The past and the future of El Niño

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If events run true to form, the present El Niño is approaching a climax — which is why, acknowledging a Christmas connection, the phenomenon was so named. Predicting these events and their consequences is a daunting task, but there is progress to report.

Over the past few months, the arrival of an El Niño event has never been out of the news. Put simply, this phenomenon is a warming of the upper Pacific Ocean, but it has global effects and has been blamed for just about every climatic and social upset in the second half of 1997. There have been claims that the current El Niño may be the strongest of this century and the harbinger of stronger events that might accompany climate change. But how well do we really understand this phenomenon?

El Niños

In general, the tropical Pacific Ocean is characterized by warm surface water (29–30°C) in the west but much cooler temperatures in the east (22–24°C). The body of warm water in the west is known as the Pacific 'warm pool'[1], and it is associated with intense rainfall and the largest region of atmospheric heating[2]. The warm pool is relatively deep, with the temperature decreasing slowly with depth to the thermocline, the region of rapidly changing temperature some 100–200 m below the surface, before dropping off more rapidly. The cooler sea-surface temperatures (SSTs) in the eastern Pacific are the result of cold water upwelled from below, forced by the trade winds converging into the warm pool. Collectively, the east–west SST gradient and the associated easterly trade winds constitute a state of quasi-equilibrium for the ocean–atmosphere system[3].

Roughly every three to seven years, this state of quasi-equilibrium breaks down — ocean warming occurs across the entire basin, and it can last for a year or occasionally longer. This is an El Niño event[4]. Typically, the warm pool is displaced to the east, causing a shift in the major precipitation regions of the tropics and the disruption of normal climate patterns at higher latitudes. During the past two decades there have been a number of major warm events. In 1982–83, the then-strongest El Niño of the century occurred. In 1986 a weaker warm event ensued and lasted through 1987. A far weaker one occurred in 1992, but was untypical because it appeared to continue for a further two years. Usually, an opposite and cooler state of the tropical Pacific follows a year or so after an El Niño. This phase, known as La Niña, is marked by a distinct cooling in the eastern Pacific, and it too is associated with perturbations of the global climate. The warming and cooling phases are interspersed with the more common, normal, or quasi-equilibrium, state.

El Niño and La Niña depend jointly on oceanic and atmospheric processes, and are the result of the instability of the quasi-equilibrium state. The onset of an El Niño is often marked by a series of prolonged westerly wind bursts in the western Pacific, which persist for one to three weeks and replace the normally weak easterly winds over the warm pool[5]. The most important impact of these wind bursts is to severely perturb the upper ocean and excite the eastward propagation of large-scale Kelvin waves — these waves, which have wavelengths of thousands of kilometres, have their maximum amplitude on the thermocline[3]. Their main effect is not to advect warm water from the warm pool to the cooler eastern Pacific, but to suppress the upwelling of cold water in the central and eastern basin[2].

El Niño is linked to the regular annual cycle of SSTs in the tropical Pacific but, instead of cooling early in the northern spring, during an event the eastern ocean continues to warm. This observation has led to the speculation that the instability that produces El Niño results from the inability of the warm pool to export enough heat each year so that its heat content increases in time. In this sense, the warm pool is preconditioned for El Niño, and the westerly wind bursts may serve as triggers to release the stored energy.

The 1997–98 El Niño

In the spring of this year, unprecedented surface warming occurred over the tropical eastern Pacific Ocean and in the subtropics to the north. The warming continued to develop at a rate far faster than is usual for an El Niño, so that in October the SST in the eastern Pacific was as much as 5 °C higher than normal (Fig. 1). The event could well turn out to be among the strongest to occur this century. It is an indication of the advances in forecasting that, as early as October and November last year, over six months before observations confirmed El Niño onset, predictions were made by a number of research groups using a new class of coupled ocean–atmosphere models[6] (see box on page 564).

Early observational indications came in the form of the westerly wind bursts in late 1996 and early 1997, which extended farther to the east than in a normal year, along with the amplification and propagation of the subsurface temperature anomaly. In the months that followed, successive westerly wind bursts encroached further eastward as SSTs increased in the central Pacific.

