Prediction limitations with ENSO models and the spring predictability barrier

1. INTRODUCTION

The El Niño Southern Oscillations (ENSOs) are generally known as a composite weather phenomena originating in the Pacific Ocean producing lasting teleconnections on the global climate system. The El Niño component of ENSO can be approximately considered to be an oceanic warming event which disrupts the normal Pacific circulation at irregular intervals of 2–7 years, whilst the Southern Oscillations are an inter-annual flip of the tropical sea level pressure between the western and eastern Pacific leading to the weakening and strengthening of the easterly trade winds across the ocean. To produce a conclusive theory for ENSOs one must be able to describe and understand the complete underlying mechanisms. One such hypothesis has yet to arise, however various attempts have been made to comprehend individual components and effects.

Bjerknes (1969) first theorised that a positive ocean-atmosphere feedback system would result in an El Niño event. An initial positive sea surface temperature (SST) anomaly in the eastern Pacific would reduce the east-west SST gradient which leads to the strengthening of the Walker circulation and thus the production of weaker trade winds across the equatorial Pacific. In a complete ENSO theory this positive system would be counterbalanced by a negative loop which returns the Pacific to its "normal" (pre-ENSO) state. Whilst Bjerknes' hypothesis failed to provide a negative feedback mechanism, Zebiak and Cane (1987) presented a model which demonstrated and outlined the coupling between the atmosphere and the ocean to produce an ENSO event. The atmospheric component used was a linear Gill-type model (Gill 1980) which describes the atmosphere's response to SST anomalies, and the ocean represented by a low-gravity system which is forced by the wind stress from the atmospheric constituent.

With their model they were able to replicate features observed during ENSO events such as equatorial westerly wind anomalies in the central Pacific and large SST anomalies in the eastern Pacific, on top of that they were able to predict the onset of the 1986–1987 and 1991–1992 ENSO events. Despite this success, they recognised their limited ability in simulating the real complete system as detailed comparisons with observational data would reveal discrepancies in their atmospheric and oceanic simulations. Furthermore, the short warm episodes in 1993 and 1994 would be missed in the predictions made with the Zebiak-Cane (ZC) model. This therefore requires more sophisticated models to better describe and forecast ENSO events.

2. PREDICTION LIMITATIONS AND THE ZEBIAK-CANE MODEL

The prediction of ENSO events is particularly difficult as there are generally two types of El Niño events to account for. The first are canonical events which generally develop along the South American coast and then propagate westwards across the Pacific, "Eastern-Pacific" events (Rasmusson and Carpenter 1982). The second type of events have non-propagating warm SST concentrated mostly in the central Pacific, "Central-Pacific" events (Ashok et al. 2007). In an attempt to test whether the ZC model can predict either types of events, it was demonstrated by Duan et al. (2013) that the model tended to do well whilst simulating Eastern-Pacific (EP) events and functioned badly when reproducing Central-Pacific (CP) events. This indicates that the ZC model may just contain the physics to explain EP events and that alterations would be required to additionally account for other events.

Additional challenges for ENSO forecasting arise due to the nonlinear and complex coupling between the ocean and atmospheric systems. Within the ZC model this relationship was constrained as a result of the researchers' initial assumptions and parameter choices when constructing their theory. For example with the simulation of monthly mean SST anomalies in the atmosphere model, concessions had to be made to ensure accurate results could be produced whilst the analysis not being computationally costly. Further experimentation would exhibit that the amplitude and time scale of the ENSO cycles would be sensitive to changes within the coupled mathematical model: an increase (or decrease) in the strength of the coupling between the atmosphere and ocean would lead to increase (or decrease) in the amplitudes and periods.

It is therefore evident that the ZC model is a simplification of the real climate system and improvements must be made to provide a better fit with the observational data. Theoretical modifications of the individual atmospheric and oceanic components plus of their inter-relationship would be key in developing the theory further. Several modern ENSO oscillator theories (Table I) employ the ZC model as a basic foundation whilst making adjustments to parts of the mathematical modelling thus improving their ability to explain and account for various ENSO effects.

Theory	**Main components**
The Delayed Oscillator (Battisti and Hirst 1988, Suarez and Schopf 1988)	Considers the effects of equatorially trapped oceanic wave propagation.
The Recharge Oscillator (Jin 1997)	Considers the buildup of warm water in the western Pacific as a precondition to the development of El Niño.
The Western Pacific Oscillator (Wang et al. 1999, Weisberg and Wang 1997)	Considers the role of the western Pacific and off-equatorial SST SST anomalies in the western Pacific.
The Advective-Reflective Oscillator (Picaut et al. 1997)	Considers the importance of the positive feedback of zonal currents that advect the western Pacific warm pool towards the east during El Niño.
The Unified Oscillator (Wang 2001)	Considers dynamics and thermodynamics of a coupled ocean-atmosphere system which is similar to Zebiak-Cane.

