Modelling the El Niño–Southern Oscillation

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The El Niño-Southern Oscillation (ENSO) phenomenon is the strongest natural climate fluctuation occurring on the short-range climatic time-scale of a few months to several years that we know of. Although originating in the tropical Pacific, it influences not only regional but also global climate. For instance, variations in major rainfall systems around the world \([4]\) are well documented (see insert). Aside from its global climate anomalies, ENSO has a significant impact on ecosystems in the tropics and the economies of several countries \([10]\). The phenomenon has thus generated enormous public interest, and its analysis has attracted scientists from many fields. They include observationalists, theoreticians, and numerical modelers who have worked together very successfully during the last several years within the International Tropical Ocean Global Atmosphere (TOGA) project (1985-95). One aim has been to better understand ENSO by developing coupled ocean-atmosphere models.

**Fig. 1** — a, upper) A typical anomaly pattern for the tropical Pacific sea surface temperature associated with the El Niño phenomenon (0.2°C contour interval) \([1]\). b, middle) Spatial structure of the Southern Oscillation showing the global-scale nature of the phenomenon \([2]\). Shown is the correlation of annual pressure anomalies at Djakata (Indonesia) with all other locations (0.2°C contour interval). c, lower) Time series of the Southern Oscillation Index (SOI; dashed line) which measures the atmospheric sea-level pressure gradient across the tropical Pacific basin and of the anomalous sea-surface temperature (SST) at Puerto Chicama in Peru (solid line) \([3]\). Both time series are normalized by their standard deviation. Shading indicates major ENSO warm phases (high SST, low SOI).
Going Beyond Bjerknes

Current theory, in adopting a slightly more complex version of the interactions envisioned by Bjerknes, regards ENSO as originating from an instability of the coupled ocean-atmosphere system in the tropical Pacific. The long-term average sea surface temperature (SST) of the Pacific along the equator is characterized by a strong gradient, with temperatures of about 20°C in the eastern Pacific and of about 30°C in the western part. This temperature difference introduces an atmospheric circulation cell of the direct type (air rising over warmer surface layers) parallel to the equator which Bjerknes named the Walker Circulation, in honour of the discoverer of the Southern Oscillation. Within the Walker Circulation, air flows westward in the surface layers as part of the trade-wind system and is heated and supplied with moisture over the warm, western Pacific. The air then rises giving deep convection and heavy rainfall. It remains at upper levels for some time before descending over the relatively cold eastern part of the Pacific Ocean, thus completing the Walker Circulation.

The stress on the ocean's surface of the westward-flowing wind has a strong impact on the circulation of the ocean near the equator. Water is piled up in the west and a gradient in the sea level of about 400 mm is established across the Pacific. This gradient is compensated for by a slope in the thermocline (the interface separating the well-mixed, warm surface waters from the cold waters found at deeper levels), which tilts upward in the east. The change of sign of the Coriolis force due to the Earth's rotation at the equator means that the associated surface currents near the equator diverge and run poleward in both the northern and southern hemispheres. This divergence drives a narrow band of equatorial upwelling. The combination of upwelling and a shallow thermocline leads to the relatively cold surface layers in the eastern Pacific, while the deep thermocline in the west is associated with a warm surface.

Anomalies amplified

A perturbation in either the Walker Circulation or the SST at the equator can be amplified by unstable air-sea interactions. Consider, for instance, a positive SST anomaly in the eastern equatorial Pacific. This anomaly reduces the east-west SST gradient and hence the strength of the Walker Circulation, resulting in weakened trade winds at the equator. The result is a deeper thermocline and reduced currents and upwelling, leading to higher SSTs in the eastern Pacific which reduces further the gradient of the SST. There is a positive feedback which can lead to instabilities in the mean state of the climate owing to interactions between the ocean and the Earth's atmosphere.

