been made, enabled scientists to follow, and anticipate, the evolution of El Niño of 1997/98 in detail.

The predictability of El Niño

The Southern Oscillation, a natural mode of oscillation of the coupled ocean–atmosphere system, at times appears to be self-sustaining and hence relatively easy to predict. The 1980s seem to have been such a period; El Niño of 1982/83 was the start of two complete cycles of the Southern Oscillation. At other times the oscillation seems to be a damped mode that is present for a cycle at most, after being excited by random disturbances. Disturbances that very effectively can excite El Niño, because their surface winds have a spatial structure that coincides with those of the Southern Oscillation, are certain brief convective activities that are associated with two-week bursts of westerly winds over the western equatorial Pacific. (These convective activities do not involve ocean–atmosphere interactions that characterise the Southern Oscillation.) This type of disturbance was influential in initiating El Niño of 1997/98. That event followed El Niño of 1992 which persisted for a surprisingly long time, and which petered out, without being followed by a significant La Niña. It appears that the Southern Oscillation was damped during the 1990s, in contrast to the 1980s when it seems to have been more self-sustaining. Consistent with this view is the performance of the coupled ocean–atmosphere models that simulate and predict El Niño; those models had far more success with the events of the 1980s than those of the 1990s.

Evidence that the Southern Oscillation is subject to long-term modulations, so that it is prominent and energetic during some decades, less so during others, is available from coral records that cover a century or more. One of the factors responsible for this modulation is the time-averaged depth of the equatorial thermocline, which depends on exchanges between the tropical and extratropical oceans. Current research on the Southern Oscillation is therefore concerned with ocean–atmosphere interactions, not only in the tropics, but also in higher latitudes.

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The 1997/98 El Niño

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During the early months of 1997 the tropical Pacific Ocean underwent a major transition from La Niña conditions in November 1996 to a major El Niño by the summer of 1997, with peak sea surface temperature (SST) anomalies in the east Pacific in excess of 5 degC (Fig. 1, p. 277). A moderate El Niño was predicted by most forecasting centres in the latter part of 1996, although its magnitude and rapid growth were underestimated. Even though the SSTs at the end of 1996 (Fig. 1(a)) still displayed La Niña conditions, the presence of an anomalously deep layer of warm subsurface water was evident in the west Pacific. These conditions are widely recognised as a precursor to the development of an El Niño event.

By early 1997 there was clear evidence of the beginnings of a major El Niño event, both in the subsurface temperature anomalies and with the emergence of warm SST anomalies along the Peruvian coast (Fig. 1(b)). El Niño then developed rapidly and by the summer a mature pattern of SST anomalies was in place (Fig. 1(c)), with the characteristic 'horseshoe' pattern of cold anomalies in the west and subtropical Pacific Ocean. Through the remaining months of 1997 El Niño continued to intensify, with the warmest anomalies gradually extending westwards into the central Pacific (Fig. 1(d)). A notable feature of the global tropical SST pattern by the end of 1997 (Fig. 1(d)) was the intensification of warm anomalies in the Atlantic and Indian Oceans which, as will be discussed later, may be attributed to the remote effects of El Niño.

There is no doubt about the exceptional nature of both the growth rate and the intensity of the 1997/98 El Niño (Fig. 2). There has been considerable speculation that it might be related to a series of strong Madden–Julian Oscillations (MJOs) which were a notable feature of the winter and spring of 1996/97. The intraseasonal oscillation, or MJO, is the dominant mode of variability in the tropics at time-scales in excess of one week but less than one season. In simple terms, the MJO can be described as a near-global scale, quasi-periodic, eastward-moving disturbance in the surface pressure, tropospheric temperature and zonal winds over the equatorial belt. Its typical time-scale lies between 30 and 60 days, and when it is active it produces a substantial modulation of the convective activity over the Indian and west Pacific Oceans (Madden and Julian 1994). The MJO has its peak activity during northern winter and spring, and intense near-surface westerly wind events over the tropical Pacific Ocean, known as westerly wind bursts (WWBs), are often related to the active phase of the MJO (*e.g.* Kiladis *et al.* 1994; Verbickas, this issue).

