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A review of ENSO prediction studies

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Abstract. A hierarchy of ENSO (El Niño/Southern Oscillation) prediction schemes has been developed which includes statistical schemes and physical models. The statistical models are, in general, based on advanced statistical techniques and can be classified into models which use either low-frequency variations in the atmosphere (sea level pressure or surface wind) or upper ocean heat content as predictors. The physical models consist of coupled ocean-atmosphere models of varying degrees of complexity, ranging from simplified coupled models of the 'shallow water'-type to coupled general circulation models. All models, statistical and physical, perform considerably better than the persistence forecast on predicting typical indices of ENSO on lead times of 6 to 12 months. The most successful prediction schemes, the fully physical coupled ocean-atmosphere models, show significant prediction abilities at lead times exceeding one year period. We therefore conclude that ENSO is predictable at least one year in advance. However, all of this applies to gross indices of ENSO such as the Southern Oscillation Index. Despite the demonstrated predictability, little is known about the predictability of specific features known to be associated with ENSO (e.g. Indian Monsoon rainfall, Southern African drought, or even off-equatorial sea surface temperature). Nor has the relative importance for prediction of different regional anomalies or different physical processes yet been established. A seasonal dependence in predictability is well established, but the processes responsible for it are not fully understood.

1 Introduction

The El Niño/Southern Oscillation phenomenon (ENSO) is the most important climate fluctuation on the short-range climatic time scale of a few months to several years. ENSO can be understood as an oscillation between a warm and cold state, commonly referred to as 'El Niño' and 'La Niña', respectively. El Niño is characterized by anomalously warm surface waters which cover a large part of the tropical Pacific for about one year. The warming is accompanied by significant anomalies in the circulation of both the tropical Pacific and the global atmosphere, such as reversals of complete current systems (Firring et al. 1983), a redistribution of heat in the Pacific (Wyrtki 1985), shifts in major rain systems (Ropelewski and Halpert 1989), or variations in global sea level pressure (Barnett 1985). In a first approximation, La Niña is simply an El Niño of opposite sign.

The ENSO phenomenon has received wide attention, because it not only influences regional and global climate, but also the ecosystems in the tropical Pacific and the economies of many countries (Rasmusson and Carpenter 1982; Barber and Chavez 1983; Cane 1983; Gill and Rasmusson 1983; Rasmusson and Wallace 1983; Oceanus 1984; Glantz et al. 1991). The understanding and ultimately operational prediction of ENSO is, therefore, of considerable public interest. During the last few years significant progress has been achieved in this issue. Presently, four prediction schemes are used routinely for ENSO prediction, two statistical schemes (one described by Graham et al. 1987a, b, and in the review of Barnett et al. 1988, and the other by Xu and Storch 1990) and two physical models (Inoue and O'Brien 1984, Cane et al. 1986).

In an earlier study, Barnett et al. (1988) described the behaviour of three prediction schemes in a case study of the 1986–1987 El Niño event and showed that this particular event was successfully forecast by the different prediction schemes several months in advance. Emphasis in this review is placed on those studies in which large ensembles of predictions have been conducted to estimate more reliable 'skills' for the prediction schemes under investigation. Some of the results have not been published previously and it therefore appears timely to compare results from as many as possible different models to obtain an overview of the 'state-of-the-art' in ENSO prediction. Emphasis is giv-

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en to the description of the performance of the prediction schemes, while model descriptions, normally described in the references cited, are kept as short as possible. The different proposed ENSO mechanisms which underlie the various prediction schemes are also discussed. This study is therefore not only designed to review the 'state-of-the-art' in the field of ENSO prediction, but also to provide a basis for discussion of how the ENSO cycle is maintained.

The prediction schemes reviewed are classified into purely statistical schemes, physical ocean models coupled to statistical atmosphere models, and coupled ocean-atmosphere models in which both components are presented by physical models (Table 1). The only scheme that is not included in this classification is the Inoue and O'Brien (1984) model, which is nevertheless described in the 'physical ocean models/statistical atmosphere models' section. We note that Table 1 is not complete. Only original models (not their derivatives) and models for which prediction "skill" measures were available have been included in Table 1. However, in the references we have tried to provide a complete list of relevant studies.

It was not possible to obtain results from the different prediction schemes in a standard format which would have allowed a direct comparison. The ensembles of predictions differ in the total number of forecasts, the time period for which they were made, the time interval between individual predictions, the predicted quantity , and the time interval over which the predictors and/or the predictands were averaged. For this reason the results are presented only in terms of anomaly correlations. It is hoped that by using sufficiently large ensembles of predictions, some of the problems which arise from intercomparing these very different sets of information are reduced. The fact that the various ENSO indices are highly correlated with each other should also eliminate some of the problem.

All prediction schemes decribed show significantly better skill than persistence at lead times of several months. No model, however, beats persistence during the first three months. The scheme of Xu and Storch (1990) is particularly interesting because it does not use any tropical information. This demonstrates the interconnections and global-scale character of the many feedbacks involved in ENSO and suggests that most successful prediction of ENSO can be achieved only through global coupled ocean-atmosphere general circulation models. Up to now only two models of this type have been applied to ENSO predictions, the model of Miyakoda et al. (1992) and the model of Latif et al. (1993a). Unfortunately, the model of Miyakoda et al. (1992) has been applied to only a small ensemble of predictions and has therefore not been included in this review.

The paper is organized as follows. In Section 2 the statistical models are described together with the hypothesis most frequently proposed to explain the ENSO mechanism. Section 3 deals with the performance of

Table 1. Table of the different ENSO prediction schemes divided into three classes

Statistical models	Physical ocean models/ statistical atmosphere models	Physical coupled ocean/atmosphere models
Barnett/Graham	Inoue and O'Brien	Cane et al.
CCA, global sea level pressure or tropical surface winds as predictors, prediction of seasonal (SST-3)-SST anomalies	Uncoupled ocean model, constant winds yes/no decision	Lamont coupled O/A model, prediction of monthly (Niño 3)-SST anomalies
Xu and Storch	Latif and Flügel	Latif et al.
POP, sea level pressure south of 15°S as predictors, prediction of monthly SOI-anomalies	MPI ocean/local feedback, prediction of monthly (Wright)-SST anomalies	MPI coupled O/A GCM, prediction of monthly (SST-3)-SST anomalies
Latif and Graham	Graham et al.	
CCA, heat content variations as predictors, prediction of monthly (SST-3)-SST anomalies	Lamont ocean/EOF atmosphere, prediction of monthly (Niño 3)-SST anomalies	
	Barnett et al.	
	MPI ocean/EOF atmosphere, prediction of monthly (SST-3)-SST anomalies	

physical ocean models which have been coupled to statistical atmosphere models. In Section 4 the performance of the fully physical coupled models is described. Section 5 addresses the seasonal dependence of the predictability. The paper is concluded with a summary and a discussion in Section 6.

2 Statistical models

Advanced statistical techniques have increasingly been used recently to identify the principal modes of climate variability on different space and time scales. These statistical methods can also be exploited for climate predictions (Davis 1977; Barnett and Hasselmann 1979; Hasselmann and Barnett 1981; Barnett and Preisendorfer 1987). The task in statistical prediction is to find an optimal set of precursors (predictors) that predicts best the future evolution of a certain quantity (predictand). However, in constructing statistical prediction schemes one has to find a trade off between statistical significance and skill. None of the data records used in ENSO prediction schemes go back earlier than 1950, so only a few realizations of ENSO events are captured. Hence care must be taken to avoid 'artificial skill' in fitting prediction parameters to such short records. The results presented here, however, are almost free of such artificial skill as described later. In contrast, physical models are not seriously affected by this problem, since model parameters are difficult to tune and generally constrained by physical laws or observations. Moreover, those model parameters that can be picked freely are typically not chosen at the values that are best for prediction purposes, as they are in statistical models.