Between the heat content of the upper layers of the ocean on the one hand and the SST and the wind stress on the other there exists the phase differences needed to maintain an oscillation. The ocean is not in equilibrium with the atmosphere and carries information associated with past winds that permits continuous oscillation [11]. The phase differences can be seen clearly in Fig. 2 showing the evolution of the equatorial SST and upper ocean heat content as a function of longitude and time, as derived from observations over 10 years. While the SST is dominated by a standing-wave component, the characteristic signature of the subsurface memory is reflected in the lead of the heat content anomalies in the western part relative to those in the eastern part. This behaviour is particularly prominent during the latter half of the record when the number of observations was increased considerably owing to the TOGA project.

A delayed action oscillator

The subsurface memory of the system can be related to ocean wave dynamics. The delayed action oscillator [13] is a conceptual model that provides a simple analogue. It illustrates very clearly the role played by the propagation of equatorial Kelvin waves and their reflections at meridional boundaries corresponding to land masses (South America and Australia/Southeast Asia in the case of ENSO; see Fig. 3). Suppose that unstable air-sea interactions produce warm SST perturbations growing in the eastern Pacific together with perturbations, to the west of the SST perturbations, in the wind that is blowing eastward (perturbations are generally called anomalies by meteorologists). The effect of the eastward wind anomalies is to deepen the thermocline in the eastern part of the basin through downwelling waves that strengthen the El Niño warming. These waves are called Kelvin waves and are essentially gravity waves. At the same time, the eastward-blowing winds force upwelling signals at the western edge of the wind anomalies and these signals propagate westward as so-called Rossby waves that push the thermocline upwards (for a Rossby wave, the restoring force is the north-south depen-

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Effect on Major Rainfall Systems

Droughts and flooding: during the El Niño phase of the El Niño-Southern Oscillation, droughts are frequently observed in Southeast Asia and in parts of Australia, while on the other side of the Atlantic, excessive rainfall and flooding are experienced over parts of South America.

Rainfall variations: correlations of ENSO with the strength of the summer monsoon in India and with interannual variations of rainfall in the Sahel region have been demonstrated (e.g., see [5]).

Atmospheric circulation: atmospheric circulation outside the tropics is influenced by ENSO, primarily during winter (e.g., [6]). A characteristic long-range influence (called the Pacific/North America connection pattern by meteorologists) describing the response of the atmospheric winter circulation associated with the extremes of the ENSO cycle has been identified [7] and exploited for short-range climate predictions for the North Pacific/North American region [8].

Impact on European climate: a significant, although, weak response to ENSO over Europe has been found [9]. In periods such as 1982/3 when the El Niño is exceptionally pronounced, the air over central Europe in winter is unusually warm so the rainfall is higher than average.

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Fig. 2: — Time-longitude plot of observed anomalies along the equator during the period 1979-88 [12]; left SST: 0.5°C contour interval; right) Heat content integrated above 275 m (100°Cm contour interval). The data have been low-pass filtered to remove variability on time-scales smaller than 17 months.
Fig. 3 — Schematic illustration of the delayed action oscillator scenario [14]. a, upper) Shown are the conditions during the warm (El Niño) phase of ENSO in the eastern Pacific. As the SST anomaly grows (corresponding to an increase in temperature in the shaded region), eastward flowing anomalies (small arrows) at the western edge of the SST anomaly excite upwelling which propagates westward as Rossby wave packets which have a maximum amplitude a few degrees north and south of the equator. They are reflected at the western boundary (Australia and Southeast Asia), and return as a Kelvin wave packet. The resulting oscillation period is the result of the superimposition of many free and forced wave modes. b, lower) Illustration showing how upwelling redistributes warm water, thereby reducing the gradient of the thermocline.

The real system is less regular than the theoretical oscillators (Fig. 1c). The inclusion of both random forcing to account for the high-frequency variability of weather fluctuations and nonlinear interactions between different time-scales (especially between the annual cycle and the ENSO mode) are possible candidates for obtaining more irregular behaviour (e.g., [17]).

Fig. 4 — The ENSO attractor displayed in a low-dimensional phase space, as derived from 20 years of tropical Pacific surface and subsurface temperatures and zonal wind stresses [15]. Shown are 10 phase-space trajectories which converge onto a limit-cycle attractor. The curves at the bottom of the box represent a projected image on this plane.

