

# Prediction limitations with the spring predictability barrier in the Zebiak-Cane model for El Niño Southern Oscillations

## 1. INTRODUCTION

The El Niño Southern Oscillations (ENSOs) are a composite weather phenomena which originate in the Pacific Ocean that occurs every few years. El Niño is 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 (Wang et al. 2017). The coupling of these two phenomena was first theorised by Bjerknes (1969) who recognised that they are two different aspects of the same phenomena.

Bjerknes hypothesised 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 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’ theory failed to provide a negative feedback mechanism, Zebiak and Cane (1987) presented a model which attempted to resolve this by outlining the atmosphere-ocean coupling to produce an ENSO event. The atmospheric component was a linear Gill-type model (Gill 1980) which describes the atmosphere’s response to SST anomalies, and the ocean was 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 a real system, thorough 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, therefore suggesting that more sophisticated models would be required 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 several types of El Niño events to consider, for example strong and weak El Niños, or even La Niña events where the Pacific cools. Generally there are only two main types accounted for in ENSO predictions. 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 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, Duan et al.

(2013) demonstrated that the ZC model tended to do well whilst simulating Eastern-Pacific (EP) events and functioned badly when attempting to reproduce Central-Pacific (CP) events. This indicated that the ZC model may just contain the physics to explain EP events and that alterations would be required to additionally account for other effects.

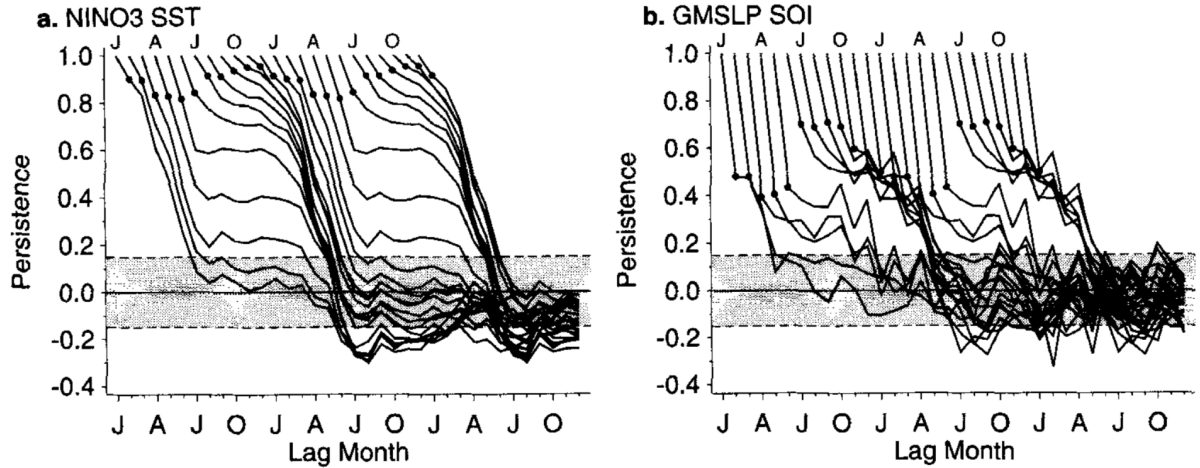
Additional challenges for ENSO forecasting arise due to the nonlinear and complex coupling between the ocean and atmospheric systems. Within the ZC model this relationship was constrained because of the researchers’ initial assumptions and parameter choices when constructing their theory. With their simulations of monthly mean SST anomalies in the atmospheric model, concessions had to be made to ensure accurate results whilst being computationally efficient. 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 better fit the observational data. One remedy is to formulate theoretical modifications for the individual atmospheric and oceanic components and for their inter-relationship to more accurately reflect nature. 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. Introducing supplemental components such as planetary scale Hadley and Walker cells (Qian and Wang 1997) improves the prediction of equatorial eastern Pacific SST anomalies which allows for the prediction of the 1970–1971 and 1992–1995 ENSO events which otherwise would have been missed.

