Computer Models for ENSO Prediction

 Relevant Theory, Model Development, and Forecast Performance—Brief Review, Historical Data, ‘Skill’ Limits, the Future

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ENSO (El Niño/Southern Oscillation) phenomenon, the largest interannual fluctuation in the world’s climate, has received wide attention in recent years because of its strong climatic and economic impact on both regional and global scales. As a result of the 10-year international Tropical Ocean Global Atmosphere (TOGA) program, monitoring and forecasting ENSO have now become reality. The extensive observational network developed during TOGA, such as the Tropical Atmosphere Ocean (TAO) array in the Pacific (Sea Technology, July 1997 and October 1995), watches for ENSO in real time and provides high-quality data for model validation and initialization.

The real forecasts of ENSO, however, have to rely on various computer models. Generally these models can be classified into three categories: the purely statistical models, the hybrid models with a physical ocean coupled to a statistical atmosphere, and the coupled models in which both the ocean and atmosphere are physically based (Latif et al., 1994).

Theoretical Basis

At present, ENSO can be predicted by statistical models several months in advance, and by physical coupled models at lead times exceeding one year. Our focus here is on the latter category of models—especially the coupled models developed and operated at Lamont-Doherty Earth Observa-

tory of Columbia University.

ENSO is a combination of El Niño and the Southern Oscillation, the two aspects of the same large-scale variation in the coupled ocean-atmosphere system. However, El Niño and the Southern Oscillation were studied separately in the early days. Bjerknes (1969, 1972) was the first to link the two together and to point out that ENSO is basically a result of the air-sea interaction in the equatorial Pacific. The essence of his theory is the “chain reaction,” or the positive feedback between the ocean and the atmosphere. That explains the unstable
growth of both the warm and cold phases of ENSO cycles, but not the turnabout from one phase to the other. The missing piece of the puzzle is the memory of the ocean, especially the crucial role of the equatorial ocean dynamics. This idea was first put forth by Wyrtki (1975, 1979), and was then confirmed by a set of numerical experiments with a forced ocean model (Busalacchi and O'Brien, 1981).

Based on the hypotheses of Bjerknes and Wyrtki, a number of simple coupled ocean-atmosphere models were developed in the 1980s (McCormick and Anderson, 1984; Zeestrak and Cane, 1987; Battisti and Hirst, 1988; Suarez and Schopf, 1988; Cane et al., 1990). Many of these models were able to simulate the characteristic features of observed ENSO, such as the recurrence of warm events at irregular intervals with a preferred period of three to four years, and the phase-locking of ENSO to the annual cycle.

On the basis of their model results, these investigators came up with a theory for the ENSO cycle: the so-called "delayed action oscillator" scenario. In this view ENSO is a low-frequency basin-wide mode of oscillation regulated by the equatorial long waves, which are the eastward-propagating Kelvin waves and the westward propagating Rossby waves. The oscillation is possible because the pure growth envisioned by Bjerknes can be...
stopped and reversed when the directly forced Kelvin signal is overcome by the delayed Kelvin signal of opposite sign. The latter comes from the reflection at the western boundary of the directly forced Rossby waves.

There are also other unstable modes in the coupled ocean-atmosphere system. Different modes may be excited depending on the coupling strength and the physical processes included in the model (Neelin et al., 1994), but the “delayed oscillator” mode appears most relevant to the observed ENSO and therefore to the design of ENSO forecast models. ENSO is predictable at long-term times because of its ocean-scale nature and its dependence on the nonlinear equatorial ocean dynamics. In principle, any model that captures the positive ocean-atmosphere feedback and the essential upper-ocean dynamical processes in the Tropical Pacific is hopeful of predicting ENSO. In practice, however, the predictive “skill” of a model depends on the formulation, parameterization, and initialization of that particular model.

Model Construction

There are now two types of physical

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During the last decade, a number of ENSO models, including ICMs and CGCMs, have shown predictive skills in both retrospective and real-time forecasting, and they are now being used for routine ENSO prediction. Among them, the Lamont model is the earliest and is still the “model to beat.” Its predictive ability has been demonstrated extensively (Cane et al., 1980; Latif et al., 1994; Chen et al., 1995, 1997).

The standard forecast procedure of the Lamont model consists of two steps. First, a full set of initial conditions is created by running the model from January 1964 up to the time when the forecast is to begin, with the observed wind stress anomalies assimilated into the model. Second, starting from the initial conditions, the model evolves on its own without further data input and forecasts are made on a monthly basis. The Lamont model forecasts were first made in 1985, and since then they have been made regularly and issued in various bulletins.

