STRATEGIES

FOR FUTURE CLIMATE RESEARCH

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ON THE SPACE-TIME STRUCTURE OF ENSO

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Abstract

We have investigated the space-time characteristics of the El Nino/Southern Oscillation (ENSO) phenomenon by analyzing observational data and data derived from an extended-range integration performed with a coupled ocean-atmosphere general circulation model. It is shown that a considerable portion of the ENSO-related low-frequency variability in both data sets is associated with a cycle that involves slow propagation in the equatorial heat content and the surface wind field. In contrast, sea surface temperature is dominated by a standing component. The existence of this cycle implies the possibility of ENSO predictions up to lead times of about one year. This is shown by conducting a large ensemble of predictions with a simple statistical prediction scheme.

1. Introduction

Large-scale air-sea interactions contribute considerably to climate variability on a wide range of time scales. On the short-range climatic time scale up to a few years the El Niño/Southern Oscillation (ENSO) phenomenon is the most prominent representative of such air-sea interactions. Bjerknes (1969) was among the first to describe ENSO as a coupled phenomenon by pointing out the close connection between the atmospheric phenomenon 'Southern Oscillation' and the oceanic phenomenon 'El Niño', both of which had been known for several decades. El Niño is characterized by the occurrence of anomalously warm surface waters in the entire tropical Pacific for about a year (Rasmusson and Carpenter (1982)), while the Southern Oscillation consists basically of a seesaw in surface pressure which involves opposite changes in the eastern and western hemispheres (Berlage (1957)). The ENSO phenomenon has received wide attention, because it not only influences regional and global climate (Rasmusson and Carpenter (1981), Cane (1983), Glantz et al. (1991)), but also the ecosystems in the Indo-Pacific region (Oceanus (1984)) and the economies of several countries.

As shown in Fig. 1a, typical indices of the Southern Oscillation and El Niño (as expressed by the so-called 'Southern Oscillation Index' (SOI) and by an index of eastern equatorial sea surface temperature (SST)) vary coherently out of phase on interannual time scales. As already hypothesized by Bjerknes (1969) these interannual variations arise from an instability of the coupled ocean-atmopshere system in the tropics (for a review see, for instance, Hirst (1990) or McCreary and Anderson (1991)). Bjerknes introduced the concept of the 'Walker Circulation', a thermodynamically direct atmospheric circulation cell parallel to the equator. The driving force for the Walker Circulation is the characteristic zonal SST gradient across the equatorial Pacific. A negative swing in the SOI, for instance, corresponds to a weak pressure gradient across the Pacific, resulting in weak winds. Since the SST in the eastern Pacific evolves as a dynamic response to the surface wind field, a drop in the SOI leads to warmer conditions in the eastern Pacific and to a weaker zonal SST gradient due to reduced upwelling of cold waters from below.

The reduction in the east-west temperature contrast reduces the strength of the Walker Circulation so that the zonal winds along the equator are further weakened, which further weakens the zonal SST gradient and so on. Conversely, a positive swing in the SOI goes along with stronger winds, stronger upwelling, with colder than normal SSTs and with an increased zonal SST gradient, which leads to a stronger than normal Walker Circulation, and stronger winds which further lower the SSTs in the eastern Pacific. Hence any initial disturbance tends to be amplified by unstable air-sea interactions.

It has now been well established that ENSO consists of a cycle which can be described as an oscillation between a warm and a cold phase, which are commonly referred to as 'El Niño' and 'La Niña', respectively (McCreary (1983), Barnett (1985), Wyrtki (1985), Zebiak and Cane (1987), van Loon and Shea (1987), Schopf and Suarez (1988), Graham and White (1988), Philander (1990), Xu and Storch (1990)). However, though there is a wide consensus of how anomalies grow during the extremes of ENSO, the proposed mechanisms for the maintenance of the ENSO cycle still differ markedly in the different studies. Here, we further investigate the ENSO mechanism by analyzing observational data from different sources and by analyzing the results of a coupled ocean-atmosphere general circulation model. We use an advanced statistical method based on the 'POP-technique' to derive the characteristic space-time structure from the data. We also discuss the possibility of ENSO predictions. It is shown that, using the characteristic precursor patterns derived in this study in a simple statistical prediction scheme, ENSO predictions are possible up to lead times of about a year.