Fig. 5 — Time-longitude plot of anomalies along the equator from the coupled general circulation model of Philander et al. [21]. Left) SST, 0.25 °C contour interval; right) Heat content integrated above 275 m, 50 °Cm contour interval [12]. The data have been low-pass filtered to remove variability on time-scales smaller than 24 months.
eastern equatorial Pacific for the intermediate coupled model of Zebiak and Cane, the first coupled model used for forecasting the ENSO.

Many coupled models, including that of Zebiak and Cane, are limited to the tropical Pacific region and cannot be used directly to study the predictability of climate anomalies outside the Pacific or beyond the tropics. However, the forecast tropical Pacific SSTs can be used to determine the associated atmospheric response by feeding them into global atmospheric models. Barnett et al. [24] obtained encouraging global forecasts using this two-tiered approach. Forecasts were restricted to the winter season and major ENSO extremes. The cover illustration shows the correlation between the observed anomalies at a height (about 5 km) corresponding to a mean atmospheric pressure of 500 hPa with the forecasts for two seasons ahead. Significant correlations are found, both inside and outside the tropics. So various global coupled ocean-atmosphere models are currently being developed further to forecast simultaneously tropical and extratropical climate anomalies.

For lead times of a few months, the coupled models do not perform better than a persistence forecast, i.e., a forecast that assumes that the SST anomalies remain constant throughout the forecast period (see Fig. 6). This is because up to now observed ocean currents have not been used to initialize the coupled models. Instead, the observed wind stresses are used to initialize the ocean component. Errors in the forcing and the formulation of the model thus manifest themselves as considerable errors in the initial SST anomaly fields. Significant improvement of the forecasts at small lead times can be expected by representing the El Niño-Southern Oscillation. The phenomenon demonstrates, for instance, a pronounced variability over the time-scale of the oceans around the globe. Furthermore, particular periods in the past have been turned out to be unpredictable; the reasons need to be explored, and theoretical limits on predictability determined. Improved understanding of the interactions between ENSO and other phenomena and time-scales is also required. For instance, it is well established, that ENSO affects the monsoon in Asia, but it is unclear if the monsoon feeds back to ENSO. Another interesting question is whether or not ENSO is affected by anthropogenic climate change such as tropical deforestation or a possible greenhouse warming. Finally, the systems for forecasting ENSO are still at a rather low level of sophistication relative to numerical weather-prediction models. The initialization problem clearly needs to be addressed more carefully, and the first encouraging results are starting to emerge.

There are also related problems which will be addressed by a new international programme (see insert). In general, however, the ENSO phenomenon has had an influential effect on climate research, and a fruitful international collaboration between specialists in several fields has led to a reasonably advanced understanding. It stimulated the development of coupled ocean-atmosphere models and is providing them with a test-bed which is relevant for global greenhouse warming. ENSO forecasts represent the first successful examples of short-range climate forecasting; they are currently conducted at several institutions for use by governments in several countries, notably those whose economies are affected.

### Outlook Encouraging

Much remains to be done in modelling the El Niño-Southern Oscillation. The phenomenon accounts for pronounced variability over the time-scale of decades which needs to be explained (it might be related to variations in the circulation of the oceans around the globe). Furthermore, particular periods in the past have been turned out to be unpredictable; the reasons need to be explored, and theoretical limits to predictability determined. Improved understanding of the interactions between ENSO and other phenomena and time-scales is also required. For instance, it is well established, that ENSO affects the monsoon in Asia, but it is unclear if the monsoon feeds back to ENSO. Another interesting question is whether or not ENSO is affected by anthropogenic climate change such as tropical deforestation or a possible greenhouse warming. Finally, the systems for forecasting ENSO are still at a rather low level of sophistication relative to numerical weather-prediction models. The initialization problem clearly needs to be addressed more carefully, and the first encouraging results are starting to emerge.

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### References

15. Gritzer B. & Latif M., Climate Dynamics, in press.

### COVER ILLUSTRATION

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