<b>Theory</b>	<b>Main components</b>
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.

However further shortfalls exist within ENSO modelling which limits their accuracy and applicability. In particular, many models have the limitation known as the “spring predictability barrier” (SPB) where seasonal predictions for 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 is evidenced in oceanic circulation models



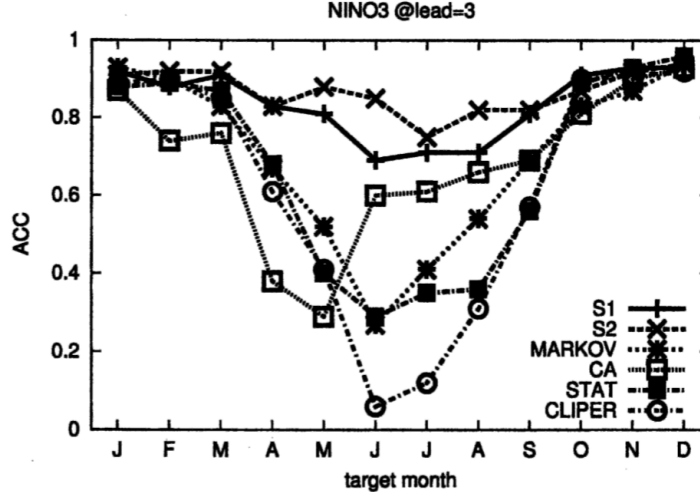
**FIG. 1:** Data showing persistence between different months of the year (Torrence and Webster 1998): (a) Persistence of NINO3 surface sea temperature (SST) with each curve shifted to line up with the starting month on the top axis (JAJO=January, April, July, October), and the corresponding lag month 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).

(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 is 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 potential 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 the barrier occurs in theoretical modelling. Performing an investigation with dynamical and statistical models, these frameworks often have origins in seasonal forecasting which make 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 which were adapted from research by the European Centre for Medium-Range Weather



**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).

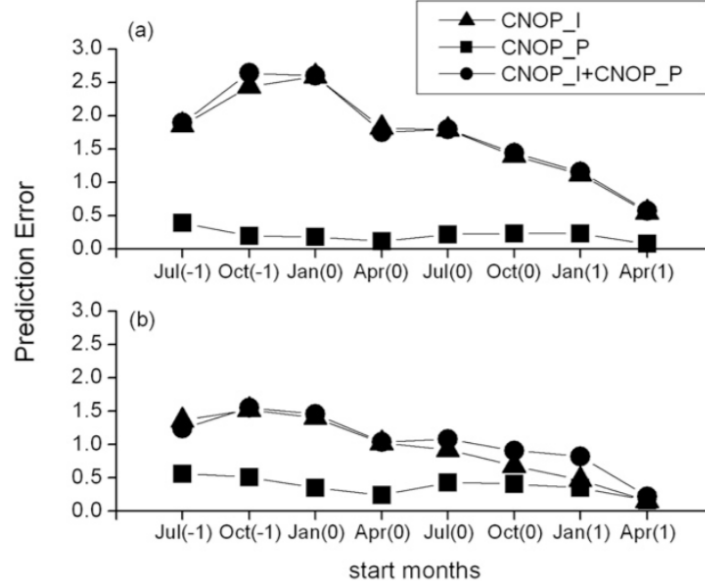
Forecasts (ECMWF). What became apparent was whilst the SPB does arise in the modelling, it appears that they emerge at different times within the year (Fig. 2). However this may just be an effect of testing the ECMWF models individually, if combinations of the models (multi-model ensembles, MMEs) were used, the results may have better aligned with the data and the variability in barrier period may have reduced.