Various studies (*e.g.* Kindle and Phoebus 1995) have suggested that WWBs have a direct effect on the ocean through the initiation of equatorially trapped Kelvin waves; these display downward propagation and deepen the thermocline as they travel eastwards across the Pacific Ocean towards South America. Their presence can be clearly seen as eastward-propa-

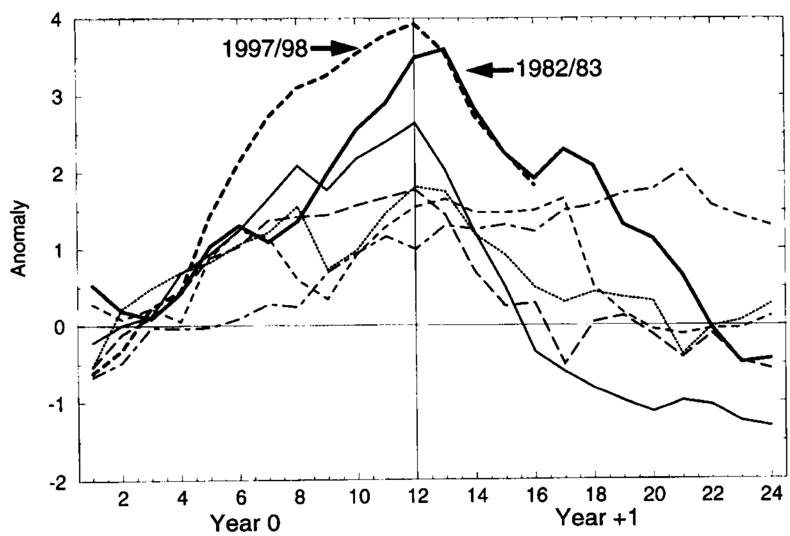

Fig. 2 Evolution of the monthly mean Niño3 sea surface temperature (SST) anomalies (degC) for the six major El Niño events since 1950 compared with the growth of the 1997/98 El Niño event. Year 0 and Year +1 correspond to the typical life cycle of El Niño in which it peaks around Christmas at the end of Year 0. (SST anomalies in the Niño3 (5°N–5°S, 90–150°W) region of the central and east Pacific are often used to describe the state of El Niño.)

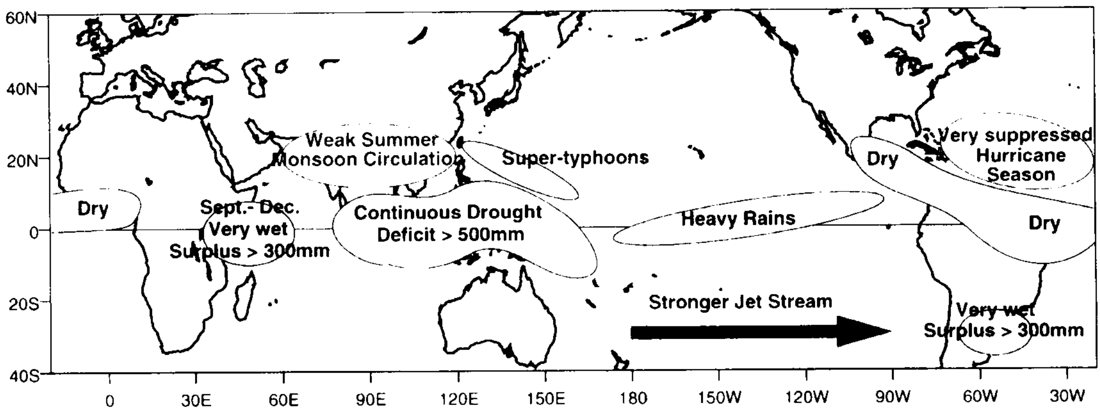

Fig. 4 Schematic showing the major impacts of El Niño during the period June to December 1997

gating events in the anomalous depth of the 20 °C isotherm during 1997 (Fig. 3(a), p. 278). The ability of these Kelvin waves to perturb the thermocline has led to the suggestion that a potential link between El Niño and the MJO might exist. For example, Kessler and McPhaden (1995) have suggested that intraseasonal oceanic Kelvin waves, possibly excited by the MJO (Kessler *et al.* 1995), played a prominent part in the prolonged warm event of the early 1990s.