The forecast skill of a model is often measured by the comparison of model prediction and observation over certain ENSO indices. As an example, the forecasts made by the Lamont model are compared to observations in the figure in terms of the NINO3 index—the SST anomaly averaged over an area in the Eastern/Central Equatorial Pacific (5°S to 5°N; 90°W to 150°W). The model is capable of forecasting ENSO more than one year in advance. The large warming and cooling events in the 1980s are particularly well predicted. However, the model does a poorer job for the 1970s and 1990s, suggesting decadal variations in predictive skill. For instance, the 1976-77 event is largely overpredicted, and the short warm episodes in 1993 and 1994 are missed. A second figure shows the correlations and root mean square (rms) errors between predicted and observed NINO3 for the period from 1972 to 1995, and for three sub-periods of eight years each. Also shown is the prediction forecast which is used as a lower bound of useful prediction. The model prediction beats the persistence forecast in both correlation and rms error scores. On average it seems to have useful skill up to a lead time of 24 months, but the skills in the three sub-periods are quite different from one another, again indicating decadal variability in ENSO predictability.

The Lamont model is known to be able to reproduce the gross character of the Eastern Pacific ENSO anomaly, but underestimates its meridional and westward extent. It is clearly seen in the third figure which shows the spatial distribution of SST correlation between model prediction and observation. The correlation score is relatively high in the Eastern and Central equatorial Pacific, but decreases toward the west and higher latitudes. Some other models seem to have higher skill in the Central Equatorial Pacific but lower skill in the East (Rennet et al., 1993). Nevertheless, the overall
Concluding Remarks

The present computer models of the coupled ocean and atmosphere have achieved considerable skill in forecasting certain indices of ENSO, but even the best available models are far from perfect and there is still considerable room for improvement in modeling, observation, and forecasting technique. Factors that limit the current skill of ENSO forecasts include: (1) inherent limits to predictability because of the chaotic and random nature of the natural system; (2) model flaws such as oversimplified physics; (3) gaps in the observing system; and (4) flaws in the way the data is used (data assimilation and initialization). It seems likely that the inherent predictability limits for ENSO are years rather than weeks or months, though more theoretical study is needed in this area. The observing system is improving, but still far from satisfactory. Thus a challenge facing the modelers is how to improve model forecasts by making the most reasonable and efficient use of available data.

In the past few years much effort has been made to assimilate various observational data into the initial state of forecast models. The most common approach is to improve the ocean initial conditions in a stand-alone mode by assimilating observations of SST, thermocline depth, or sea level into an ocean model prior to coupling with an atmosphere model (Ji et al., 1995). One problem with this approach is that no interaction is allowed between the ocean and atmosphere during initialization, so the coupled system may not be well balanced initially and may experience a shock when the forecast starts. Recently a new initialization-assimilation procedure is shown to significantly improve the predictive skill of the Lamont model (Chen et al., 1995, 1997). The success of the new scheme is attributed to its explicit consideration of ocean-atmosphere coupling, and the associated reduction of initialization shock and random noise.

Although the predictive skill of an ICM such as the Lamont model is most likely to be limited by its greatly reduced physics, the more sophisticated CGCMs have not yet achieved better forecast scores, at least in terms of the Tropical Pacific SST. On the other hand, the CGCMs do have the potential to produce more detailed prediction and to accommodate more observational data for initialization.

Since the ocean contains the memory of the coupled tropical ocean and atmosphere system, it is reasonable to couple an upper ocean GCM with a simplified atmosphere model. Such a coupled model, which is computationally more costly than ICMs but still much more efficient than CGCMs, is being developed at Lamont.

As to predicting the global impact of ENSO, a two-tiered approach proves to be practical: a simplified regional model is first used to predict tropical SST fields, and these fields are then used as boundary conditions for a global atmospheric GCM to predict the global distribution of atmospheric disturbances. Because of limited computer resources and difficult model problems, there are no global, high-resolution CGCMs now available at present for operational climate prediction.

References


Dr. Dake Chen has worked on a broad span of oceanographic and climatic problems of various time and space scales, ranging from the vertical turbulent mixing in estuaries and shallow seas to the climate fluctuations associated with ENSO. He received his doctorate in physical oceanography from the State University of New York at Stony Brook in 1989, and then worked at University of Rhode Island for five years before he joined the senior staff at Lamont-Doherty Earth Observatory.