Other preliminary signals were apparent

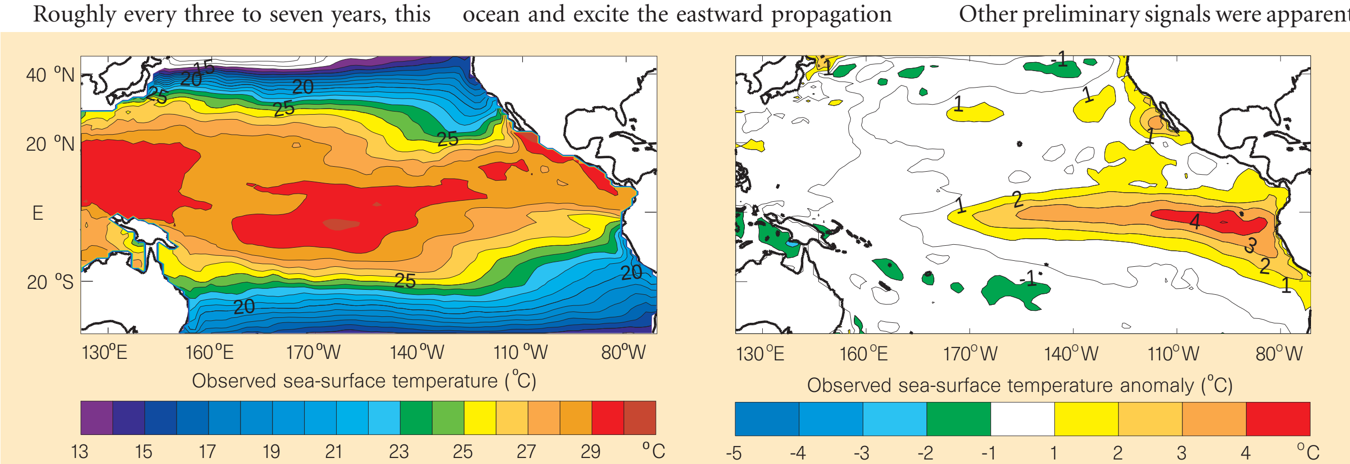

Figure 1 Left, **Observed mean sea-surface temperature for October 1997.** Right, **Deviation of the October 1997 sea-surface temperature from the long-term (1980–95) October average. The warming in the eastern Pacific is more than 5 °C. (Data from ref. 19.)**

in the subsurface structure of the Pacific, and became clear several months before surface warming was evident. In fact, the subsurface upper ocean had been warming well before the SST in the eastern Pacific had indicated that a major El Niño was under way (Fig. 2). Early in 1996 a 2–3 °C anomaly existed, indicating a moderate increase in the heat storage of the western Pacific warm pool. This anomaly persisted in the western Pacific throughout the year. During early 1997, the temperature anomaly slowly extended eastward, growing in intensity in the spring and progressively dominating the eastern Pacific Ocean; it finally surfaced in early summer. The subsurface temperature anomaly in the eastern Pacific is now in excess of 9 °C.

The consequences

El Niños are a regional phenomenon, but their 'footprint' is global. They are usually accompanied by severe drought over Australia and Indonesia, together with a weakened summer monsoon rainfall over South Asia[7]. Catastrophic flooding often occurs along the Pacific coast of South America and fish stocks disappear as ocean upwelling, containing high-nutrient cold water, diminishes. For societies where the impacts of El Niño are most direct, homes might be flooded, or destroyed by forest fire, and crops destroyed and fisheries ruined. Distinct disease patterns follow the waxing and waning of an event, through the contamination of water supplies by flooding and the creation of increased breeding areas for vectors such as mosquitoes. Water-borne diseases (hepatitis, dysentery, typhoid and cholera) have cycles associated with El Niño, as do vector-borne diseases (malaria, dengue and yellow fever, encephalitis, plague, hantavirus and schistosomiasis)[8]. El Niño also influences tropical cyclones, reducing their frequency in the Atlantic, but increasing it in parts of the Pacific.

Moreover, the climate of the extratropical regions remote from the Pacific may be affected by 'teleconnections' between tropical precipitation fields and large-scale circulation patterns in the extratropical atmosphere[9]. Teleconnections tend to change the probability of certain weather regimes in a particular region[10]. For example, the chance of stronger winter storms is greatly increased over southern California and the southern United States during El Niño. Beyond these severe regional impacts there is a broad influence on the global economy. Many of the commodities that are sensitive to El Niño, such as cereal crops, are traded on the world markets. Finally, the insurance industry is affected by the changing location of severe storms and hurricanes.

Cause and effect?

Can one say, however, that El Niños have 'caused' a particular perturbation to climate in some part of the world remote from the tropical Pacific? How can they have a predictable impact, a season or more ahead, on a system whose day-to-day fluctuations are not predictable beyond a couple of weeks? The answers lie in the nonlinearity of the climate system — El Niño will not have a predictable influence on the instantaneous state of the atmosphere itself; rather, that influence falls on probabilities associated with the atmospheric state.