The development of the 1997 El Niño is potentially another striking example of how intraseasonal activity in the atmosphere, generating intraseasonal activity in the ocean, may have a major impact on the interannual behaviour of the coupled ocean–atmosphere system. Active MJO events in December 1996 (A), March 1997 (B) and June 1997 (C) were characterised by periods of strong westerly zonal winds, in each case the westerlies penetrating further east beyond the dateline (Fig. 3(b)). The first MJO event in December 1996 (A) produced a strong WWB event in late December associated with twin cyclones (see Fig. 1 of Verbickas, this issue). This triggered the first oceanic Kelvin wave evident in Fig. 3(a). The second MJO event in March 1997 (B) produced one of the strongest WWBs on record and was associated with a series of intense cyclones in the Southern Hemisphere. This WWB produced a major displacement of the thermocline and excited a second, more intense oceanic Kelvin wave (Fig. 3(a)). The strong, persistent westerlies associated with this MJO also displaced a body of warm surface water to the east giving rise to local SST anomalies in excess of 1 degC near the dateline during March and April (Fig. 1(b)). These local warm SST anomalies appear to have contributed to the migration of the main area of convection eastwards and to the persistence of westerly wind anomalies near 160°E during April 1997, all of which contributed to the conditioning of the coupled ocean–atmosphere system towards El Niño.

The growth of the 1997 El Niño was more rapid than any other since 1950 (Fig. 2) and the SST anomalies in the east and central Pacific were larger during the summer months of 1997 than in any other summer on record. The impact on the tropical circulation has been dramatic with substantial rainfall anomalies in many parts of the tropics. Figure 4 summarises the principal weather anomalies in the period June to December 1997 which can be directly attributed to El Niño.

It is well known that El Niño modulates the Walker circulation by moving the main ascending branch eastwards into the central Pacific in association with the heavy rainfall triggered by the anomalously warm SSTs. The main descending branches of the Walker circulation then occur over the maritime continent and the tropical Atlantic Ocean, giving rise to the pronounced drought over Indonesia, dry conditions in Brazil and west Africa, and the virtual cessation of hurricane activity over the Atlantic