2. Data

2.1 Observations

We used in our analysis bimonthly anomalies of SST, zonal surface wind stress, and the depth of the 20°C-isotherm (a measure of upper ocean heat content). It is known from linear stability analysis that these three quantities are the most important ones in tropical air-sea interactions. The analyzed period extends from 1967 to 1986. SST and surface wind stress anomalies cover the domain 124°E to 80°W and 20°N to 20°S. The 20°C-isotherm data were only available for the domain 120°E to 140°W and 20°N to 20°S. Observations with such a spatial and temporal coverage have not been used before in a simultaneous statistical analysis. The SST data come from a combination of Comprehensive Ocean Atmopshere Data Set (COADS) and Climate Analysis Center (CAC) analyses and are described by Graham and White (1990). The wind stresses were obtained from the Florida State University (FSU) data set (Goldenberg and O'Brien (1981), Legler and O'Brien (1984)). The data for the 20°C-isotherm have been compiled from subsurface temperature measurements by Mizuno and White (1991). The data coverage for this data set, especially in the first half of the analyzed period, is poor, resulting in large spatial and temporal gaps. These gaps have been simply filled with climatology or equivalently with zero anomaly. In order to remove high frequency noise and fluctuations with periods much longer than the characteristic ENSO period of a few years, we band-pass filtered the data retaining variations on time scales of 16 to 120 months. Each of the three quantities was then normalized with its mean field standard deviation so that all of them have the same weight in the statistical analysis.

2.2 Model data

In addition, we used data derived from a 26-year integration with a coupled ocean-atmosphere general circulation model (Neelin et al. (1991), Latif et al. (1992)), which is based on a zonally global high-resolution tropical ocean model and a global low order spectral atmosphere model. The coupled model simulates pronounced interannual variability, as can be inferred from the time series of the anomalous Southern Oscillation Index and of anomalous eastern equatorial SST (Fig. 1b). As in the observations (Fig. 1a), both indices vary coherently out of phase and fluctuate irregularly with a preferred time scale of about 3 years.

We used monthly anomalies of SST, zonal wind stress, and sea level. Sea level was chosen instead of the 20°C-isotherm, because it is a model variable and because it is also a good measure of upper ocean heat content. In order to account for spin-up problems, we omitted the first two years of the