2.1 Atmospheric models

In a series of studies it has been shown that low-frequency variability in global sea level pressure (SLP) exhibits a slowly evolving mode which is clearly associated with the ENSO phenomenon (e.g. Barnett 1983, 1985; van Loon 1984; van Loon and Shea 1985; Graham et al. 1987a; Xu and Storch 1990; Barnett et al. 1991). As shown by Barnett et al. (1991) using the technique of 'complex empirical orthogonal functions' (CEOFs) (Barnett 1983), this mode involves a slow eastward propagation of SLP anomalies from the Indian Ocean to the eastern tropical Pacific (Fig. 1 middle panel). Atmospheric general circulation models (AGCMs) also simulate this characteristic propagation when forced by observed SSTs (Fig. 1 upper panel). The corresponding amplitude time series (Fig. 1 lower panel) demonstrate the clear relationship to ENSO, with the most active periods in 1972/1973, 1976, and 1982/1983. However, the time series also exhibits quiet periods, as in 1974/1975. As will be discussed later, the quiet periods are less predictable than the active periods.

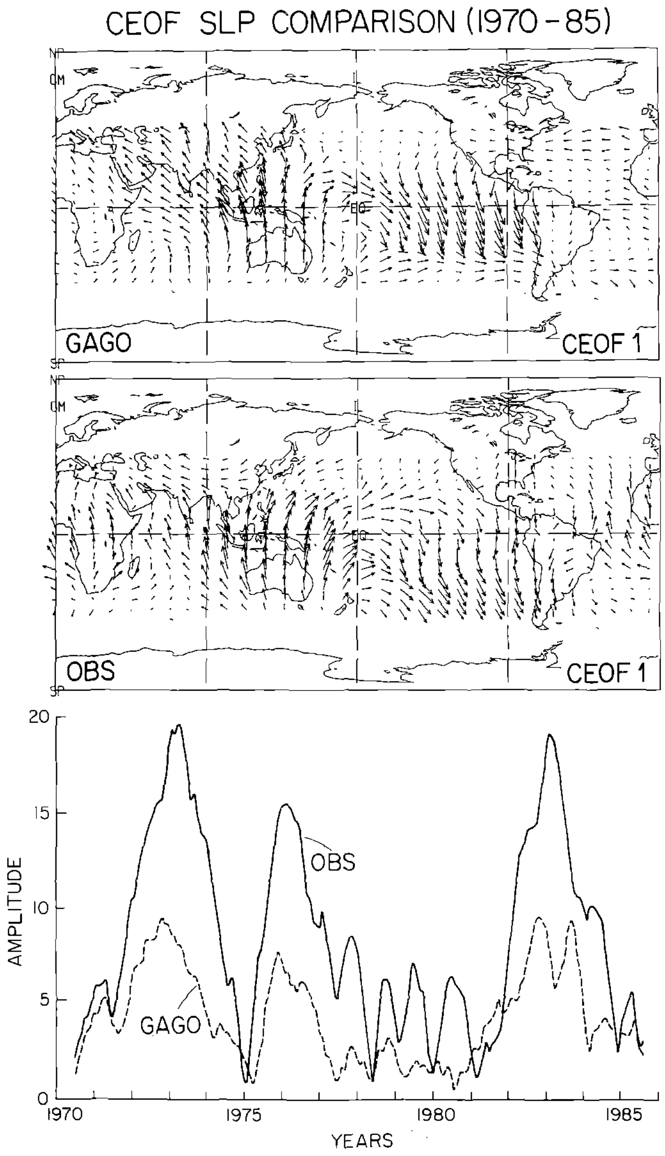

Fig. 1. Complex empirical orthogonal function (*CEOF*) analysis of band pass filtered (2 to 6 y) global sea level pressure anomalies. *Upper two panels:* amplitude-phase diagrams derived from an atmospheric GCM forced by observed SSTs (explained variance 48%) and from observations (explained variance 49%). The *length* of the *arrows* measures the amplitude of the anomaly, while the *direction* of the *arrow* measures the phase relative to Darwin (Australia) (*arrow* pointing to the *north*). If the *arrows* rotate *clockwise* when following them in an eastward direction, sea level pressure anomalies propagate eastward. *Lower panel,* corresponding amplitude functions. From Barnett et al. (1991)

Several explanations have been offered for the observed low-frequency variability in sea level pressure. Here only two are described. The first is based on an interaction of land surface processes and the hydrological cycle over Eurasia with the Monsoon circulation and the Pacific trade wind field (Barnett et al. 1989). Numerical experiments with an AGCM showed that heavier than normal snow cover over Eurasia reduces the warming of the continent in summer due to the combined effects of snow, soil and atmospheric moisture, thus leading to a weakening of the Indian summer monsoon (Hahn and Shukla 1976). The remote response associated with this perturbation involves also a weakening of the western Pacific low pressure system, which results in a weakening of the trade winds and the occurrence of persistant westerly surface wind anomalies in this region. As shown in Barnett et al. (1989), these surface wind anomalies may have a significant effect on the SST in the equatorial Pacific, which could be amplified by unstable air-sea interactions.

A competing hypothesis was offered by van Loon (1984) and van Loon and Shea (1985). According to this hypothesis, the trough in the westerlies over the South Pacific fails to amplify to its normal strength north of 45°S in the year before a warm event. This results in northerly surface wind anomalies in the region of the South Pacific convergence zone (SPCZ), which leads to a warming of the surface waters in this region, enhanced convection, and a lowering of sea level pressure over large parts of the tropical and subtropical Pacific. As shown by Xu and Storch (1990), this sequence of events results in a slow eastward propagation of SLP anomalies (see Fig. 1 middle panel). Further support of this picture was provided by numerical experiments with an atmospheric general circulation model by Storch et al. (1988a), in which the sensitivity of the circulation to SST anomalies in the region of the SPCZ was investigated. They suggested that the SST anomalies in the region of the SPCZ can lead to atmospheric conditions favourable for El Niño, i.e. persistent westerly wind anomalies in the western equatorial Pacific.

The low frequency variations in sea level pressure have been used in several statistical prediction studies as predictors for the future development of the ENSO cycle (Graham et al. 1987a, b; Barnett et al. 1988; Xu and Storch 1990; Barnston and Ropelewski 1992). Here we show only results from the schemes of Barnett/Graham and Xu and Storch (Table 1). The scheme of Barnston and Ropelewski (1993) is very similar to the Barnett/Graham canonical correlation analysis (CCA) technique (Hotelling 1935; Barnett and Preisendorfer 1987; Graham et al. 1987a, b; Barnett et al. 1988), which identifies the dominant patterns in each of the two data sets which are most highly correlated. As predictors the time history of one year of the SLP anomaly field is used. The predictand is an area average of SST anomalies over the 'SST-3' region (5°N–5°S, 170°W–120°W), and predictions are made on a seasonal basis for the period 1970 to 1989. The results of the predictions (Fig. 2) have been cross validated in the sense that the statistical model was developed using data from a time period which was excluded (and essentially uncorrelated with) from the prediction time period (Graham et al. 1987a, b). The results can, therefore, be regarded as true 'forecast skills'. The CCA model gives significantly better results than the persistence forecast at lead times longer than one season. If one adopts a threshold value for the anomaly correlation of 0.5 for useful predictions, the CCA model has useable skill up to three seasons. As pointed out by Barnett et al. (1988), the success of the CCA model at lead times longer than two seasons is due to SLP variations outside the tropical Pacific. This is consistent with the evolution of SLP anomalies shown in Fig. 1 and emphasizes again the global nature of ENSO. However, this result does not necessarily imply a causal relation: it is possible that SLP changes over the Indian Ocean are a detectable response to ocean-atmosphere interactions in the Pacific sector.