For example, El Niño introduces an asymmetry into the probability distribution of large-scale weather patterns, making some less likely and others more likely. Such patterns may correspond to periods of enhanced westerly winds or to more stagnant anticyclone conditions. Based on climatological records, one can associate probabilities with the occurrences of these weather patterns and, in this respect, in the extratropics, El Niño's effect is strongest over the north Pacific and North America[10].

Further away, the influence of El Niño on weather patterns is generally statistically weaker, though certainly not negligible. In this sense, it is impossible to say that particularly severe weather in the extratropical latitudes has definitely been caused by El Niño. But it is perfectly reasonable to ask whether the probability of such weather occurring is increased (or decreased) by El Niño. Take, for instance, two regions of the Northern Hemisphere, Europe and India, which this past summer experienced two different climate anomalies. Central Europe suffered devastating flooding associated with prolonged periods of rainfall. Over India, on the other hand, where the climatological links to El Niño are well established, monsoon rains were close to normal when drought was expected (J. Shukla, personal communication). Why?

As it happens, six-month coupled ocean–atmosphere ensemble forecasts, stemming from work at the institution of one of us (T.N.P.), did predict a statistically significant probability of higher than normal summer rainfall over parts of central and southern Europe[6]. Because these forecasts also correctly predicted the El Niño, and the Pacific SST anomalies were the largest anywhere in the globe, it is probable that the forecast of increased likelihood of central European rainfall was linked to El Niño. But a probability is only a probability — if an identical El Niño developed three or four years from now, we could not say with certainty that

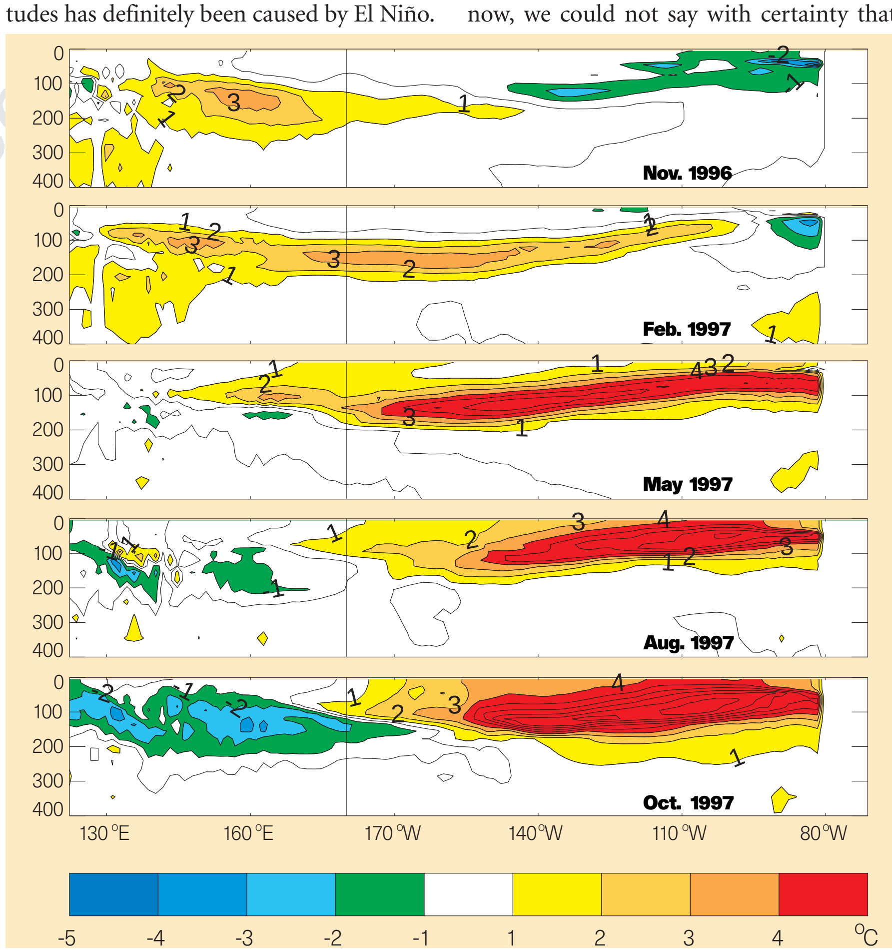

Figure 2 **Cross-sections of ocean temperature along the Equator in the Pacific for November 1996, and February, May, August and October 1997. Contours show deviations from the long-term (1980–95) monthly mean distributions. Starting with a 3 °C anomaly in the western Pacific, the subsurface anomaly strengthens and moves eastwards during 1997, surfacing in the eastern Pacific in the northern spring. (Data from ref. 19.)**

similar prolonged and heavy rain would occur.