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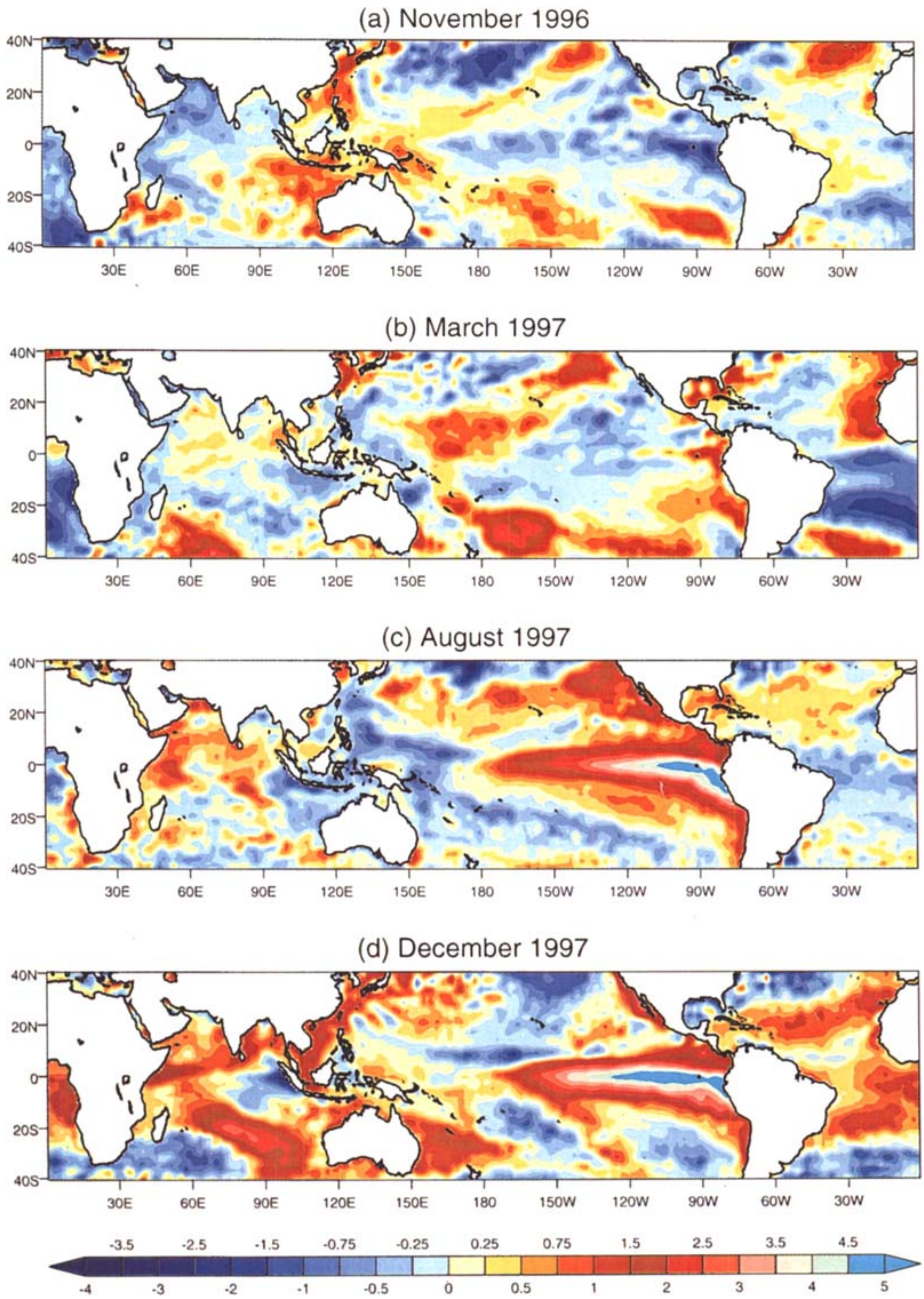

Fig. 1 Monthly mean sea surface temperature anomalies (degC) for (a) November 1996, (b) March 1997, (c) August 1997, and (d) December 1997. The anomalies have been computed from the monthly mean climatology for 1982-96 of Reynolds and Smith (1994). *(See article on p. 274.)*