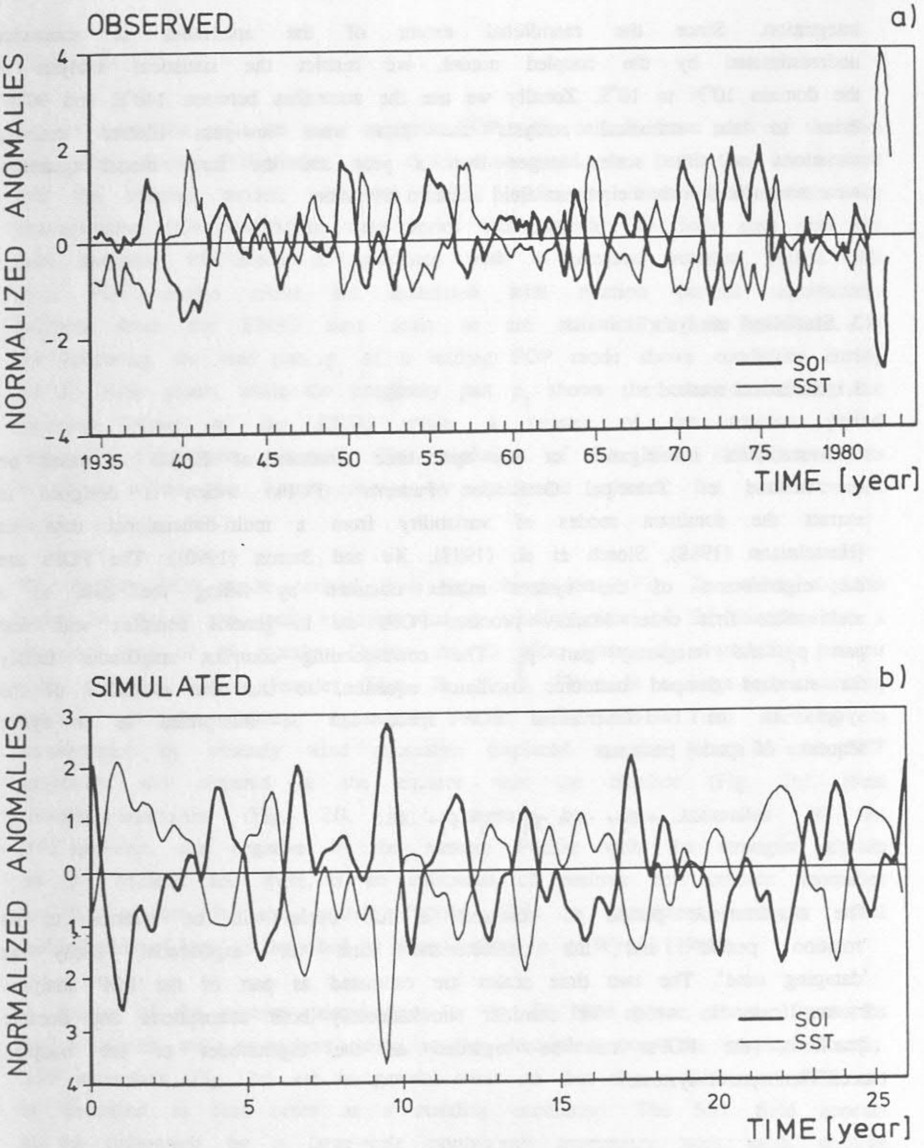

Figure 1: a) Time series of the Southern Oscillation Index (SOI) as defined by the anomalous pressure difference between Tahiti (French Polynesia) and Darwin (Australia) and of anomalous sea surface temperature in the eastern Pacific (Puerto Chicama, Peru). b) Same as in a), but derived from the extended range integration with the coupled ocean-atmosphere general circulation model. The model-SOI is defined as the anomalous pressure difference between an average over the eastern Pacific and the Indian Ocean. SST anomalies have been averaged over the Niño-3 region, which is an average over the eastern equatorial Pacific. All time series are normalized with their long-term standard deviation.

integration. Since the meridional extent of the anomalies is somewhat underestimated by the coupled model, we restrict the statistical analysis to the domain 10°N to 10°S. Zonally we use the anomalies between 140°E and 90°W. Prior to the statistical analysis the data were low-pass filtered retaining variations on time scales longer than a year and the three model quantities were normalized with their mean field standard deviation.

3. Statistical analysis

3.1 Statistical method

Our statistical investigation of the space-time structure of ENSO is based on the method of 'Principal Oscillation Patterns' (POPs) which is designed to extract the dominant modes of variability from a multi-dimensional data set (Hasselmann (1988), Storch et al. (1988), Xu and Storch (1990)). The POPs are the eigenvectors of the system matrix obtained by fitting the data to a multivariate first order Markov process. POPs are in general complex with real part p_1 and imaginary part p_2. The corresponding complex amplitudes satisfy the standard damped harmonic oscillator equation, so that the evolution of the system in the two-dimensional POP space can be interpreted as a cyclic sequence of spatial patterns:

$$\ldots\ldots \rightarrow p_1 \rightarrow -p_2 \rightarrow -p_1 \rightarrow p_2 \rightarrow p_1 \rightarrow \ldots\ldots \qquad (1)$$

The characteristic period to complete a full cycle will be referred to as 'rotation period' and the characteristic time for exponential decay as 'damping time'. The two time scales are estimated as part of the POP analysis. In our case, in which we consider simultaneously both atmospheric and oceanic quantities, the POPs can be regarded as the eigenmodes of the coupled ocean-atmosphere system.

3.2 Results

Here we describe only the most energetic POP-mode derived from each of the two data sets. These POP-modes are clearly associated, in both the observations and the coupled model, with the ENSO cycle, as was inferred from the corresponding POP coefficient time series (not shown). In both data sets the next energetic POP-mode is associated with a biennual rotation period. All other POP modes either are associated with rotation periods significantly different from the ENSO time scale or are statistically not significant. In the following, the real part p_1 of a leading POP mode shows conditions during the El Niño phase, while the imaginary part p_2 shows the conditions during the transition phase of the ENSO cycle, a quarter of the rotation period previously ('precursor patterns'). The evolution of La Niña (cold) conditions is given within this linear concept by the same patterns, but with reversed signs.

The leading POP mode derived from the observations (Fig. 2), which explains about 24 % of the total variance, has a rotation time of 39 months and a damping time of 48 months. During the El Niño phase the variability patterns show the well known features (Figs. 2b, d, f). There is a large-scale warming centered in the eastern equatorial Pacific (Fig. 2d). This warming is accompanied by westerly wind anomalies displaced to the west of the SST anomalies and centered at the equator near the dateline (Fig. 2b). Heat content anomalies (Fig. 2f), as expressed by the anomalies of the 20°C-isotherm, are negative in the western Pacific with the strongest signals off the equator, and there is an indication of positive heat content anomalies at the equator in the central Pacific. This is consistent with a zonal redistribution of heat, as described by many authors (e. g. Wyrtki (1985)).

