Theoretical predictions of the El Niño Southern Oscillations with the Zebiak-Cane model

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 fails 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. LIMITATIONS WITH 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 normally develop along the South American coast and then propagates westwards across the Pacific, "Eastern-Pacific" events (Rasmusson and Carpenter 1982). The second type of events have warm SST mostly centred in the central Pacific which do not propagate, "Central-Pacific" events (Ashok et al. 2007). The ZC model can be demonstrated to predict the Eastern-Pacific events well and the Central-Pacific types badly (Duan et al. 2013). This indicates that the ZC model is more suited for deriving results for Eastern-Pacific events and may contain just the essential physics to do so in a perfect model environment.

There are additional challenges for the forecasting of ENSOs as the coupling between the ocean and atmospheric systems are nonlinear and complex, this requires various theoretical modifications of the original model to maintain a simple dynamical system whilst providing a better fit with the observational data. Several modern ENSO oscillator theories (Table I) employ the ZC model as a basic foundation model whilst making adjustments to the atmospheric or oceanic components.

Theory	**Overview**
The Delayed Oscillator (Battisti and Hirst 1988, Suarez and Schopf 1988)	Considering the effects of equatorially trapped oceanic wave propagation.
The Recharge Oscillator (Jin 1997)	Considering the buildup of warm water in the western Pacific as a precondition to the development of El Niño.

TABLE I: Various ENSO oscillator theories and their main differences from the Zebiak-Cane model.

the delayed oscillator (Battisti and Hirst 1988, Suarez and Schopf 1988), the recharge oscillator (Jin 1997), the western Pacific oscillator (Wang et al. 1999, Weisberg and Wang 1997), and the advective-reflective oscillator (Picaut et al. 1997).

In an attempt to explore the effect of model errors on the prediction uncertainties for ENSO events, Duan and Zhao (2015) explored the nonlinear forcing singular vector (NFSV) approach which optimises an objective function to return a minimum point in phase space. The NFSV method is key in demonstrating the effects of nonlinearity in El Niño predictability.

thus the uncertainties within the model are difficult to obtain as there are no effective approaches.

3. IMPROVING THE ZEBIAK-CANE MODEL

References

Ashok, K., Behera, S. K., Rao, S. A., Weng, H. and Yamagata, T. (2007), 'El Niño Modoki and its possible teleconnection', Journal of Geophysical Research: Oceans **112**(C11).

Battisti, D. S. and Hirst, A. C. (1988), 'Interannual Variability in a Tropical Atmosphere–Ocean Model: Influence of the Basic State, Ocean Geometry and Nonlinearity', Journal of the Atmospheric Sciences **46**(12), 1687–1712.

Bjerknes, J. (1969), 'Atmospheric teleconnections from the equatorial Pacific', Monthly Weather Review **97**(3), 163–172.

Duan, W., Yu, Y., Xu, H. and Zhao, P. (2013), 'Behaviors of nonlinearities modulating the El Niño events induced by optimal precursory disturbances', Climate Dynamics **40**(5-6), 1399–1413.

Duan, W. and Zhao, P. (2015), 'Revealing the most disturbing tendency error of Zebiak–Cane model associated with El Niño predictions by nonlinear forcing singular vector approach', Climate Dynamics **44**(9-10), 2351–2367.

Gill, A. E. (1980), 'Some simple solutions for heat-induced tropical circulation', Quarterly Journal of the Royal Meteorological Society **106**(449), 447–462.

Jin, F.-F. (1997), 'An Equatorial Ocean Recharge Paradigm for ENSO. Part I: Conceptual Model', Journal of the Atmospheric Sciences **54**(7), 811–829.

Picaut, J., Masia, F. and du Penhoat, Y. (1997), 'An Advective-Reflective Conceptual Model for the Oscillatory Nature of the ENSO', Science **277**(5326), 663–666.

Rasmusson, E. M. and Carpenter, T. H. (1982), 'Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño', Monthly Weather Review **110**(5), 354–384.

Suarez, M. J. and Schopf, P. S. (1988), 'A Delayed Action Oscillator for ENSO', Journal of the Atmospheric Sciences **45**(21), 3283–3287.

Wang, C., Weisberg, R. H. and Yang, H. (1999), 'Effects of the wind speed–evaporation–SST feedback on the El Niño–Southern Oscillation', Journal of the atmospheric sciences **56**(10), 1391–1403.

Weisberg, R. H. and Wang, C. (1997), 'A Western Pacific Oscillator Paradigm for the El Niño-Southern Oscillation', Geophysical Research Letters **24**(7), 779–782.

Zebiak, S. E. and Cane, M. A. (1987), 'A Model El Niño–Southern Oscillation', Monthly Weather Review **115**(10), 2262–2278.