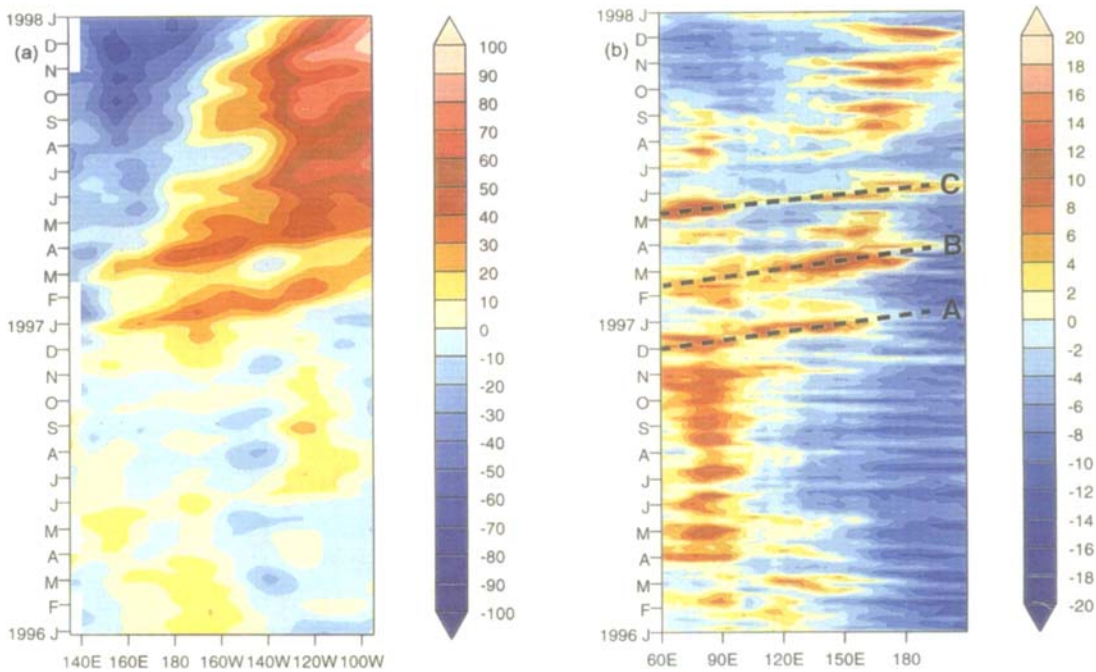

Fig. 3 Longitude–time diagrams of (a) anomalous depth (m) of the 20°C isotherm, and (b) 850 mbar zonal wind (m s^{-1}). The zonal winds are 5-day averages taken from the operational ECMWF analyses. The isotherm depth anomalies are based on 5-day averages of the Tropical Atmosphere Ocean (TAO) buoy data averaged between 2°N and 2°S. (See article on p. 274.)

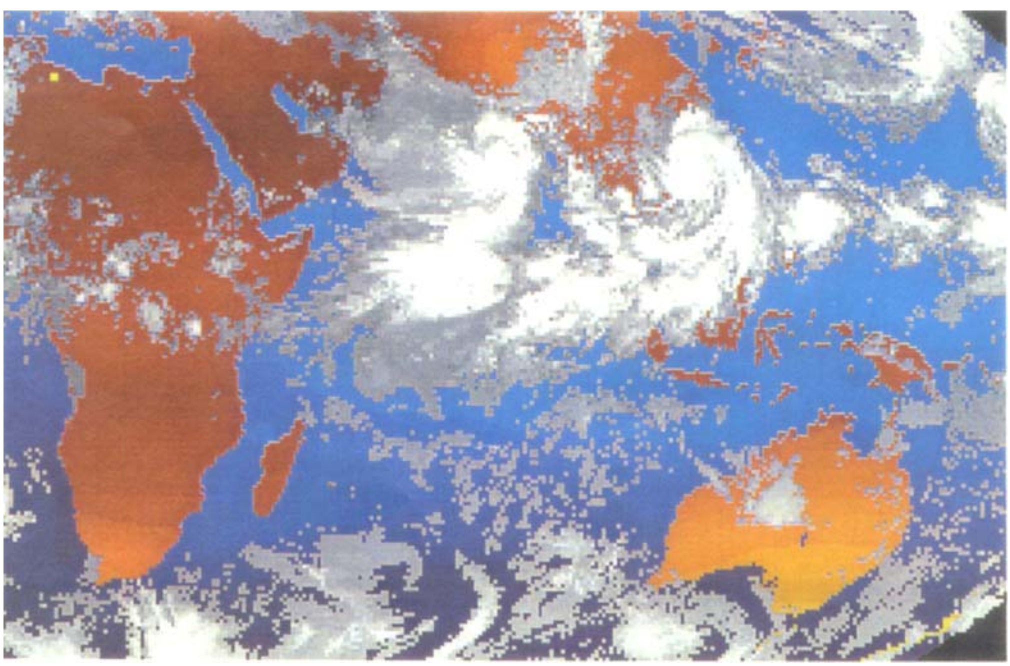

Fig. 4 Satellite imagery (composite of cloud and temperature imagery) at 1200 GMT on 21 August 1997 (see article on p. 284)

