predicted by the steady wind forecast. This lends support to the choice of the three-month running mean as the predictand, and it also indicates that the interannual variability of the eastern Pacific response for the period 1979–82 is due mainly to the incoming Kelvin waves generated in the western and/or central Pacific. It is interesting to note in Fig. 7 that there appears to be an underlying periodic signal with a period of nearly a year, the amplitude of which seems to grow with time. Only those values between December wind and April wind are used in the forecast (corresponding $D$ values are given in Table 1), for which forecast criteria have been identified in the previous section. The forecast values of $D_3$ are presented in Table 2 together with $C$ value and $1 - \beta$ value, which correspond to $\alpha = 0.01$. Those $D_3$ values exceeding $C$ in each monthly column will produce an El Niño warning.

Throughout 1979 and 1980, $D_3$ remains relatively low. Therefore, it appears unlikely that an El Niño warning would have been issued in either of those two years. In 1981, $D_3$ started with a low value in March 1981 (wind data through January 1981 were used). There was a sharp rise between March 1981 and May 1981, reaching more than 13 m in May. However, this peak was short-lived and $D_3$ plunged to a negative value in July. For the threshold criterion of $\alpha \leq 0.01$, no warning would have been issued in 1981. There is some observational evidence supporting the occurrence of a short-lived peak in sea level in

Jenkins, 1970) to remove the long-term trend. It is interesting to note, however, that the $D$ values for each of the seven months do not show an apparent long-term trend. Hence, the assumption of quasi-stationarity in this study is considered to be acceptable.

5. Application of the forecasting scheme to an independent data set

The feasibility of the forecasting scheme for predicting El Niño is tested using an independent data set, the shipboard observed wind for the period 1979–82. This interval includes the onset of the 1982/83 El Niño. The wind data are treated in the same way as before, i.e., the interannual components of the zonal and meridional wind stress were obtained by subtracting from the monthly winds the 18-year mean (1961–78) for that month. Starting from November 1978 three-month steady-wind integrations

Fig. 7. Forecast of the model upper layer thickness anomaly (ULTA) in the eastern Pacific. The crosses are forecast values using three-month steady-wind integrations, and solid lines are for observed continuous wind. Only those values indicated by circles are used in the forecast.
Table 1. Model upper layer thickness anomaly (ULTA) (in m) in the eastern Pacific after three months of steady wind integration. Month refers to the month when the wind field was held steady over the following three-month integration period. Year refers to the year for which forecast simulation was made.

<table>
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<td>-26.7</td>
<td>0.4</td>
<td>11.3</td>
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<td>-28.1</td>
<td></td>
</tr>
<tr>
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<td>26.4</td>
<td>-16.3</td>
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<tr>
<td>1981</td>
<td>-27.4</td>
<td>-30.3</td>
<td>1.8</td>
<td>16.0</td>
<td>21.7</td>
<td>-17.4</td>
<td>-18.8</td>
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<tr>
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<td>-30.8</td>
<td>17.0</td>
<td>-3.7</td>
<td>17.1</td>
<td>25.6</td>
<td>11.8</td>
<td>-7.2</td>
<td></td>
</tr>
</tbody>
</table>

* El Niño year.

early 1981. The pressure records from 20 m depth at the Galápagos Islands (Halpern et al., 1983) show an increase of about 16 mb in March and April of 1981, but there was a sharp drop in May.

In 1981–82, $D3$ increased sharply between March 1982 and May 1982, and remained high through July. For the criterion of $\alpha \leq 0.01$, a warning would have been issued in May 1982 (wind data through April 1982 would have been required). The longer persistence of the thicker upper layer in the eastern Pacific in early 1982, in contrast to 1981, would have provided more confidence in issuing a warning.

Despite the stringent criterion used, surprisingly, the 1982/83 El Niño is predicted following the analysis of the April 1982 surface wind data. It is widely publicized that the 1982/83 El Niño was unusual in that it started in the middle of the year in response to the massive collapse of the easterly trade winds near the date line, which took place around June 1982 (Rasmusson and Wallace, 1983). Figure 8 shows the interannual components of the east–west wind pseudostream (i.e., $\mathcal{S}$ = $UW$, where $U$ is zonal wind, $W$ is the magnitude of the horizontal wind speed defined by $W^2 = U^2 + V^2$ and $V$ is meridional wind) averaged over $\pm 5^\circ$ latitude of the equator. The wind condition in the equatorial Pacific in 1982 was characterized by an extensive westerly anomaly, which first appeared in the western Pacific in the beginning

Table 2. Forecast values of $D3$ from December to April for the period 1979–82. Critical value of $D3$ ($C$) and probability of detecting the occurrence of an El Niño ($1 - \beta$) which corresponds to $\alpha = 0.01$ are also listed.