A quarter of the rotation period prior to the El Niño phase, about 10 months earlier, ocean and atmosphere seem to be decoupled over the tropical Pacific. SST anomalies (Fig. 2c) are in general weak so that the evolution of SST can be described to first order as a standing oscillation. The SST field appears to be dominated by a large-scale north-south asymmetry with weak positive anomalies north of and at the equator and weak negative anomalies south of the equator. This pattern is reminiscent of the annual cycle and might reflect the well-known phase locking of ENSO to the annual cycle. Although SST anomalies

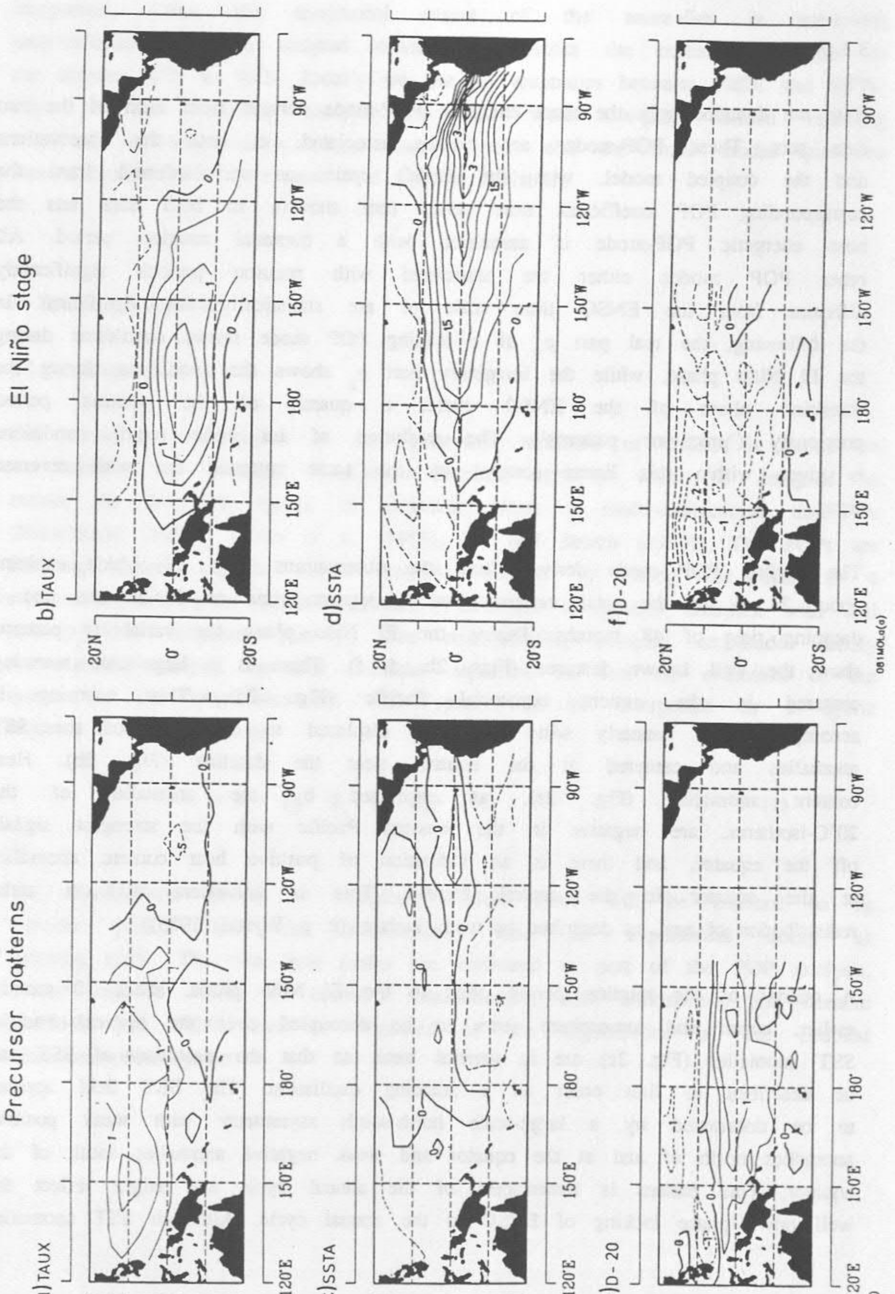

Figure 2: Evolution of anomalies during a typical El Niño as derived from the observations. The panels on the left-hand side show the precursor patterns of zonal wind stress (a), SST (c), and of the depth of the 20°C-isotherm (e), which preceed the El Niño stage by about 10 months. The panels on the right-hand side show the anomalous zonal wind stress (b), SST (d), and depth of the 20°C-isotherm (f) during an El Niño.