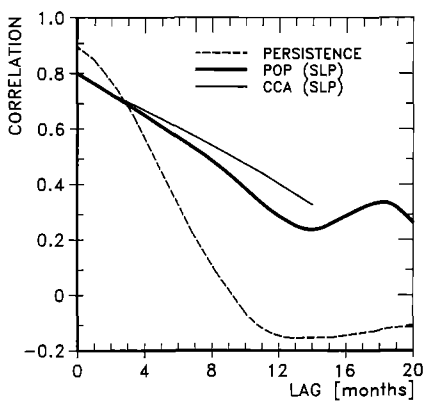

Fig. 2. Correlation skill of the sea level pressure models as function of the lead time (months). The *CCA*-model is based on seasonal predictions of SST anomalies averaged over the 'SST-3' region. Correlations for this model are drawn at the centre of a particular season. The *POP*-model is based on monthly predictions of the Southern Oscillation Index (*SOI*). For reference also shown is the persistence of a slightly smoothed version of the *SOI*

Similar results were obtained from the prediction scheme of Xu and Storch. This scheme is based on the technique of principal oscillation patterns (POPs) (Hasselmann 1988; Storch et al. 1988b). The POPs represent the eigenvectors of a first order autoregressive (Markov) model fitted to the data. The POPs generally occur in complex conjugate pairs, their amplitudes satisfying the standard damped harmonic oscillator equation. The prediction therefore consists simply of a damped rotation in the two dimensional POP space. Xu and Storch designed their POP prediction model to test the 'SPCZ-hypothesis' of van Loon and Shea (1985) and therefore use as predictors only SLP variations in the latitude band 15°S to 40°S. Predictions have been performed on a monthly basis for the period April 1974 to September 1988. The predictand is a slightly smoothed version of the traditional Southern Oscillation index 'Tahiti – Darwin' (SOI), which is highly correlated with typical SST indices, such as 'SST-3' or 'Niño-3', and represents a good description of the state of ENSO. As discussed by Xu and Storch (1990), the artificial skill in their POP predictions is expected to be small, because they only used a single dominant POP mode in their prediction scheme. Their skills nevertheless represent 'hindcast skills', since the POP model was not constructed from an independent time period. The hindcast skills of the POP model are slightly lower than the forecast skills of the CCA model (Fig. 2), but the study of Xu and Storch (1990) shows clearly that useful information on the future development of ENSO can be obtained from the regions outside the equatorial belt in the Southern Hemisphere. In summary, both SLP-models, the CCA and the POP model, emphasize the global character of ENSO.

2.2 Oceanic models

The importance of the subsurface memory, as expressed by slow variations in equatorial Pacific upper ocean heat content, for the maintenance of the ENSO cycle has been shown in many observational and modeling studies (Wyrtki 1975, 1985; Busalacchi et al. 1983; McCreary 1983; White et al. 1987; Zebiak and Cane 1987; Schopf and Suarez 1988; Graham and White 1988; Philander et al. 1991; Chao and Philander 1991; Latif and Graham 1992; Latif et al. 1993a, b). Wyrtki (1985) describes the ENSO cycle as ‘a combination of atmospheric randomness and a deterministic ocean’. He hypothesized that prior to El Niño events, warm water is accumulated in the western Pacific until the warm water pool becomes unstable to high frequency forcing by the atmosphere. Wyrtki (1985) showed that El Niño is associated with a loss of heat of the entire equatorial region and explained the time between El Niños as the time required to refill the equatorial heat reservoir. The important role of mean equatorial heat content was also confirmed by coupled model experiments described by Zebiak and Cane (1987), who showed that interannual oscillations did not occur if the mean thermocline was too shallow (so that the integrated heat content was always too low).

Although Wyrtki’s ‘pile up’ hypothesis is inherently non-linear, it can be approximated by wave dynamics, as expressed by the ‘delayed action oscillator’ of Schopf and Suarez (1988) (also see Battisti 1988; Cane et al. 1990; Chao and Philander 1991). This is supported by the work of Graham and White (1988) and a POP analysis of equatorial Pacific sea level anomalies for the period 1975 to 1988 (Fig. 3) (Latif and Flügel 1991). The same data analyzed by Latif and Flügel (1991) have been used by Wyrtki (1985). The POP mode shown accounts for 39% of the total variance and is clearly associated with the ENSO phenomenon as can be inferred from the POP coefficient time series (Fig. 3c). Similar results were obtained by Latif and Flügel (1991) and Latif and Graham (1992) from an analyses of equatorial surface and subsurface temperature anomalies (Fig. 4). The temperature variations were taken from a run with an oceanic general circulation model (OGCM) which was forced by observed winds. The evolutions of anomalous sea levels and temperatures are both consistent with the ‘delayed action oscillator’.

According to the ‘delayed action oscillator’ – scenario, the easterly wind anomalies over the western Pacific prevailing during the cold phase (La Niña) force an upwelling Kelvin wave packet which propagates eastward along the equator and causes cooling at the sea surface in the eastern Pacific, where the thermocline is shallow. The ocean response to the easterly winds in the west, however, also consists of a downwelling Rossby wave packet, which propagates westward. This Rossby wave response has its strongest signals off the equator (Fig. 3b). It does not influence the SST, because the thermocline is deep in the western Pacific. The Rossby waves then reflect at the western boundary into a packet of downwelling Kelvin waves which have maximum amplitudes at the equator and propagate eastward (Fig. 3a). Once it has propagated far enough into the eastern Pacific, it is able to affect the SST, and a positive SST anomaly develops which can grow by unstable air-sea interactions into an El Niño (Fig. 3b, but with reversed signs) which is characterized by anomalously high sea levels in the eastern and anomalously low sea levels in the western Pacific.

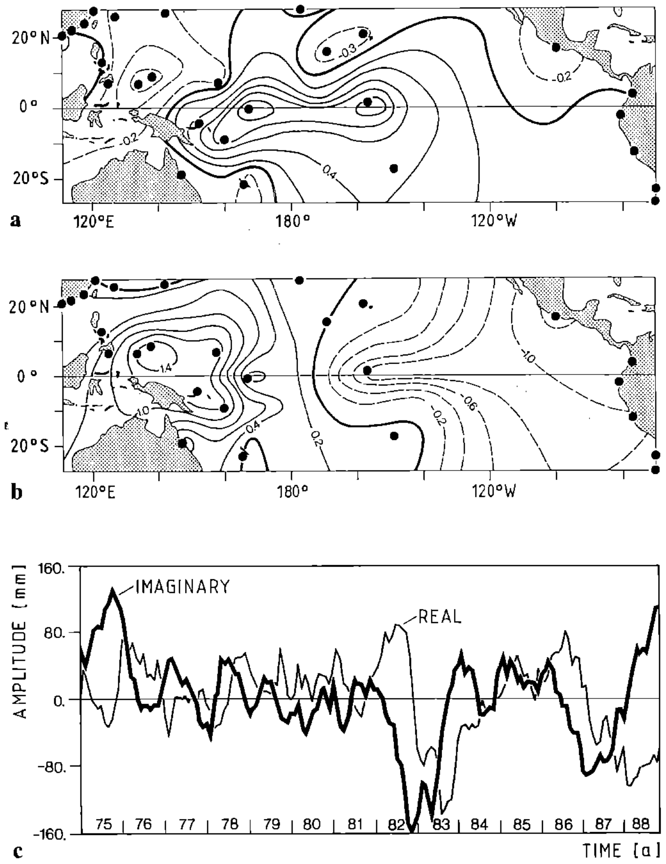

Fig. 3a–c. POP analysis of observed sea level anomalies in the tropical Pacific. The rotation period is 40 months and the decay time is 16 months. The explained variance amounts to 39%. **a** Real part; **b** imaginary part; **c** *POP* coefficient time series. From Latif and Flügel (1991)

In this view ENSO is a low-frequency basin-wide mode of oscillation. Many wave modes are excited and the effective propagation speeds would be expected to be much slower than those expected for single waves (Cane and Sarachik 1981; Münnich et al. 1991; Chao and Philander 1991). This is supported by our POP analysis. The estimated phase speed obtained by following the sea level anomalies along the equator in the POP patterns is about 25 cm/s, which is about an order of magnitude less than the speed of the gravest Kelvin wave mode. The slow eastward propagation of anomalies can be seen also in the subsurface temperatures at