Similarly, Jin et al. (2008) investigated other types of 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

##### a. Parameter and initial errors in the Zebiak-Cane model

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 (Duan et al. 2009). This method identifies the optimal error perturbations (initial or parameter) in the ZC model within given constraints through reducing evolution equations (Mu et al. 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 an initial-error only framework (CNOP-I) produces significant SPBs (Fig. 3). If both are coupled together as in a realistic system, then the



**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).

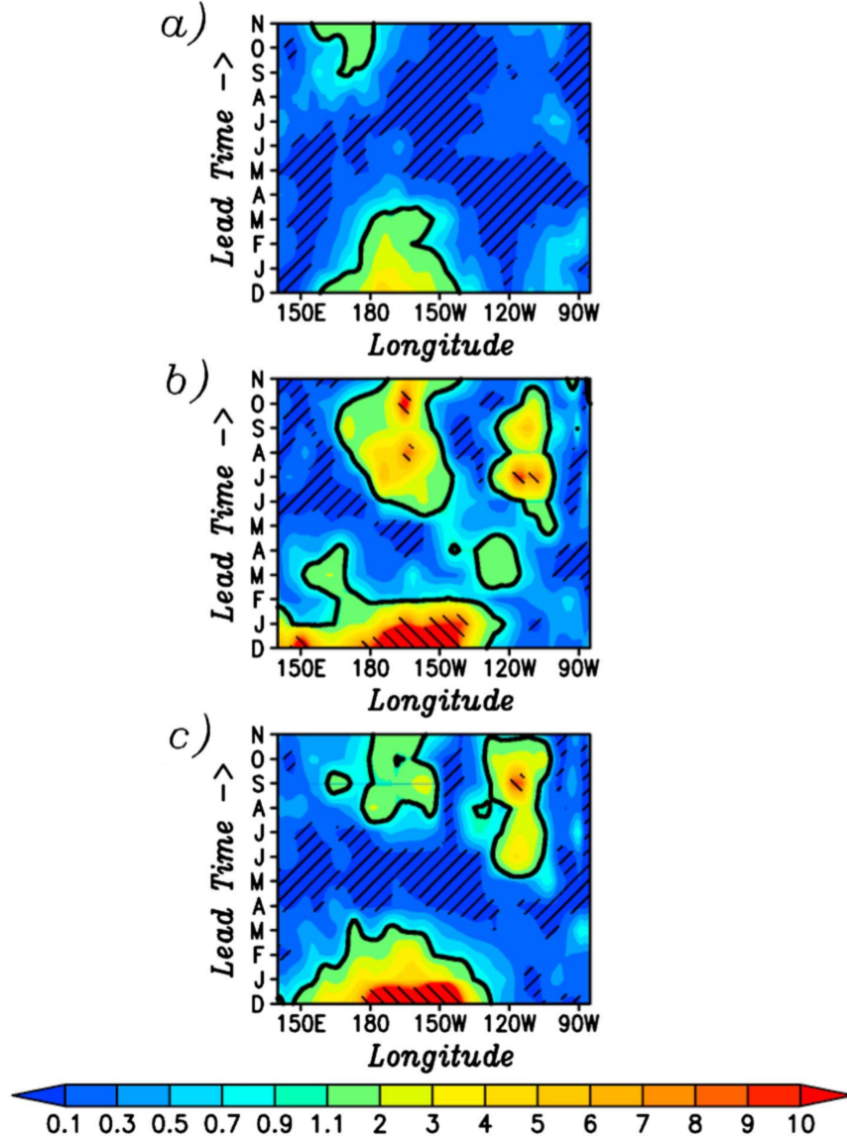
prediction errors are weighted by the CNOP-I results and a substantive SPB arises.

To reduce the effect of CNOP-I uncertainties on the prediction results, it is suggested that an ensemble forecast technique based on a multi-initial condition ensemble could be used in predicability studies and operational forecasts (Kirtman et al. 2001). However this would require an alternative prediction model and there is yet to be one which accurately considers enough climate system components.