are weak, SST gradients are not negligible. The main gradients in the precursor pattern of the SST anomalies are a moderate meridional gradient near the equator in the central Pacific and a weak SST gradient in the north-west.

Clear signals can be identified in the precursor pattern of zonal wind stress (Fig. 2a) and upper ocean heat content anomalies (Fig. 2e). The precursor pattern of the 20°C-isotherm shows a signal in equatorial heat content propagating into the equatorial wave guide (Fig. 2e). These heat content anomalies were presumably generated during the preceding cold phase (Fig. 2f with reversed signs) and then 'reflected' at the western boundary. Overall the evolution of equatorial heat content is consistent with equatorial wave dynamics summarized in a conceptional model proposed by Schopf and Suarez (1988), which was generalized by Philander (1990). According to this 'delayed action oscillator' the ocean is not in equilibrium with the atmosphere and has a memory to past winds. The simplest version of the 'delayed action oscillator' involves only single wave modes. Let us briefly describe the evolution of an El Niño with the aid of this most simple version. The easterly wind anomalies over the western Pacific prevailing during La Niña force an upwelling Kelvin wave which propagates eastward along the equator and causes cooling in the eastern Pacific, where the thermocline is shallow. The ocean response to the easterly winds in the west, however, consists also of a downwelling Rossby wave, which propagates westward. This Rossby wave has its strongest signals off the equator. It does not influence the SST, because the thermocline is deep in the western Pacific. The Rossby wave then reflects at the western boundary into a downwelling Kelvin wave, which propagates eastward along the equator. Once it gets far enough into the eastern Pacific, it is able to affect the SST and, if the signal is strong enough, a positive SST anomaly might develop, which could grow by air-sea interactions into an El Niño. However, as pointed out by Philander (1990), the interpretation in terms of single wave modes is problematic, because at low frequencies many wave modes are excited so that the propagation speeds would be expected to be much slower than those expected from single waves. This is supported by our POP analysis (Fig. 2). The estimated phase speed obtained by following the anomalies in the 20°C-isotherm in the POP patterns p_1 and p_2 (Figs. 2 e, f) is about 25 cm/s, which is about one order of magnitude less than the speed of the gravest Kelvin wave mode.

The precursor pattern of the zonal wind stress anomaly shows the occurrence of a large scale westerly anomaly north of the equator, centered in the western Pacific near 150°E (Fig. 2a). Thus the zonal wind stress also involves a propagating mode. Most studies have attributed this feature to an interaction of the Pacific Trade Wind Field with processes outside the tropical Pacific (e. g. Barnett (1983), van Loon and Shea (1987)). Other studies relate the propagation in the zonal wind to an internal low-frequency mode in the atmosphere. However, it is also possible that the wind anomaly is directly forced by the SST gradient in the north-western Pacific (Fig. 2c), because the surface waters are very warm in this region so that even small changes in SST can have a significant impact on the atmospheric circulation. The meridional SST gradient, which is strongest near the equator in the vicinity of 150°W, could also drive westerly winds north of the equator. We return to this point later.

The leading POP mode derived from the extended range integration with the coupled model (Fig. 3) explaining 28 % of the variance is associated with a rotation period of 32 months and a damping time of 27 months. A cross-spectral analysis of the two coefficient time series revealed a longer rotation period of about 4 years (not shown). However, estimates of time scales from such relatively short records are subjected to large uncertainties. Overall, the evolution of El Niño in the coupled model appears to be very similar to the observed evolution (Fig. 2). While zonal wind stress and heat content anomalies are dominated by a propagating mode, SST anomalies evolve approximately as a standing oscillation.