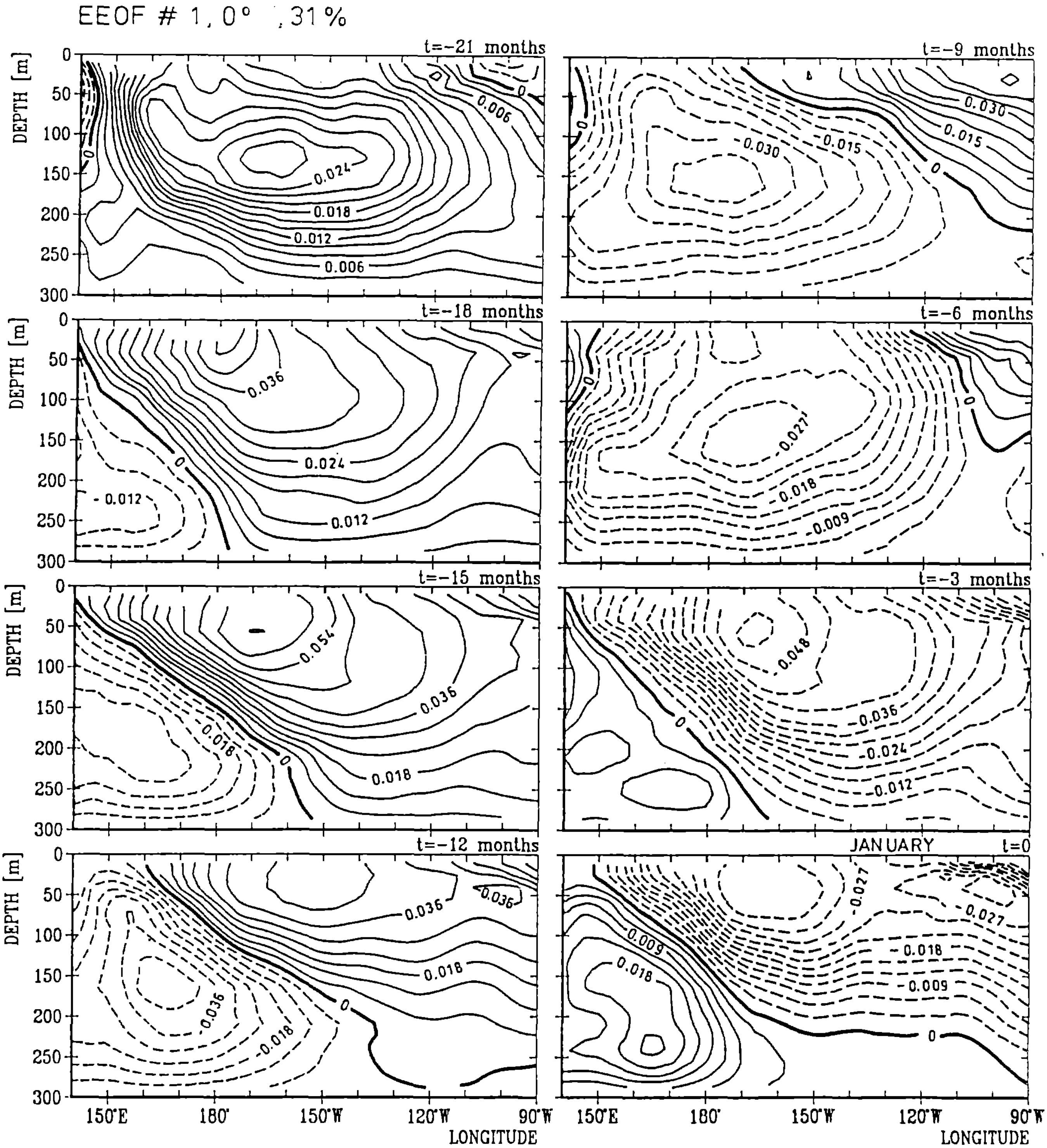

Fig. 4. Spatial patterns of the leading extended empirical orthogonal function (*EEOF*) derived from equatorial temperature anomalies simulated by an OGCM forced by observed winds for the period 1963–1985. Individual maps are three months apart from each other. The explained variance of this mode amounts to 31%. From Latif and Graham (1992)

the equator in the numerical simulation with the OGCM (Fig. 4).

The study of White et al. (1987) was the first in which the slow variations of equatorial heat content were used as predictors in a statistical prediction scheme. However, White et al. (1987) focused on the northwestern part of the Pacific basin only, where Rossby wave activity is expected to be strongest (see also Fig. 3b). Using the technique of complex empirical orthogonal functions (CEOFs), White et al. (1987) constructed a hindcast index from the output of a wind-driven reduced gravity model (Busalacchi et al. 1983) with which they were able to predict ENSO about one year in advance.

More recently, Latif and Graham (1992) used the output of an OGCM forced by observed winds to predict tropical Pacific SST. The pediction scheme is based on CCA analysis. Time evolutions of temperature anomalies in vertical sections along certain latitudes, expressed in terms of extended empirical orthogonal functions (EEOFs) were used as predictors. Predictions were made on a monthly basis for the time period 1962 to 1986. The results are summarized in Fig. 5, which shows the cross validated anomaly correlations of the predicted with the observed SST anomalies averaged over the 'SST-3' region. At lead times beyond six months, the highest skills are attained from a model that uses the time history of temperature anomalies in the section along 5°N. The strongest signals at this latitude were shown to be located at subsurface levels between 150 m and 200 m. The results of Latif and Graham (1992) are consistent with the results of White et al. (1987) and demonstrate the importance of off-equatorial heat content anomalies for the ENSO cycle. If the wind stresses over the tropical Pacific (which drive the OGCM) in place of the temperature anomalies are used as predictors in the statistical prediction scheme, no skill was obtained at lead times longer than a few months. This indicates that the role of the ocean as a complicated integrating space-time filter of the driving wind stresses is essential for achieving deterministic ENSO predictions. If the ocean model was linear, a linear statistical scheme could in principal also derive the necessary information directly from the wind field. The construction of such a statistical scheme, however, would require very long time series.

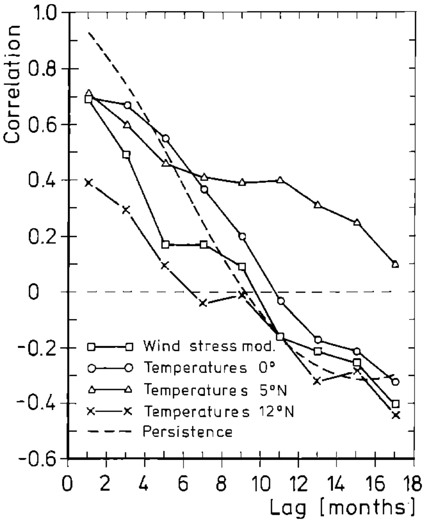

Fig. 5. Statistical prediction of SST anomalies averaged over the 'SST-3' region using surface and subsurface temperature anomalies at different latitudes. The temperature anomalies were derived from an oceanic GCM forced by observed winds. Shown are cross-validated correlations as function of the lead time (months). Also given for reference are the results of the persistence forecast and when the wind stresses used to drive the ocean model are used as predictors in the CCA prediction scheme. From Latif and Graham (1992)

3 Physical ocean models/statistical atmosphere models

The next step in the hierarchy of prediction schemes introduces the physical laws that govern the ocean's response to varying atmospheric boundary conditions. The feedback loop is completed by expressing the atmosphere's response to variations in the oceanic boundary conditions by a statistical (empirical) model inferred from data. The use of statistical atmosphere models can be justified, because at low frequencies the atmosphere over the tropical Pacific can be regarded as a strongly forced quasi-equilibrium system governed by the state of tropical Pacific SST. Since the empirical atmosphere models are derived from data, they can simulate the full atmospheric feedback loop. However, because the atmosphere is assumed to have no inertia the memory of a coupled system consisting of such a 'slave' atmosphere and a dynamical ocean model resides entirely in the ocean.