### b. Stochastic forcing and westerly wind bursts

It can be seen that the strength of the SPB can be reduced through considerations of the initial error values established in the prediction model. Nonetheless the origins and fundamental mechanisms of the barrier are still in debate and there is yet to be a single conclusive argument. There are two main hypotheses which attempt to justify the ENSO prediction skill during spring. The first is the ZC model which suggests that the air-sea coupling strength is the weakest during the boreal spring (Zebiak and Cane 1987). The second relates the seasonality of the SST anomaly (SSTA) variance compared with that of the stochastic noise forcing (Webster and Yang 1992, Xue et al. 1994). Having said that, there is the potential for alternative theories which include Westerly Wind Bursts (WWBs) to solve the problem of ENSO forecast skill seasonality.

The inclusion of parameterised WWBs in prediction experiments is motivated because of their occurrence in nature and the need to model a more realistic system rather than an idealised one. Incorporating wind bursts into the Community Climate System Model Version 3 (Collins et al. 2006) (CCSM3+WB) allows for the observed SSTA to be retrospectively predicted. Producing yearly forecasts for 1982–1998 provides a large sample for



**FIG. 4:** Composites of the signal-to-noise ratio for zonal wind stress across the equatorial Pacific for (a) observed, (b) idealised CCSM3 model without WWBs, and (c) idealised CCSM3+WB which includes WWBs (Lopez and Kirtman 2014).

prediction experiments and model testing (Lopez and Kirtman 2014). It can be seen that there is a significant decrease in the signal-to-noise (S/N) ratio during the spring period for zonal wind stress across the equatorial Pacific. This S/N decrease is most notable in observational data (Fig. 4(a)) and in CCSM3+WB models (Fig. 4(c)), however it is also prevalent in non-WWB models (Fig. 4(b)) but with less strength. Analysing correlation statistics for real prediction experiments shows that there is a pronounced drop in skill with the WWB model during spring, whereas the change is more dramatic when there are no WWBs. These results imply that the SPB is influenced by the existence of WWBs and to produce better skilled predictions, climate models should account for them.

## 5. CONCLUSIONS

To summarise, understanding the mechanisms for ENSO prediction and formation is currently limited as models such as ZC simplify the coupling between the atmosphere and ocean which limits the applicability to non-regular El Niño events. An additional challenge also arises in the form of the SPB where the predictive skill across March–May is low when compared to predictions originating from other points in the year. This barrier is evident from data and modelling, but there is yet to be a conclusive model which explains why it exists. Current research suggests that the barrier maybe related to weak climate coupling during spring or it may arise from stochastic noise forcing. However, these models fail to account for the potential for WWBs to be the source of the seasonality in ENSO forecast skill. Incorporating WWBs into prediction models suggests the SPB may be materialising due to the presence of the WWBs and they are potentially an important component in the dynamics of ENSOs.