TABLE I: Various ENSO oscillator theories and their main differences from the ZC model.

Changes to the ZC model are not limited to just the atmospheric and oceanic components, as a response to the model failing to agree with observations from 1992 to 1995, Qian and Wang (1997) introduced planetary scale Hadley and Walker cells which improved the prediction of equatorial eastern Pacific SST anomalies for 1970–1971 and in 1992–1995.

However further shortfalls exist within the modelling for ENSOs which limits their accuracy and applicability. In particular, there is a limitation found in many models known as the "spring predictability barrier" (SPB) where the seasonal predictions for

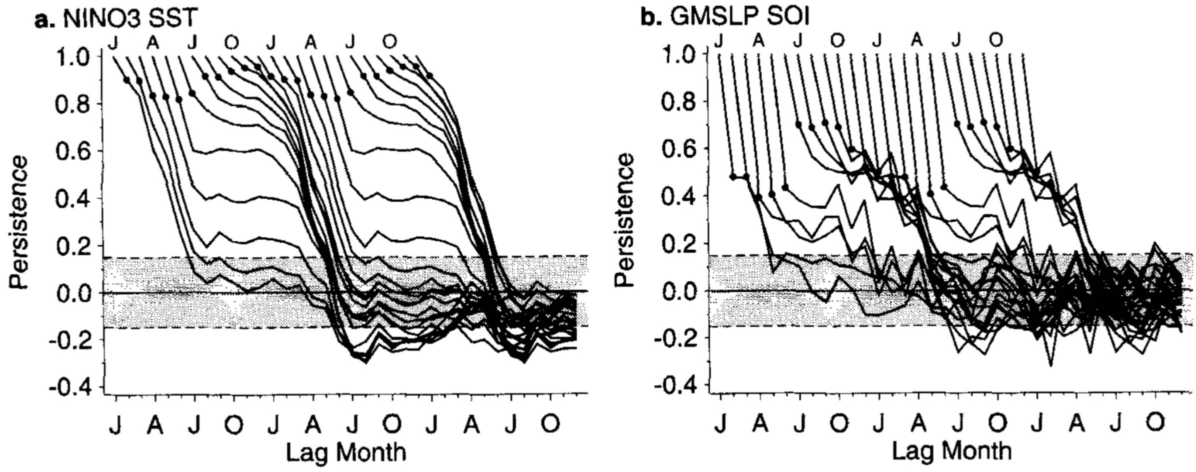

FIG. 1: Data showing persistence between different months of the year (Torrence and Webster 1998): (a) Persistence of NINO3 surface sea temperature (SST) with each curve shifted to line up with the starting month on the top axis (JAJO=January, April, July, October), and the corresponding lag month on the lower axis. The black dots show the lag-1 persistence, and all twelve curves for one year were repeated for clarity; (b) Same analysis applied but for the GMSLP Southern Oscillation Index (SOI).

ENSOs made during or before boreal spring (March–May) have much lower skill than those made at other times of the year (Torrence and Webster 1998). This barrier can be evidenced in oceanic circulation models (Latif and Graham 1992), in dynamical-statistical models (Balmaseda et al. 1994), and in coupled ocean-atmosphere models (Goswami and Shukla 1991, Xue et al. 1994). To better predict ENSO events, this barrier therefore must be understood and accounted for within climate modelling.

3. EVIDENCE FOR THE SPRING PREDICTABILITY BARRIER

Examinations of the correlation between ENSO data sets through autocorrelation and persistence provides one method for identifying the predictability barrier (Torrence and Webster 1998).

The autocorrelation of a time series is the correlation between itself and a copy of the data which has been time-lagged. Analyses of monthly sea level pressures across the Pacific Ocean yields the SST and Southern Oscillation Index (SOI) to have high autocorrelations which agrees with the general observation that ENSO events normally persist for several months (Trenberth 1976).

Persistence focuses on the fixed-phase correlation between different months within a single time series. Contrasting with autocorrelation which is independent of the starting month, persistence shows any seasonal changes in the correlations between one month and the next (Troup 1965). Analysis by Torrence and Webster (1998) of NINO3 SST and GMSLP SOI data shows that persistence has distinct, regular structure which is phase locked to an annual cycle (Fig. 1). Regardless of starting month, the persistence has a rapid decline in the March–April–May period which can be attributed as the manifestation of the spring predictability barrier.