The empirical atmospheric models considered so far are anomaly models in which the anomaly fields are defined relative to the seasonal cycle (however, there is, in principal, no problem in including the annual cycle, as shown by Syu et al. (1992)). By running the empirical atmosphere models in a hindcast mode with prescribed observed SST anomalies, they have been shown to successfully simulate the observed variations in surface wind stress over the equatorial Pacific (Latif and Flügel 1991; Barnett et al. 1993). The empirical atmospheric models have the advantage of being very economical so that when coupled to an ocean model large ensembles of predictions can be conducted to estimate reliable skills.

The simplest scheme in case is that of Inoue and O'Brien (1984) in which the atmospheric feedback is assumed to be constant. This scheme is based on a linear reduced gravity ocean model that successfully simulates variations in thermocline depth or sea level in the tropical Pacific (Busalacchi et al. 1983). In the predictive mode, the ocean model is spun up with observed wind stress anomalies up the prediction start time. Thereafter the wind stress anomaly is held constant, while the ocean evolves freely. The scheme shows significant skills up to about 3 months and can be regarded as a useful scheme for forecasting the onset of major extremes in the ENSO cycle, including the demise of warm events.

At longer lead times, changes in the atmospheric feedback become important. Latif and Flügel (1991) were the first to use an empirical atmosphere model in coupled prediction experiments. They used an OGCM coupled to an extremely simple empirical feedback model in which the anomalous surface wind stress at a given grid point was expressed only in terms of the local SST anomaly. The seasonal variation of the feedback was not taken into account. Although this coupled model showed marginal skill at lead times up to about one year in perfect model experiments, the model is not well suited for the prediction of observed SST anomalies at these lead times.

In a later study, Graham et al. (1992) coupled the oceanic component of the coupled model of Zebiak and Cane (1987) to an empirical atmospheric model. They determined the atmospheric feedback from a regression analysis of SST and wind stress anomalies in EOF space, so that remote influences in the SST anomaly field could be taken into account. Furthermore, the statistical model accounts for the seasonal dependence of the feedback by using different models for each month. Results of two sets of predictions are shown. In the first case (case I), prediction experiments were conducted for each month within the period 1967 to 1990 and the atmospheric feedback was determined from the same time period, but a cross validation procedure was applied. In the second case (case II), the feedback was determined from the independent time period 1967 to 1975 and predictions were made for the period 1976 to 1990, thus simulating a real forecast situation. Initial conditions for the predictions were obtained in both cases from a run with the ocean model forced by observed wind stresses. Verifications were made for monthly SST anomalies averaged over the 'Niño-3' region (5°N–5°S, 150°W–90°W).

This coupled model yields useful ENSO predictions for lead times up to about one year (Fig. 6). However, more encouraging than the actual level of the correlation at a certain lead time, say at a lead of one year, is the shape of the skill curve, which decreases only slowly with increasing lead time. Some marginal skill is found even at lead times longer than a year. This behaviour is markedly different from the purely statistical models, which show a much faster drop in the anomaly correlation. This demonstrates the potential long lead time-advantage of coupled models and the inherent limitations in statistical prediction. This will be found to be even more pronounced when both oceanic and amtospheric models are considered fully physical.

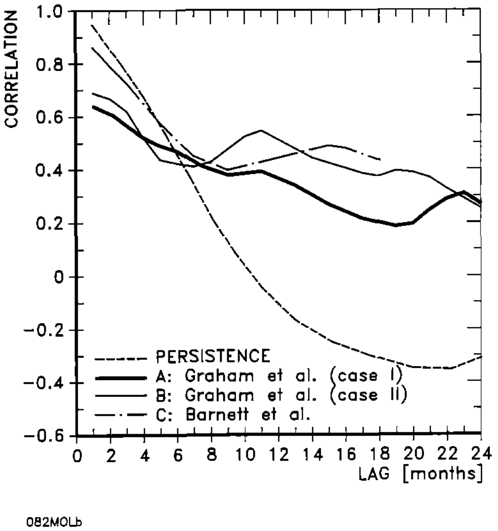

Fig. 6. Prediction of SST anomalies averaged over the 'Niño-3' region with physical ocean models coupled to statistical atmosphere models. The *thick solid curve* shows the cross-validated results obtained for the period 1967–1990 (Graham et al. case I). The *thin full curve* shows the results for a real forecast situation, when the statistical atmosphere model was constructed from the period 1967–1975 and predictions were made for the period 1976–1990 (Graham et al. case II). The *dashed dotted curve* shows the correlation skill of the Barnett et al. model. The *dashed curve* gives the results for the persistence forecast

Similar results were obtained by Barnett et al. (1992) (Fig. 6). They coupled an OGCM to a statistical (EOF) atmosphere that was derived using the same procedure as Graham et al. (1992). The statistical atmosphere model was derived from the period 1967 to 1985 and predictions were made for the period 1967 to 1990. Both 'hybrid' coupled models exhibit substantial skill at lead times of 12 to 18 months in particular regions of the tropical Pacific. While the Graham et al. (1992) model shows highest skills in the eastern Pacific and performs less satisfactory in the central Pacific, the Barnett et al. (1993) model performs better in the central Pacific and less satisfactory in the eastern Pacific. Outside the equatorial wave guide (e.g. 10° latitude), both coupled models do poorly due to lack of information on air-sea heat exchange. A fully coupled ocean-atmosphere GCM will be required to overcome this latter deficiency. In the meantime, the skill of the two coupled models appears adequate to provide winter SST forecasts that then can be used in a contemporaneous atmospheric general circulation model (AGCM) to predict Northern Hemisphere winter climate.

4 Physical coupled ocean-atmosphere models

The tropical behaviour of many coupled ocean-atmosphere models were recently described by Neelin et al. (1992). Two major sources of tropical interannual variability were identified. Coarse-resolution coupled models (e.g. Meehl 1990; Lau et al. 1992) prefer the 'SST mode' (Neelin 1991), for which processes within the surface mixed layer are crucial. Slow zonal phase propagation in SST and zonal wind stress is characteristic for this type of variability. In contrast, the interannual variability in high-resolution models (e.g. Philander et al. 1992; Latif et al. 1993a) is consistent with the 'delayed action oscillator' – scenario. SST and zonal wind stress evolve in place and equatorial wave propagation is essential to maintain the oscillation. The coarse-resolution models are generally global models and therefore allow the investigation of the global-scale nature of ENSO. Although such models were not yet applied to ENSO predictions, they were shown to capture some aspects of the global nature of ENSO, which is important with respect to the predictability of extra-tropical ENSO-related climate anomalies.

Only two high-resolution fully physical coupled ocean-atmoshere models have been used in ensembles of ENSO predictions. Firstly the non-linear anomaly model of Zebiak and Cane (1987), hereafter referred to as 'Lamont-model', and secondly the coupled general circulation model of Latif et al. (1993a). The Lamont model has been widely used in prediction and predictability studies (Cane et al. 1986; Battisti 1988; Goswami and Shukla 1991; Cane 1991; Graham et al. 1992). It is a regional model covering the domain of the tropical Pacific. Thus, in this model there is an inherent assumption that the cause of ENSO lies entirely in this region. The model simulates realistically interannual variability in tropical Pacific SST. The mechanism for the interannual variability is closely related to the subsurface memory of the system (Zebiak and Cane 1987; Battisti and Hirst 1989) as described with respect to the statistical schemes based on heat content variations (Sect. 2.2).

Predictions were initialized each month in the period 1972 to 1991 and verified versus the observed SST anomalies averaged over the 'Niño-3' region. Oceanic initial conditions are obtained in the same way as by Graham et al. (1992) from an uncoupled control integration in which the ocean model is forced by observed winds. The atmospheric initial conditions are obtained by forcing the atmospheric model with the SST anomalies simulated by the ocean model in the same control integration. The anomaly correlations (Fig. 7) are slightly higher than in the case with empirical feedback (Fig. 6), which indicates a sensitivity to the details of the coupling.

The coupled general circulation model of Latif et al. (1993a) consists of a high-resolution ocean model extending over all three oceans between 70°N and 70°S and a global low resolution atmosphere model. The two models exchange information within the region 30°N to 30°S. The models are coupled without any flux correction, such as the technique of Sausen et al. (1988). Although the coupled GCM exhibits considerable climate drift, it simulates realistically the ENSO cycle in a 26 year control integration. As in the Lamont model, the subsurface memory of the coupled system plays an important role for the interannual variability.