*Final word count: 1940*

## 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).
- Balmaseda, M. A., Anderson, D. L. and Davey, M. K. (1994), ‘ENSO prediction using a dynamical ocean model coupled to statistical atmospheres’, Tellus A **46**(4), 497–511.
- 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.
- Collins, W. D., Bitz, C. M., Blackmon, M. L., Bonan, G. B., Bretherton, C. S., Carton, J. A., Chang, P., Doney, S. C., Hack, J. J., Henderson, T. B. et al. (2006), ‘The community climate system model version 3 (CCSM3)’, Journal of Climate **19**(11), 2122–2143.
- Duan, W., Liu, X., Zhu, K. and Mu, M. (2009), ‘Exploring the initial errors that cause a significant “spring predictability barrier” for El Niño events’, Journal of Geophysical Research: Oceans **114**(C4).
- 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.
- Gill, A. E. (1980), ‘Some simple solutions for heat-induced tropical circulation’, Quarterly Journal of the Royal Meteorological Society **106**(449), 447–462.
- Goswami, B. and Shukla, J. (1991), ‘Predictability of a coupled ocean-atmosphere model’, Journal of Climate **4**(1), 3–22.
- Jan van Oldenborgh, G., Balmaseda, M. A., Ferranti, L., Stockdale, T. N. and Anderson, D. L. (2005), ‘Did the ECMWF seasonal forecast model outperform statistical ENSO forecast models over the last 15 years?’, Journal of climate **18**(16), 3240–3249.
- Jin, E. K., Kinter, J. L., Wang, B., Park, C.-K., Kang, I.-S., Kirtman, B., Kug, J.-S., Kumar, A., Luo, J.-J., Schemm, J. et al. (2008), ‘Current status of ENSO prediction skill in coupled ocean–atmosphere models’, Climate Dynamics **31**(6), 647–664.
- Jin, F.-F. (1997), ‘An Equatorial Ocean Recharge Paradigm for ENSO. Part I: Conceptual Model’, Journal of the Atmospheric Sciences **54**(7), 811–829.
- Kirtman, B., Shukla, J., Balmaseda, M., Graham, N., Penland, C., Xue, Y. and Zebiak, S. (2001), ‘Current status of ENSO forecast skill: a report to the CLIVAR working group on seasonal to interannual prediction’.
- Latif, M. and Graham, N. E. (1992), ‘How much predictive skill is contained in the thermal structure of an oceanic GCM?’, Journal of Physical Oceanography **22**(8), 951–962.
- Lopez, H. and Kirtman, B. P. (2014), ‘WWBs, ENSO predictability, the spring barrier and extreme events’, Journal of Geophysical Research: Atmospheres **119**(17), 10–114.
- Mu, M., Duan, W., Wang, Q. and Zhang, R. (2010), ‘An extension of conditional nonlinear optimal perturbation approach and its applications’, Nonlinear Processes in Geophysics **17**(2), 211–220.
- 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.
- Qian, W. and Wang, S. (1997), ‘Multiple time-space scale atmosphere-ocean interactions and improvement of Zebiak-Cane model’, Science in China Series D: Earth Sciences **40**(6), 577–583.
- 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.
- Torrence, C. and Webster, P. J. (1998), 'The annual cycle of persistence in the El Niño/Southern Oscillation', Quarterly Journal of the Royal Meteorological Society **124**(550), 1985–2004.
- Trenberth, K. E. (1976), 'Spatial and temporal variations of the Southern Oscillation', Quarterly Journal of the Royal Meteorological Society **102**(433), 639–653.
- Troup, A. (1965), 'The 'southern oscillation'', Quarterly Journal of the Royal Meteorological Society **91**(390), 490–506.
- Wang, C. (2001), 'A unified oscillator model for the El Niño–Southern Oscillation', Journal of Climate **14**(1), 98–115.
- Wang, C., Deser, C., Yu, J.-Y., DiNezio, P. and Clement, A. (2017), El Niño and southern oscillation (ENSO): a review, in 'Coral Reefs of the Eastern Tropical Pacific', Springer, pp. 85–106.
- 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.
- Webster, P. J. and Yang, S. (1992), 'Monsoon and ENSO: Selectively interactive systems', Quarterly Journal of the Royal Meteorological Society **118**(507), 877–926.
- 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.
- Xue, Y., Cane, M., Zebiak, S. and Blumenthal, M. (1994), 'On the prediction of ENSO: A study with a low-order Markov model', Tellus A **46**(4), 512–528.
- Yu, Y., Mu, M. and Duan, W. (2012), 'Does model parameter error cause a significant "spring predictability barrier" for El Niño events in the Zebiak–Cane model?', Journal of Climate **25**(4), 1263–1277.
- Zebiak, S. E. and Cane, M. A. (1987), 'A Model El Niño–Southern Oscillation', Monthly Weather Review **115**(10), 2262–2278.