The El Niño phase is characterized by large-scale warming centered in the eastern equatorial Pacific (Fig. 3d). This warming is accompanied by westerly wind anomalies (Fig. 3b). However, although the occurrence of westerly wind anomalies is consistent with the observations (Fig. 2b), they are simulated not far enough to the west of the SST anomalies, being centered near 150°W. The sea level during the El Niño phase shows an increase in heat content in the eastern and a reduction in heat content in the western Pacific. Positive anomalies in the east are centered at the equator and exhibit a Gaussian shape. The negative heat content anomalies in the west are strongest off the equator at about 7°N and 7°S. Such a structure in heat content is reminiscent of Rossby- and Kelvin wave structure.

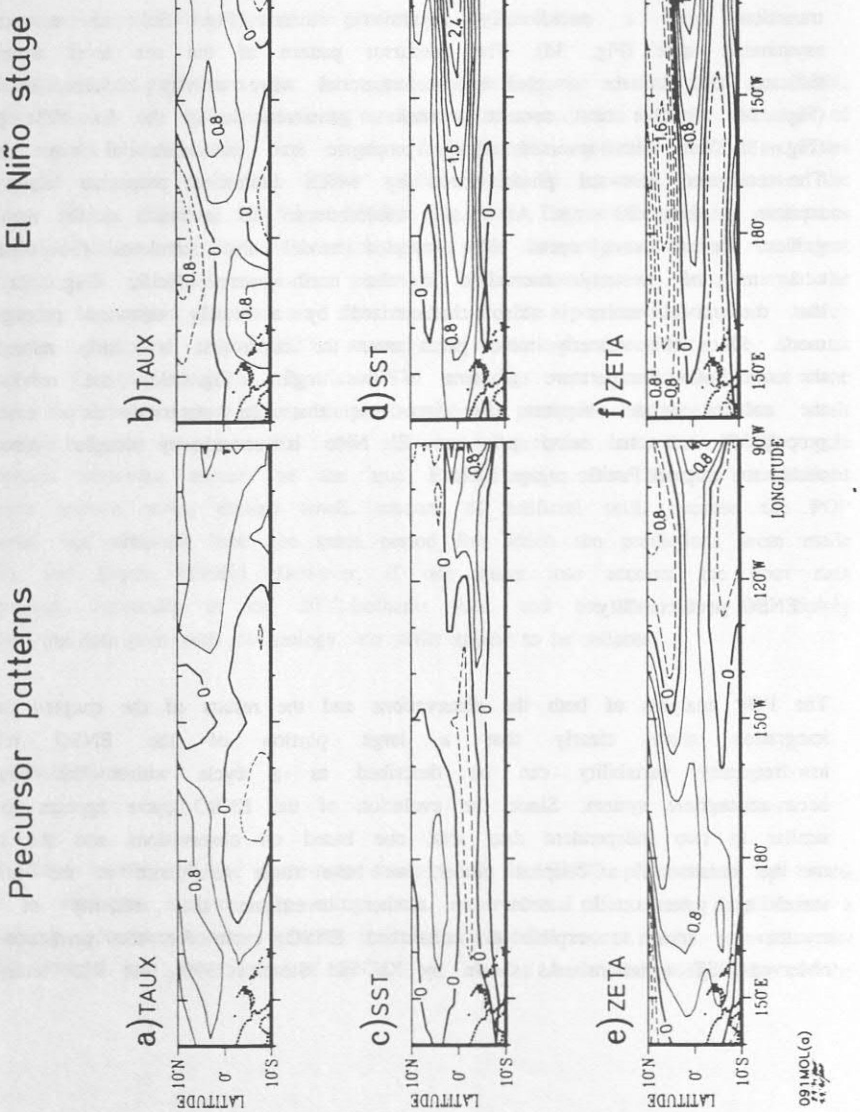

Figure 3: As Figure 2, but as derived from the run with the coupled ocean-atmopshere general circulation model. Instead of the depth of the 20°C-isotherm sea level was used as an alias of upper ocean heat content in e) and f).

The gross features of the precursor patterns (Figs. 3a, c, e) are also consistent with the observations (Figs. 2a, c, e). SST anomalies are rather weak and dominated by a north-south asymmetry with a moderate meridional gradient near the equator in the central Pacific (Fig. 3c). However, compared with the observations (Fig. 2c), the position of the region of strongest meridional gradient is somewhat displaced to the west. Nevertheless, it is interesting that the evoulution of SST in the coupled model also involves a transition from a meridionally asymmetric state (Fig. 3c) to a zonally asymmetric state (Fig. 3d). The precursor pattern of the sea level anomalies indicates that in the coupled model equatorial wave activity is also important (Fig. 3e). Positive heat content anomalies, generated during the La Niña phase (Fig. 3f, but with reversed signs), propagate into the equatorial wave guide. The estimated eastward phase speed by which anomalies propagate along the equator is about 20 cm/s. As in the observations, this is much slower than the gravest Kelvin wave speed. The coupled model also simulates the observed occurrence of westerly anomalies in the north-western Pacific (Fig. 3a) so that the model stress is also characterized by a slowly eastward propagating mode. Since the westerly wind patch over the north-west is clearly related to the meridional temperature gradient in this region (Fig. 3c), the results of the coupled model support the hypothesis that the observed slow eastward propagation in zonal wind prior to El Niño is caused by coupled processes within the tropical Pacific region itself.