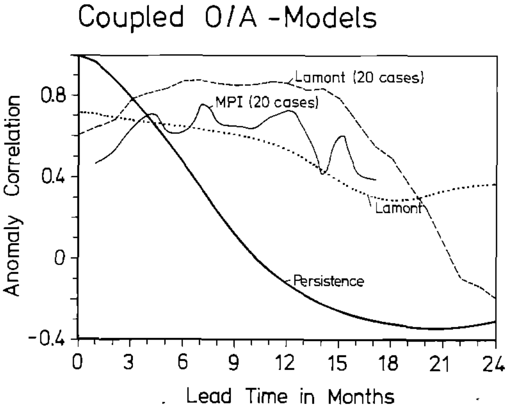

Fig. 7. Prediction of equatorial SST anomalies with fully coupled ocean-atmosphere models. Shown are correlations as function of the forecast lag (months). The curve labelled '*Lamont*' shows the results obtained with the coupled model of Zebiak and Cane (1987). The curve labelled '*MPI*' shows the results obtained with the coupled general circulation model of Latif et al. (1993a). The curve labelled '*Lamont (20 case)*' shows the anomaly correlations for the case in which the Lamont model is applied to the same 20 cases the MPI model was applied to. Shown are also for reference the results of the persistence forecast

For predictions, the coupled model is initialized as follows (Latif et al. 1993b). The ocean model is spun up with observed wind stress anomalies, which are added to the climatological wind stresses obtained in the 26 year control integration with the coupled model. Thereafter the atmospheric model is forced by the ocean model's SST for one month. This procedure minimizes the 'climate drift' problem, which arises from the fact that the observed and coupled model climates deviate and are characterized by different air-sea fluxes. Predictions were initialized for the warm periods of 1972, 1982/1983, and 1986/1987, and for the cold periods of 1973 and 1988. Each period was predicted using four sets of different initial conditions separated by three months. This yields a total of only 20 predictions. SST anomalies are computed by subtracting the climatology obtained in the coupled 26 year control integration. The coupled GCM is successful in predicting the observed changes in SST in the 'Niño-3' region up to lead times of one year (Fig. 7). Only 'events' were chosen for the prediction experiments, however, so that the results should be treated with considerable caution, since it is well known that active periods are more predictable than quiet periods. Thus, a direct comparison of the Lamont with the MPI coupled model is premature. Consequently, the performance of the Lamont model for the same 20 cases is also shown in Fig. 7. In summary, both coupled ocean-atmosphere models demonstrate the possibility of useful routine ENSO forecasts for lead times of about one year.

5 Seasonality

Many of the described prediction schemes show a pronounced seasonal dependence in their skills. Common to the schemes of Barnett/Graham; Latif and Graham; Latif and Flügel; Graham et al.; Barnett et al.; and Cane et al. is a marked drop in the skill of spring or summer predictions, while the highest skill is obtained in predicting fall or winter SST anomalies. This is consistent with the study of Wright (1985), who showed that the persistence of equatorial Pacific SST anomalies also exhibits a pronounced minimum during spring. No information on the seasonal dependence was available from the schemes of Xu and Storch and Inoue and O'Brien. The number of predictions in the scheme of Latif et al. is too small to estimate a seasonal dependence.

A typical example derived from the Cane et al. scheme is given in Fig. 8, which shows the anomaly correlations of the predicted with the observed SST anomalies in the eastern equatorial Pacific, averaged over the 'Niño-3' region, as a function of the initialization month. Two points should be emphasized. First, there is a pronounced tilt of the isolines, indicating that SST anomalies in spring are not easily predictable (compare the tilt with the straight dashed line which indicates the month of April). Second, the skill increases again for longer lead times. A discussion of this behaviour is given later.

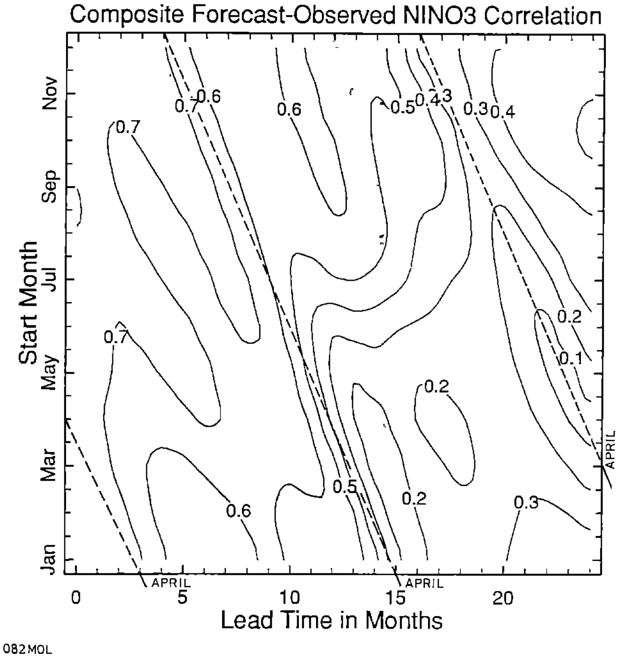

Fig. 8. Seasonal dependence of the predictive skill of the Lamont coupled model. Shown are the correlations of the predicted and observed SST anomalies as function of the initialization month and the lead time (month). The *dashed diagonal lines* denote the month of April

6 Discussion

We have described in this study the performance of different ENSO prediction schemes ranging from purely statistical schemes to comprehensive coupled ocean-atmosphere models. It is shown that simple indices of ENSO are predictable on an average about one year in advance. The most successful schemes, the fully physical coupled ocean-atmosphere models, show significant but modest skill even beyond one year. On short lead times of a few months, however, none of the prediction models beats persistence. The skills are highly dependent on the season, exhibiting a tendency to drop rapidly during spring.

Strong cyclic components can be identified in both the global atmosphere and the tropical Pacific. The existence of these cyclic components is crucial for the predictability of ENSO. However, it is not yet clear how these cycles are related to each other. The high predictive skill of the limited domain Lamont coupled ocean-atmosphere model demonstrates the important role of slow heat content variations in the equatorial Pacific for the maintenance of the ENSO cycle. This is also supported by the results of the coupled GCM. On the other hand, the neglect of all processes outside the tropical Pacific might be a limiting factor in the Lamont model. Purely statistical prediction schemes which use global sea level pressure anomalies to predict ENSO exhibit significant skills out to about three seasons. At lead times beyond two seasons the skill was attributed to SLP variations outside the tropical Pacific. This result does not necessarily imply a causal relationship, such that the memory of the coupled system resides in the atmosphere; the slow variations in the atmosphere can be caused by slowly varying boundary conditions. In any case, to address this topic in more detail further observational studies and simulations with global coupled ocean-atmosphere models are needed.

Of the different prediction methods discussed, the physical coupled ocean-atmosphere models show the best performance in predicting tropical Pacific SST anomalies, exhibiting significant skills at lead times exceeding one year. Up to the present initial conditions for the coupled models are obtained by forcing the oceanic component with observed wind stress variations and the atmospheric component with the SSTs simulated by the ocean model. As can be seen from the zero-lag correlations (Fig. 7), however, the initial conditions for the coupled models are seriously flawed. The errors arise from errors in the wind stresses used to spin up the ocean model and errors in the model formulation. Since no use has been made of ocean observations in the coupled models, further progress can be expected from the assimilation of in situ ocean observations (Hayes et al. 1991), which are becoming increasingly available, and/or observations from space (Tai et al. 1989). However, this requires a stronger reduction of the climate drift for coupled general circulation models.