With the SPB apparent from observational data, it would be logical to consider where

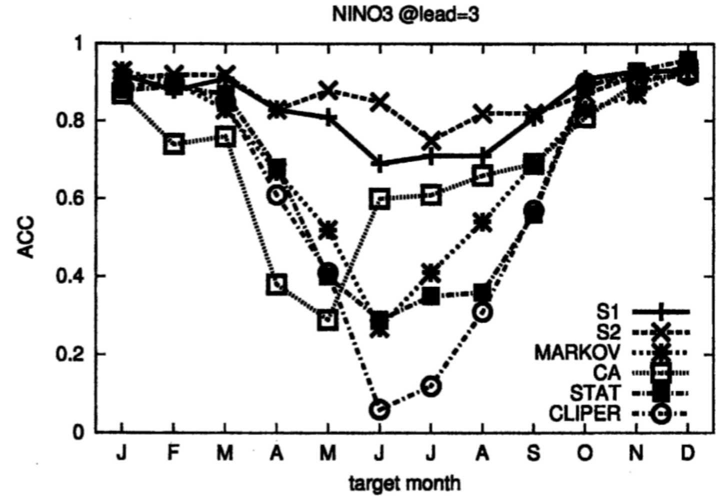

FIG. 2: Plot of the anomaly correlation coefficients of six dynamical and statistical models (S1, S2, MARKOV, CA, STAT, CLIPER) against the months of the year. This demonstrates the skill in predicting monthly Niño-3 index with a lead time of +3 months (Jan van Oldenborgh et al. 2005).

the barrier occurs in theoretical modelling. Providing an initial look at dynamical and statistical models, these frameworks often have origins in seasonal forecasting making them ideal in ENSO forecasting as they couple the dynamics of the atmosphere, ocean and land.

Jan van Oldenborgh et al. (2005) tests the skill of the six models adapted from research by the European Centre for Medium-Range Weather Forecasts (ECMWF). What became apparent was whilst the SPB does arise in the modelling, it appears that they emerge at different times within the year (Fig. 2). However this may just be an effect of testing the ECMWF models individually, if combinations of the models (multi-model ensembles, MMEs) were to be applied, the results may better align with the data and the variability in barrier period may reduce.

In a similar vain, Jin et al. (2008) investigated alternative coupled general circulation models (CGCMs) and analysed how they performed in ENSO prediction. With their testing they quantified that the forecast skill of individual models and MMEs depends strongly on the ENSO phase and intensity, and on the season. They found that for forecasts which start in February or May, the skill drops more sharply than predictions made in August or November. This is yet again a demonstration of the SPB and further highlights the need to understand this limitation within ENSO modelling.

4. OVERCOMING THE SPRING PREDICTABILITY BARRIER

As demonstrated, the SPB is a prevalent characteristic of ENSO forecasts which exists within statistical and coupled models. Whilst it may not be feasible to entirely eliminate the barrier from predictions, it would be beneficial to reduce its effect. One potential line of inquiry is understanding the initial and parameter errors within the ZC model which leads to the SPB. Through adopting an approach of conditional nonlinear optimal perturbations (CNOP), the errors can be isolated and their impact on the SPB quantified. This method identifies the optimal error perturbations (initial or parameter) in the ZC model within given constraints through reducing evolution equations (Mu et al.

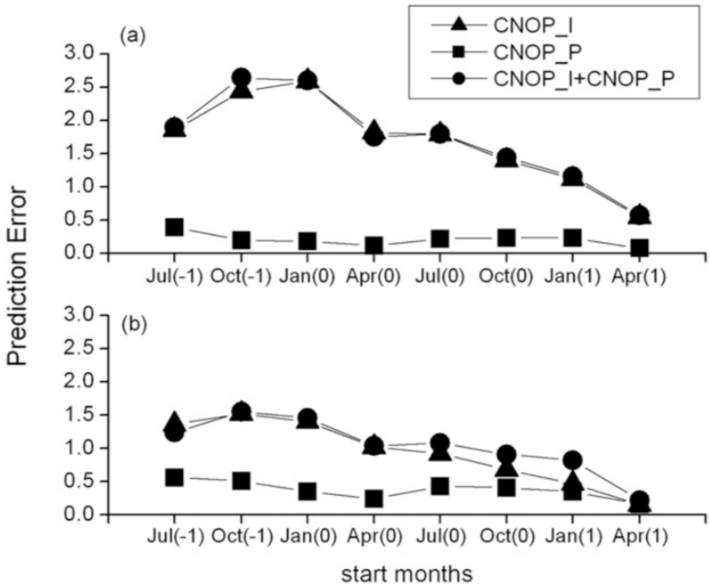

FIG. 3: Plots of the mean prediction errors for 16 El Niño events with a lead time of 12 months for each starting month: (a) prediction errors caused by CNOP-I errors, CNOP-P errors, and their combined mode with an initial constraint of $\| u_0 \|_\alpha \leq 0.8$; (b) same analysis but with $\| u_0 \|_\alpha \leq 0.4$ (Yu et al. 2012).

2010). Applications of CNOP in retrospective forecasts reveals that prediction errors for a parameter error only system (CNOP-P) are small which generates a weakened SPB, on the other hand in an initial error exclusive framework (CNOP-I) significant SPBs can be produced (Fig. 3). If both are coupled together as they would be in a realistic system, then the prediction errors are weighted by the CNOP-I results.

To reduce the effect of the CNOP-I errors

5. CONCLUSIONS

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