The incidence of average, rather than below average, summer precipitation over India is equally intriguing. One school of thought holds that monsoons should be highly predictable[11]. When the empirical relationship between Pacific SSTs and Indian rainfall fails, as it did this past summer, then it is presumed there are other precursor climate anomalies (such as the snow depth over the Eurasian continent during the spring season) that have conspired against El Niño to produce a normal monsoon. But there is a different view, one which we take[12]. The Indian monsoon, like the extratropical circulations, has a chaotic component associated with an irregular alternation between periods of excessive rain or drought persisting from one to three weeks during a summer monsoon[7]. According to this perspective, El Niño would influence the probabilities of these rainy and drought regimes, making the drought phase more likely and the active phase less likely. However, compared with the chaotic fluctuations, the influence of El Niño would not be strong enough to make the occurrence of a normal monsoon impossible during an El Niño year.

The outlook

The 1997–98 El Niño has been the best described and best modelled yet. It has been the first to be observed with the full network of moored Tropical Atmosphere–Ocean (TAO) buoys deployed to monitor atmospheric and ocean conditions between 135° E and 95° W and 10° N and 10° S (ref. 13). The flow of data stemming from these observational platforms, a system envisaged under the international Tropical Ocean–Global Atmosphere (TOGA) programme[14], has contributed to the success of forecasting the current event — which, after future analysis, will become the benchmark for major El Niños.

The 1997–98 event is expected to grow in intensity, reaching a maximum within the next few weeks. If it runs true to form, we may expect increased rainfall in the southwestern United States and on the Pacific coast of Peru and Equador; furthermore, the drought should continue over Indonesia and New Guinea, and become more pervasive over Australia. If the warm SST anomalies extend through the northern spring, there is an increased probability of poorer than average rainfall in South Asia in the summer of 1998, and maybe, some say, of above average rain over central Europe.

Many models are already predicting that the Pacific Ocean will move into the opposite phase, La Niña, later in 1998. These predictions will be a discriminating test of the new generation of forecast models, which in turn are being used to forecast global climate change. Success in evaluating natural climate fluctuations can give us confidence that such models will in time be able to meet another great challenge — quantitative prediction of the effects that mankind is having on the Earth's climate. □

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Models for prediction

A great deal of progress has been made in forecasting El Niños. For example, the event of 1982–83 was only evident once it had started. At that time, seasonal predictions were made using empirical models whose equations were based on statistical relationships derived from historical time-series data[15]. In 1986, however, Cane and Zebiak[16] demonstrated the possibility of making very useful forecasts several seasons ahead, by taking the basic equations which describe Newton's laws of motion, together with the laws of thermodynamics, and applying them to describe the coupled dynamics of the ocean and atmosphere of the tropical Pacific. By the standards of comprehensive numerical weather-prediction models, the Cane–Zebiak model is relatively simple[17]. But, impressively, during the late 1980s and early 1990s it was used to predict the timing and magnitude of the variations of sea-surface temperatures in the tropical Pacific (and hence El Niño).

Those successes led to the development of comprehensive ocean–atmosphere models, where the atmospheric component was either a numerical weather-prediction model, or a global climate model, and where the ocean component covered all of the ocean basins[6]. For a decade, it has been hard to prove that the comprehensive coupled models were better than the Cane–Zebiak model. That may have changed with the 1997–98 event, which comprehensive coupled models forecast whereas the Cane–Zebiak model did not.

Part of the answer may lie in the relatively simpler way that models of Cane–Zebiak complexity handle the data used to create the initial conditions for the ocean–atmosphere forecasts. Essentially, the comparatively large systematic errors of the simple models makes them harder to use when assimilating these initial data. (Indeed, this was probably the case with the 1997–98 warming – later experiments have indicated that if a more comprehensive initial data set had been run on the Cane–Zebiak model, it too would have forecast a major El Niño with a similar lead time.) The comprehensive models also have such errors, but these have been reduced over the years and, in the long run, there is more scope to reduce them further than in the simpler models.

Empirical models can still be useful in prediction. Unlike the dynamically based models, however, their skill is obtained from statistical relationships derived from earlier, training data. Therein lies the rub, because on timescales of decades and centuries the world's climate is not stationary (which may or may not be due to anthropogenic effects)[18], and that will always limit the predictive power of empirical models. **P.J.W. & T.N.P.**

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