Despite the encouraging recent progress in ENSO prediction, there still remain some open questions, such as the failure of the prediction schemes during particular time periods. One of these is the period 1974/1975, known as the 'aborted El Niño'. The year 1974 was characterized in both the atmosphere and the ocean by conditions which were favourable for a warm episode to occur. In particular, the equatorial heat content in the western Pacific exhibited a rather strong positive anomaly, as expressed by anomalously high sea levels in this region. However, the following year 1975 became an anomalously cold year, which led to the unique situation that a cold event (1973) was followed by a second cold event. This indicates that certain processes must occasionally have a strong influence on the ENSO cycle which are not properly represented in the present models. In order to gain more insight into the nature of these processes a multi-national prediction effort has been initiated which focuses on the 1974/1975 time period (WMO 1992).

The cause of the pronounced seasonal dependence in the skill is still an open question. Zebiak and Cane (1987) and Battisti (1988) have discussed the seasonal dependence of the predictability in their models. They showed that the instability, although favouring growth at any time of the year, is weakest during spring time. They concluded that the predictability of the system should be smallest during spring, because the system loses part of its 'memory' during this season. However, since the system supports unstable growth during the other seasons, the predictability should not be lost completely, because the time during which the growth is small is significantly shorter than the characteristic wave transit time. The discussion of Zebiak and Cane (1987) and Battisti (1988) explains the spring-predictability gap and the recovery of the skill after spring. This view is also supported by a PIP-analysis (Hasselmann 1988) performed by Weese 1990). From an investigation of observed sea level pressure and SST data he showed that the system is most stable during spring and most unstable during late summer. On the other hand, during spring the intertropical convergence zone (ITCZ) is close to the equator which favours unstable air-sea interactions in the eastern equatorial Pacific, where SST reaches its maximum during this time of the yeaer. However, since gradients are weak during spring a large variety of possible spatial structures can be amplified, including small scale noise.

Blumenthal (1991) investigated also the seasonal dependence of the predictability of the coupled ocean-atmosphere system using a linear approximation of the Lamont model. He attributes the rapid initial error growth to the non-self-adjoint nature of the coupled system, which allows error growth even in the presence of damped modes only. In non-self-adjoint systems rapid initial error growth and thus a strong sensitivity to the choice of the initial conditions is possible, if different non-orthogonal modes obey rather different time evolutions. Furthermore, Blumenthal (1991) showed that rapid initial error growth due to the non-self-adjoint nature of the system is strongest during spring, which explains the spring-predictability gap. However, Blumenthal's (1991) explanation is rather theoretical and does not offer the physics behind the noted seasonal dependence in error growth.

Alternative explanations for the spring predictability gap might involve the tropospheric 'quasi-biennial oscillation' (QBO) which explains considerable variance in the interannual variability of the tropical climate system (e.g. Meehl 1987; Rasmusson et al. 1990; Ropelewski et al. 1992). Several observational studies (e.g. Barnett 1991; Latif et al. submitted 1993) show that significant non-linear interactions exist between the ENSO cycle and the QBO. Although the origin of the QBO is still a controversial issue, the understanding and successful simulation of the QBO and its interaction with the ENSO cycle might significantly increase our understanding of the spring predictability gap and skill in predicting ENSO. In summary, at present we cannot present a fully consistent physical explanation of the seasonal dependence of predictability.

Finally, we address the question of the factors ultimately limiting ENSO predictability. As described, Blumenthal (1991) shows that part of the problem might be system-immanent and attributed to the non-self-adjoint character of the coupled system. There remain two other possibilities, non-linearities and external noise. Non-linearities can lead to chaotic behaviour (see Münnich et al. 1991) and thus to a strong sensitivity to the initial conditions. However, the quasi-cyclic behaviour of ENSO suggest that non-linearities play a significant role only at long lead times, presumably longer than one year. External noise, such as the '30–60 day oscillation' (Madden and Julian 1972) is likely to reduce the predictability at rather short lead times. Even if high-frequency disturbances play an important role in initiating El Niños or La Niñas, as described by several authors (e.g. Wyrtki 1985), under the scenario envisoned here this would result only in an uncertainty of one or two months in determining the onset date, since ENSO is to first order based on a low-frequency cycle. This view is also supported by the predictability study of Zebiak (1989), who found external noise of only minor importance in ENSO prediction experiments.

In summarizing the state of ENSO predictions, skillful predictions of gross ENSO indices are now possible up to lead times of about one year using coupled ocean-atmosphere models. However, considerable additional effort is needed before the spatial details of ENSO can be predicted successfully. ENSO predictions are certainly only the first steps on the long way towards an operational global short-range climate forecasting capability. Improvement of the coupled models and of global data coverage, especially in the oceans, are necessary to achieve this goal.

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References

Barber RT, Chavez FP (1983) Biological consequences of El Niño. Science 222:1203–1210

Barnett TP (1983) Interaction of the Monsoon and Pacific Trade Wind system at interannual time scales. Part I: the equatorial zone. Mon Weather Rev 111:756–773

Barnett TP (1985) Variations in near-global sea level pressure. J Atmos Sci 42:478–501

Barnett TP (1991) The interaction of multiple time scales in the tropical climate system. J Clim 4:269–285

Barnett TP, Hasselmann K (1979) Techniques of linear prediction, with application to oceanic and atmospheric fields in the tropical Pacific. Rev Geophys Space Phys 17:949–968

Barnett TP, Preisendorfer R (1987) Origins and levels of monthly forecast skill for United States surface air temperatures determined by canonical correlation analysis. Mon Weather Rev 115:1825–1850

Barnett TP, Graham NE, Cane NA, Zebiak SE, Dolan SC, O'Brien JJ, Legeler DM (1988) On the prediction of the El Niño of 1986–1987. Science 241:192–196

Barnett TP, Dümenil L, Schlese U, Roeckner E, Latif M (1989) The effect of Eurasian snow cover on regional and global climate variations. J Atmos Sci 46:661–685

Barnett TP, Latif M, Kirk E, Roeckner E (1991) On ENSO physics. J Clim 4:487–515

Barnett TP, Latif M, Graham NE, Flügel M, Pazan SE, White WB (1993) ENSO and related variability. Part I: prediction of equatorial Pacific sea surface temperature with a hybrid coupled ocean-atmosphere model. J Clim (in press)

Barnston AG, Ropeleski CF (1993) Prediction of ENSO episodes using canonical correlation analysis. J Clim 5:1316–1345

Battisti DS (1988) Dynamics and thermodynamics of a warming event in a coupled tropical atmosphere-ocean model. J Atmos Sci 45:2889–2919

Battisti DS, Hirst AC (1989) Inerannual variability in a tropical atmosphere-ocean model: Influence of the basic state, ocean geometry and nonlinearity. J Atmos Sci 46:1687–1712

Blumenthal MB (1991) Predictability of a coupled ocean-atmosphere model. J Clim 4:766–784

Busalacchi AJ, Takeuchi K, O'Brien JJ (1983) Interannual variability of the equatorial Pacific. Hydrodynamics of the Equatorial Ocean. Nihoul JCJ (ed), Elsevier Oceanogr Ser vol 36

Cane MA (1983) Oceanographic events during El Niño. Science 222:1189–1195

Cane MA (1991) Forecasting El Niño with a geophysical model. In: Glantz M, Katz RW, Nicholls N (eds) Teleconnections linking worldwide climate anomalies. Cambridge University Press

Cane MA, Sarachik ES (1981) The response of a linear baroclinic equatorial ocean to periodic forcing. J Mar Res 39:651–693

Cane MA, Zebiak SE, Dolan SC (1986) Experimental forecasts of El Niño. Nature 321:827–832

Cane MA, Münnich M, Zebiak SE (1990) A study of self-excited oscillations of the tropical ocean-atmosphere system. Part I: linear analysis. J Atmos Sci 47:1562–1577

Chao Y, Philander SGH (1991) On the structure of the Southern Oscillation and evaluation of coupled ocean-atmosphere models. TOGA Notes 3:1–8

Davis RE (1977) Techniques of statistical analysis and prediction of geophysical fluid systems. Geophys Astrophys Fluid Dyn 8:245–277

Firring E, Lukas R, Sadler J, Wyrtki K (1983) Equatorial undercurrent disappears during 1982–1983 El Niño. Science 222:1121–1123

Gill AE, Rasmusson EM (1983) The 1982–83 climate anomaly in the equatorial Pacific. Nature 306:229–234