4. ENSO predictability

The POP analyses of both the observations and the results of the coupled model integration show clearly that a large portion of the ENSO related low-frequency variability can be described as a cycle within the coupled ocean-atmosphere system. Since the evolution of the ENSO cycle appears to be similar in two independent data sets, one based on observations and the other on the results of a coupled model, we have some confidence in the derived variability patterns. In order to further investigate the reliabilty of our results, we tried to exploit the described ENSO cycle for the prediction of observed SST variations. As shown by Xu and Storch (1990), the POP technique contains an inherent, rather simple prediction scheme, which works as follows. First, the coupled ocean-atmosphere system is projected into the two-dimensional POP space. The prediction then simply consists of a rotation within the POP space, because the POP coefficients fulfill the standard damped harmonic oscillator equation. If, for instance, the coupled system is in a state which corresponds to the precursor patterns given in Fig. 2, then a quarter of the rotation period later, the coupled system is assumed to be in the El Niño phase. After the rotation in the POP space the fields are reconstructed and verifications of the predictions can be made.

We initialized predictions for each bimonth during the period 1967 to 1986. This amounts to 120 predictions in total. Each prediction has a duration of two years. Verifications are made for central equatorial SST anomalies averaged over the so called 'SST-3' region, which is an area average over the region 5°N - 5°S and 170°W - 120°W (Fig. 4a). The results of the predictions are summarized in Fig. 4b, which shows the anomaly correlation coefficient between the predicted and the observed SST anomalies as function of the forecast lag. Also shown are the results of the persistence forecast, which assumes that the initial SST anomaly is constant throughout the forecast period. Central equatorial Pacific SST anomalies are predictable about one year in advance with our simple statistical prediction scheme. This result provides further support that our statistical description of the ENSO cycle captures important aspects of the true ENSO cycle. Our anomaly correlations might contain some, though small, amount of artificial skill, because the POP model was obtained from the same period for which the predictions were made (Xu and Storch (1990)). However, if one takes into account the poor data coverage, especially in the 20°C-isotherm data, and the fact that we simply filled the data gaps with climatology, our skills appear to be reliable.

5. Conclusions

We have investigated the space-time structure of the ENSO phenomenon by means of a statistical analysis. By using both observational data and data from a coupled ocean-atmosphere general circulation model our results provide not only insight into the nature of ENSO but also a basis for comparison of the