<table>
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<th>Month</th>
<th>December</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
</tr>
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<tbody>
<tr>
<td>Critical value of $D3^*$ (m)</td>
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<td>13.9</td>
<td>16.6</td>
<td>18.9</td>
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<td>Probability of detecting the occurrence of an El Niño*</td>
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<td>0.48</td>
<td>0.27</td>
<td>0.14</td>
<td>0.28</td>
</tr>
<tr>
<td>$D3$ value (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td>-10.8</td>
<td>-5.0</td>
<td>-1.8</td>
<td>-11.3</td>
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<td>1980</td>
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<td>1.2</td>
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<tr>
<td>1981</td>
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<td>-4.2</td>
<td>13.1</td>
<td>6.8</td>
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<tr>
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<td>-5.9</td>
<td>10.1</td>
<td>13.0</td>
<td>18.2**</td>
<td>10.1</td>
</tr>
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</table>

* Corresponds to $\alpha = 0.01$.

** Is critical for forecast criterion of $\alpha \leq 0.01$. 

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of the year, a requirement noted previously (Barnett, 1977), and by the end of 1982 had almost reached the South American coast. There was an area of strong westerly anomaly which developed in February and March to the west of 170°E. This westerly anomaly created a downwelling Kelvin wave which, upon its arrival at the eastern boundary in April and May of 1982, forced the pycnocline downward, creating a thicker-than-normal upper layer. This corresponds to the observed increase of about 9 cm in sea level at Santa Cruz (Galápagos Islands). Beginning in June 1982, there was another increase of westerly anomalies west of 160°W that gradually expanded eastward. This led to the sharp increase in sea level at the Galápagos Islands after August 1982. However, according to our forecasting scheme, there was a precursor in the spring of 1982, which was strong enough to give an El Niño warning as early as May 1982. This is interesting since no existing forecasting scheme was able to predict the 1982/83 El Niño as early as the spring of 1982.

The precursor (spring of 1982) is predicted quite well, suggesting that the eastern Pacific response during the onset phase of the 1982/83 El Niño was due mainly to the incoming Kelvin waves generated in the western Pacific. Granted that the precursor in the spring of 1982 was strong enough to be classified as the onset phase of the 1982/83 event, it is interesting to examine our model performance against the major onset characterized by the sharp increase in sea level at the Galápagos Islands after August 1982. The model predicts D3 to start increasing in October (August wind data though were used) and the general increasing trend is well predicted. However, there appears to be a time lag of almost a month in the forecast values with respect to the observed continuous wind case. It appears that the major onset was due to the wind changes which took place to the east of the first westerly anomaly. This is supported by Fig. 9, which shows that, with two months lead time, the forecast model performs much better. The statistical prediction model of Barnett (1984), which uses anomalous components of the zonal and meridional wind field in the equatorial Pacific as the predictors and the SST anomalies off the coast of South America.

FIG. 9. Forecast of the model upper layer thickness anomaly (ULTA) in the eastern Pacific. The crosses are forecast values using two-month steady-wind integrations, and solid lines are for observed continuous wind.
as the predictand, shows excellent forecasting skill with a forecast lead time of four months for the major onset of this event. The four months lag time of the SST anomalies is also consistent with the dominant effect of Kelvin wave propagation coming from the western and/or central Pacific on the major onset phase of this event.

A question that needs to be addressed is the legitimacy of using the 1982/83 El Niño, which is considered by many to be the strongest in this century (e.g., Cane, 1983). To see how the statistical criteria change if the 1982/83 El Niño was included as a realization of the dependent data, the independent data set was added to the dependent data set. Histograms of $D3$ for this case (not presented here) do not show significant differences from those in Fig. 4. This is because the forecast period (November 1981 to May 1982) does not cover the mature stage of the 1982/83 event. For this event, the question should not be whether its occurrence would have been predicted (any prediction scheme could have recognized it if one waited long enough); rather, the question should be when it would have been predicted. The result of the independent test appears encouraging.

6. Relevance to atmospheric and climate predictions

After the onset of El Niño events, there appears to be a strong feedback from the ocean to the atmosphere, leading to the strengthening of anomalies in the atmospheric conditions (Rasmusson and Wallace, 1983). The 1982/83 event was no exception. Beginning in late 1981, equatorial SST started to rise in a linear trend in the central Pacific following a pattern very similar to the usual pattern observed in the previous six El Niño events. In contrast, in the eastern Pacific, SST did not begin to rise until September 1982 (Rasmusson and Wallace, 1983). The subsequent gradual eastward movement of the warm pool of water in the central Pacific appeared to be associated with a similar eastward movement of the atmospheric convection zone (Gill and Rasmusson, 1983). This gave rise to the unprecedented number of tropical cyclones and heavy precipitation in the central Pacific (Gill and Rasmusson, 1983). Extremely heavy precipitation was observed in the desert regions of northwest Peru, which resulted in severe flooding, while severe drought conditions persisted in Australia and Indonesia (Rasmusson and Wallace, 1983). Anomalies in the atmospheric conditions, which are apparently associated with this El Niño event, were observed at the middle and high latitudes as well (Krueger, 1983). The potential usefulness of the forecasting scheme in terms of atmospheric and climate predictions becomes apparent in light of the observation that the various anomalies in the oceanic and atmospheric conditions neither became evident nor were recognized to be associated with an El Niño event until late 1982.