Glantz MH, Katz RW, Nicholls N (eds) (1991) Teleconnections linking worldwide climate anomalies. Cambridge University Press, Cambrige, UK

Goswami BN, Shukla J (1991) Predictability of a coupled ocean-atmosphere model. J Clim 4:-22

Graham NE, White WB (1988) The El Niño cycle: a natural oscillator of the Pacific Ocean-atmosphere system. Science 240:1293–1302

Graham NE, Michaelsen J, Barnett TP (1987a) An investigation of the El Niño-Southern Oscillation cycle with statistical models. 1. Predictor field characteristics. J Geophys Res 92, C13:14251–14270

Graham NE, Michaelsen J, Barnett TP (1987b) An investigation of the El Niño-Southern Oscillation cycle with statistical models. 2. Model results. J Geophys Res 92, C13:14271–14289

Graham NE, Barnett TP, Latif M (1992) Considerations of the predictability of ENSO with a low-order coupled model. TOGA Notes 7:11–15

Hahn DJ, Shukla J (1976) An apparent relationship between Eurasian snow cover and Indian monsoon rainfall. J Atmos Sci 33:2461–2462

Hayes SP, Magnum LJ, Picaut J, Sumi A, Takeuchi K (1991) TOGA-TAO: a moored array for real-time measurements in the tropical Pacific Ocean. Bull Am Meteorol Soc 72:339–347

Hasselmann K (1988) PIPs and POPs: the reduction of complex dynamical systems using principal interaction and oscillation patterns. J Geophys Res 93, D9:11015–11021

Hasselmann K, Barnett TP (1981) Techniques of linear prediction for systems for periodic statistics. J Atmos Sci 38:2275–2283

Hotelling H (1935) Relations between two sets of variates. Biometrica 28:321–377

Inoue M, O'Brien JJ (1984) A forecasting model for the onset of El Niño. Mon Weather Rev:112, 2326–2337

Latif M, Flügel M (1991) An investigation of short range climate predictability in the tropical Pacific. J Geophys Res 96, C2:2661–2673

Latif M, Graham NE (1992) How much predictive skill is contained in the thermal structure of an OGCM? J Phys Oceanogr 22:951–962

Latif M, Sterl A, Maier-Reimer E, Junge MM (1993a) Climate variability in a coupled GCM. Part I: the tropical Pacific. J Clim (in press)

Latif M, Sterl A, Maier-Reimer E, Junge MM (1993b) Structure and predictability of the El Niño/Southern Oscillation phenomenon in a coupled ocean-atmosphere general circulation model. J Clim (in press)

Lau NC, Philander SGH, Nath MJ (1992) Simulation of ENSO-like phenomena with a low-resolution coupled GCM of the global ocean and amtosphere. J Clim 5:284–307

Madden RA, Julian PR (1972) Description of global-scale circulation cells in the tropics with a 40–50 day period. J Atmos Sci 24:1109–1123

McCreary JP (1983) A model of tropical ocean-atmosphere interaction. Mon Weather Rev 111:370–387

Meehl GA (1987) The annual cycle and interannual variability in the tropical Pacific and Indian Ocean regions. Mon Weather Rev 115:27–50

Meehl GA (1990) Seasonal cycle forcing of El Niño-Southern Oscillation in a global coupled ocean-atmosphere GCM. J Clim 2:72–98

Miyakoda K, Rosati A, Gudgel R (1992) Toward the GCM seasonal forecasts. CAS Group of Rapporteurs on Medium- and Long-range Weather Prediction Research. Toulouse, 10–14 February, 1992

Münnich M, Cane MA, Zebiak SE (1991) A study of self-excited oscillations of the tropical ocean-atmosphere system. Part II: nonlinear cases. J Atmos Sci 48:1238–1248

Neelin JD, Latif M, Allaart MAF, Cane MA, Cubasch U, Gates WL, Gent PR, Ghil M, Gordon C, Lau NC, Mechoso CR, Meehl GA, Oberhuber JM, Philander SGH, Schopf PS, Sperber KR, Sterl A, Tokioka T, Tribbia J, Zebiak SE (1992) Tropical air-sea interaction in general circulation models. Clim Dyn 7:73–104

Oceanus (1984) El Niño. Vol 27, no. 2, summer

Philander SGH, Pacanowski RC, Lau NC, Nath MJ (1991) A simulation of the Southern Oscillation with a global atmospheric GCM coupled to a high-resolution, tropical Pacific ocean GCM. J Clim 5:308–329

Rasmusson EM, Carpenter TH (1982) Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. Mon Weather Rev 10:354–384

Rasmusson EM, Wallace JM (1983) Meteorological aspects of the El Niño/Southern Oscillation. Science 222:1195–1202

Rasmusson EM, Wang X, Ropelewski CF (1990) The biennial component of ENSO variability. J Mar Sys 1:71–96

Ropelewski CF, Halpert MS (1989) Precipitation patterns associated with the high index phase of the Southern Oscillation. J Clim 2:268–284

Ropelewski CF, Halpert MS, Wang X (1992) Observed tropospheric biennial variability and its realtionship to the Southern Oscillation. J Clim 5:594–614

Sausen R, Barthel K, Hasselmann K (1988) Coupled ocean-atmosphere models with flux correction. Clim Dyn 2:145–163

Schopf PS, Suarez MJ (1988) Vacillations in a coupled ocean-atmosphere model. J Atmos Sci 45:549–566

Storch H, van Loon H, Kiladis GH (1988a) The Southern Oscillations. Part VIII: sensitivity to SST anomalies in the tropical and subtropical regions of the South Pacific Convergence Zone. J Clim 1:325–331

Storch H, Bruns T, Fischer-Bruns I, Hasselmann K (1988b) Principal oscillation analysis of the 30 to 60 day oscillation in a GCM. J Geophys Res 93, D9:11022–11036

Syu H, Neelin JD, Weibel W, Gutzler D (1992) Tropical ocean-atmosphere interaction in a hybrid coupled GCM: seasonal cycle and interannual oscillations. Abstract Volume, Fourth Symposium on Global Change Studies, Jan. 18–21, Anaheim, Calif, American Meteorological Society, Boston

Tai CK, White WB, Pazan SE (1989) Geosat crossover analysis in the tropical Pacific. 2. Verification analysis of altimetric sea level maps with expendable bathythermograph and island sea level data. J Geophys Res 94, C1:897–908

van Loon H (1984) The Southern Oscillation. Part III: associations with the trades and with the through in the westerlies of the South Pacific Ocean. Mon Weather Rev 112:947–954

van Loon H, Shea DJ (1985) The Southern Oscillation. Part IV: the precursors south of 15° S to the extremes of the oscillation. Mon Weather Rev 113:2063–2074

Weese U (1991) Principal Interaction/Oscillation Patterns. Theorie und Analysen zum El Niño/Southern Oscillation-Phänomen. PhD Thesis, Max-Planck-Institut für Meteorologie, Hamburg, FRG

WMO (1992) Report on the Fifth Session of the TOGA Numerical Experimentation Group, San Francisco, Dec. 1991, WMO/TD-No 487. World Meteorological Organization, Geneva, Switzerland

White WB, Pazan SE, Inoue M (1987) Hindcast/forecast of ENSO events based upon the redistribution of observed and model heat content in the western tropical Pacific, 1964–86. J Phys Oceanogr 17:264–280

Wright PB (1985) The Southern Oscillation. An ocean-atmosphere feedback system? Bull Am Meteorol Soc 66:398–412

Wyrtki K (1975) El Niño – The dynamic response of the equatorial Pacific Ocean to atmospheric forcing. J Phys Oceanogr 5:572–584

Wyrtki K (1985) Water displacements in the Pacific and the genesis of El Niño cycles. J Geophys Res 90, C4:7129–7132

Xu JS, Storch H (1990) Principal oscillations patterns – prediction of the state of ENSO. J Clim 3:1316–1329

Zebiak SE, Cane MA (1987) A model El Niño – Southern Oscillation. Mon Weather Rev 115:2262–2278