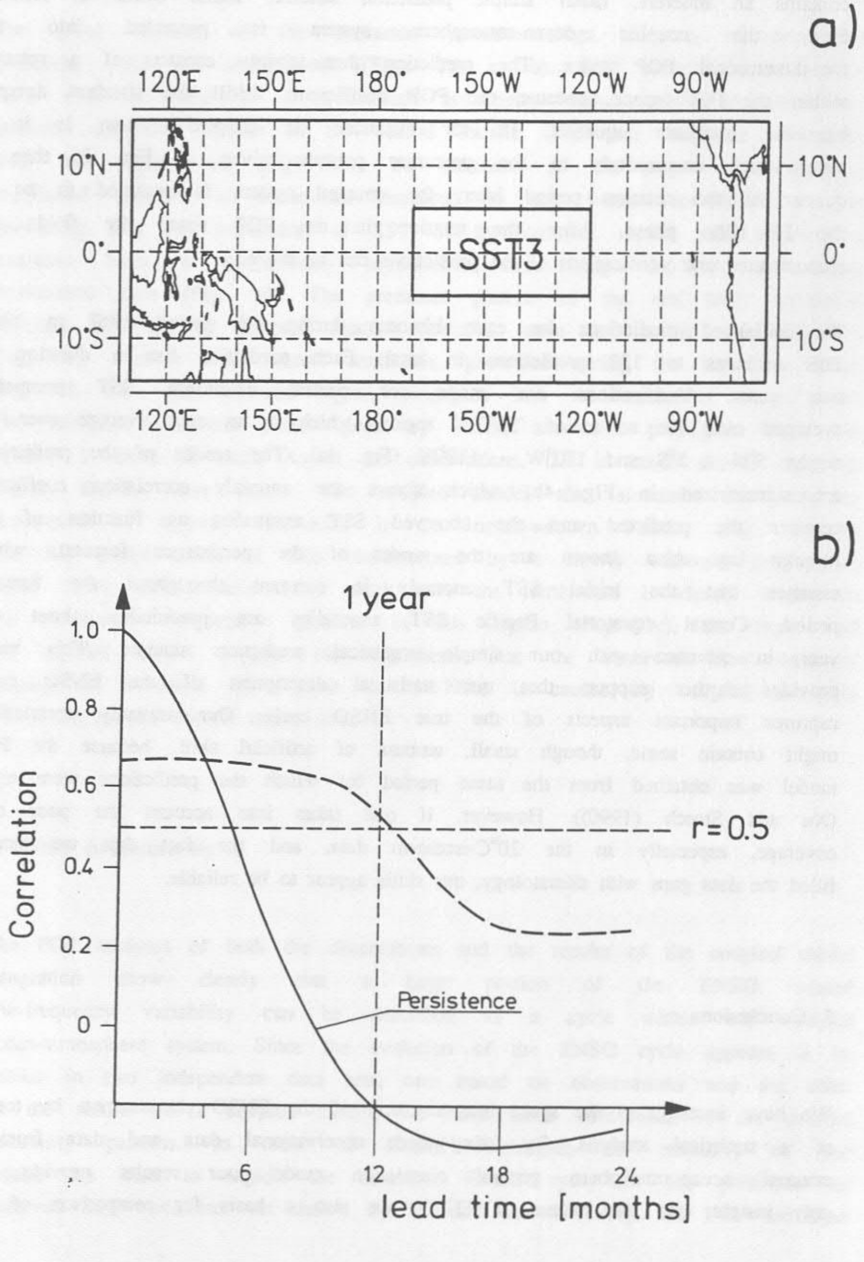

Figure 4: a) 'SST-3' region over which the results of the ENSO predictions have been averaged and verifications have been made for. b) Anomaly correlation coefficients of the ENSO predictions with the observed SST anomalies as a function of the forecast lag (dashed line). For comparison the results of the persistence forecast are shown as well (solid line).

performance of our coupled model with observations. Our results show that ENSO is definitely based on a cycle that involves standing SST anomalies and slow propagation in the upper ocean heat content and the surface wind field. A similar result using the coupled model of Zebiak and Cane (1987) is reported by Cane (1991, pers. communication). Variations in the oceanic heat content are clearly associated with the propagation of equatorial waves as expressed by the 'delayed action oscillator' (Schopf and Suarez (1988), Graham and White (1988)) in its generalized form (Philander (1990)).

The propagation in the surface wind field might also result from air-sea interactions over the tropical Pacific, as indicated by both the observations and the model results. We have shown that the SST anomaly field is characterized by a transition from a meridionally asymmetric state several months prior to El Niño to a zonally asymmetric state during El Niño. The meridionally asymmetric state resembles the pattern of the annual cycle and is characterized by weak absolute anomalies and a moderate meridional gradient near the equator. The changes in the winds are shown to be consistent with the evolution of the SST. However, the observations are certainly not good enough to address this point adequately.

The applied statistical technique of 'Principal Oscillation Patterns' (POPs) is also a convenient and powerful method to verify climate models. By comparing the dominant POP modes derived from the observations and the coupled model we have shown that present 'state of the art' coupled general circulation models are successful in simulating important aspects of the observed interannual variability in the tropical Pacific. As in the observations, the 'model ENSO' exhibits a strong cyclic component and similar propagation characteristics in all three analyzed quantities.

The existence of a cycle enables ENSO predictions to be made up to lead times of about a year, and this has been confirmed by our statistical predictions. Since all three analyzed quantities, SST, heat content, and zonal wind are important quantities in large-scale tropical air-sea interaction, and since these quantities can be measured with some accuracy from space, we can expect significant progress in ENSO predictions by assimilating satellite data into coupled ocean-atmosphere general circulation models. However, before these models can be used in ENSO predictions, the climate drift problem has to be carefully addressed (Neelin et al. (1991)).

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