7. Summary and conclusions

The feasibility of a forecasting scheme for predicting the onset of a major El Niño is demonstrated using a linear numerical model and the interannual components of the observed wind for 1961–82. A salient feature of the scheme is that it is based on simple physics and statistics, rather than solely on statistics.

The forecasting scheme used in this study can be considered as a dynamical version of the linear prediction model of Barnett (1984). It should be noted that a set of linear equations based on dynamics were used as a transfer function in this study, rather than the linear prediction equation used by Barnett. The dynamical model presented in this study should provide further information on how various disturbances generated in different regions of the equatorial Pacific propagate into the eastern Pacific, sometimes leading to the onset of a major El Niño.

The model upper layer thickness anomaly in the eastern Pacific, which was used as the predictand, was estimated after three months of steady wind integration. A lag time of three months is used to permit the propagation of a large El Niño type Kelvin wave across the Pacific Ocean. If the necessary wind changes required to generate a large El Niño type Kelvin wave have already taken place in the western and/or central Pacific, El Niño could be predicted one to three months in advance from knowledge of the wind field alone. Starting in November 1963, three-month steady-wind integrations were performed for the wind condition of each of the seven months (November to May), for each of the 15 years (1964 to 1978), the period that includes four El Niño years. The probability distribution function of the three-month running mean of the ULTA in the eastern Pacific after three-month steady-wind integrations was estimated separately for the El Niño and the non-El Niño groups using bootstrap estimates. Separation of the two probability distribution functions allows the use of the three-month running mean of ULTA as a criterion for forecasting El Niño. An independent wind data set for the period 1979–82 was used to test the feasibility of the forecasting scheme. Using a forecast criterion for false positive error (false alarm rate) $\leq 0.01$ that corresponds to false negative error $\geq 0.52 \sim 0.86$ (that corresponds to a probability of detecting the occurrence of an El Niño $\leq 0.14 \sim 0.48$), the 1982/83 El Niño would be forecast to be underway following the analysis of the April 1982 surface wind field, in striking contrast to the previously published reports that the 1982/83 El Niño started in the middle of the year. We caution that the details of a forecast criterion should be tailored to meet the requirements of any particular forecast.

A thicker-than-normal upper layer observed in the spring of 1982 in the eastern Pacific is considered to be a precursor of the 1982/83 El Niño. This is mainly
because it was significantly thick based on the historical data and, also, the major onset of the event followed this precursor by a few months. Another piece of information supporting this contention comes from the observed equatorial SST in the central Pacific, which started to rise in late 1981 and continued to increase following the usual El Niño pattern. In the eastern Pacific, although SST did not start increasing significantly until the major onset, slightly warm SST anomalies were already observed in May and June 1982. The way in which the precursor was related to the major onset should await further study.

The utility of the numerical model lies in the capability of issuing an early warning one to three months ahead of the arrival of a large El Niño type Kelvin wave at the eastern Pacific, provided timely wind data are available. The necessity of using the shipboard observed wind data limits exercises of this kind to only hindcasting simulation at the present time. Prospects of making satellite wind stress measurements at frequent intervals over the ocean in the next few years (Satellite Surface Stress Working Group, 1982) suggest the possibility of achieving even more reliable operational capability for early warning. Early forecasts of an El Niño event with a two- to three-month lead time is a minimum requirement for the successful execution of any field program to observe El Niño.

The most recent El Niño event, which started in 1982, appears to have been influenced significantly by the higher order baroclinic modes, particularly in the later stages of the event (Leetmaa, personal communication, 1983). It should be noted, however, that the initial pulse is carried by the first baroclinic mode. Therefore, the numerical model with only the equivalent first baroclinic mode should have sufficient resolution to forecast the arrival of the initial pulse at the eastern Pacific. Moreover, the apparent importance of the higher order baroclinic modes in the later stages of El Niño events should allow enough time to prepare for field observations like the one planned for the El Niño Rapid Response Project (National Research Council, 1983).

Despite the success of the forecasting scheme against the 1982/83 El Niño, relatively large β given by this technique needs to be addressed. It should be noted that the objective of this study was to establish a forecasting scheme for predicting the onset of a major El Niño. Therefore, the method is chosen to be one of low risk and low power in prediction performance. Better wind data certainly could improve forecast capability. However, further significant improvements in forecast performance and forecast lead time should wait for the establishment of a complete air–sea interaction model that takes into account the feedback from the ocean to the atmosphere.

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