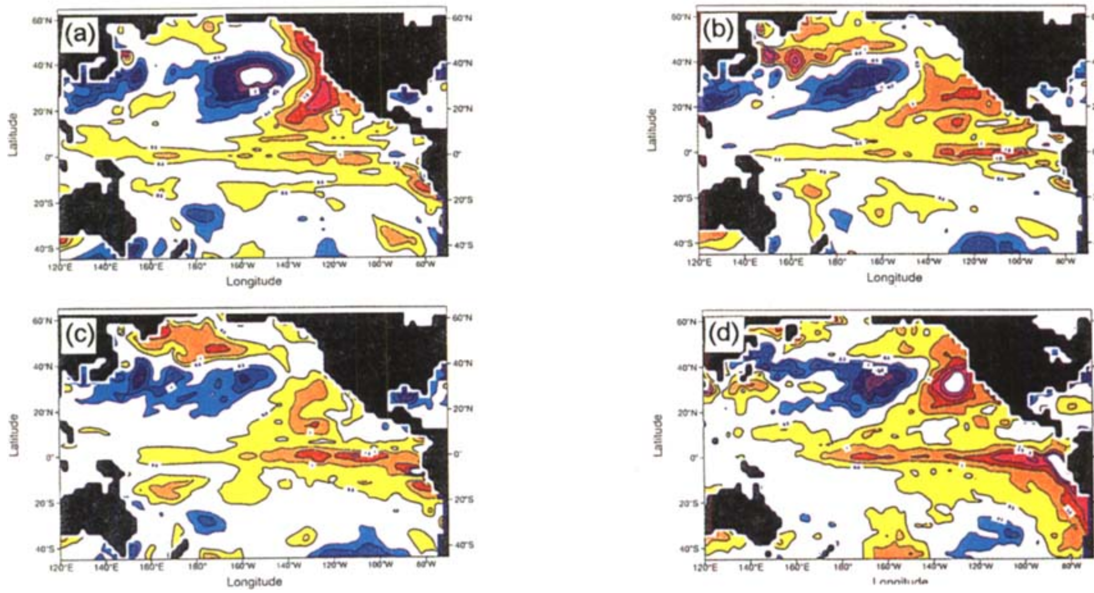

Fig. 3 Predicted SST anomalies for May 1997, from forecasts with atmosphere initial conditions from (a) 21 December (b) 22 December (c) 23 December 1996 and (d) the observed SST anomaly for May 1997. Contour interval is 0.5 degC with contours starting at 0.5 and −0.5. Temperature anomalies between −0.5 and 0.5 are not plotted. Despite the identical ocean initial conditions there are significant differences between the plots showing the influence of differences in atmospheric initial conditions. Nonetheless all show the same basic El Niño development which was similar to that which was later observed. (See article on p. 303.)

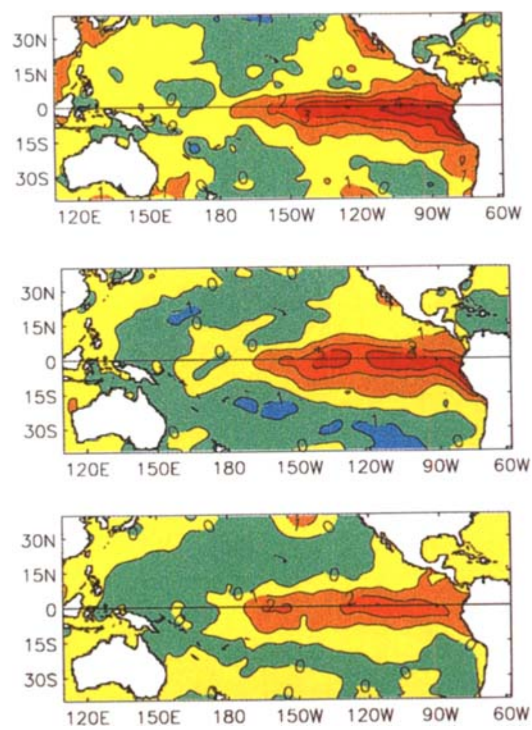

Fig. 6 Sea surface temperature anomalies for November and December 1997, January 1998 (top), November and December 1982, January 1983 (middle), and November and December 1972, January 1973 (bottom). (See article on p. 295.)

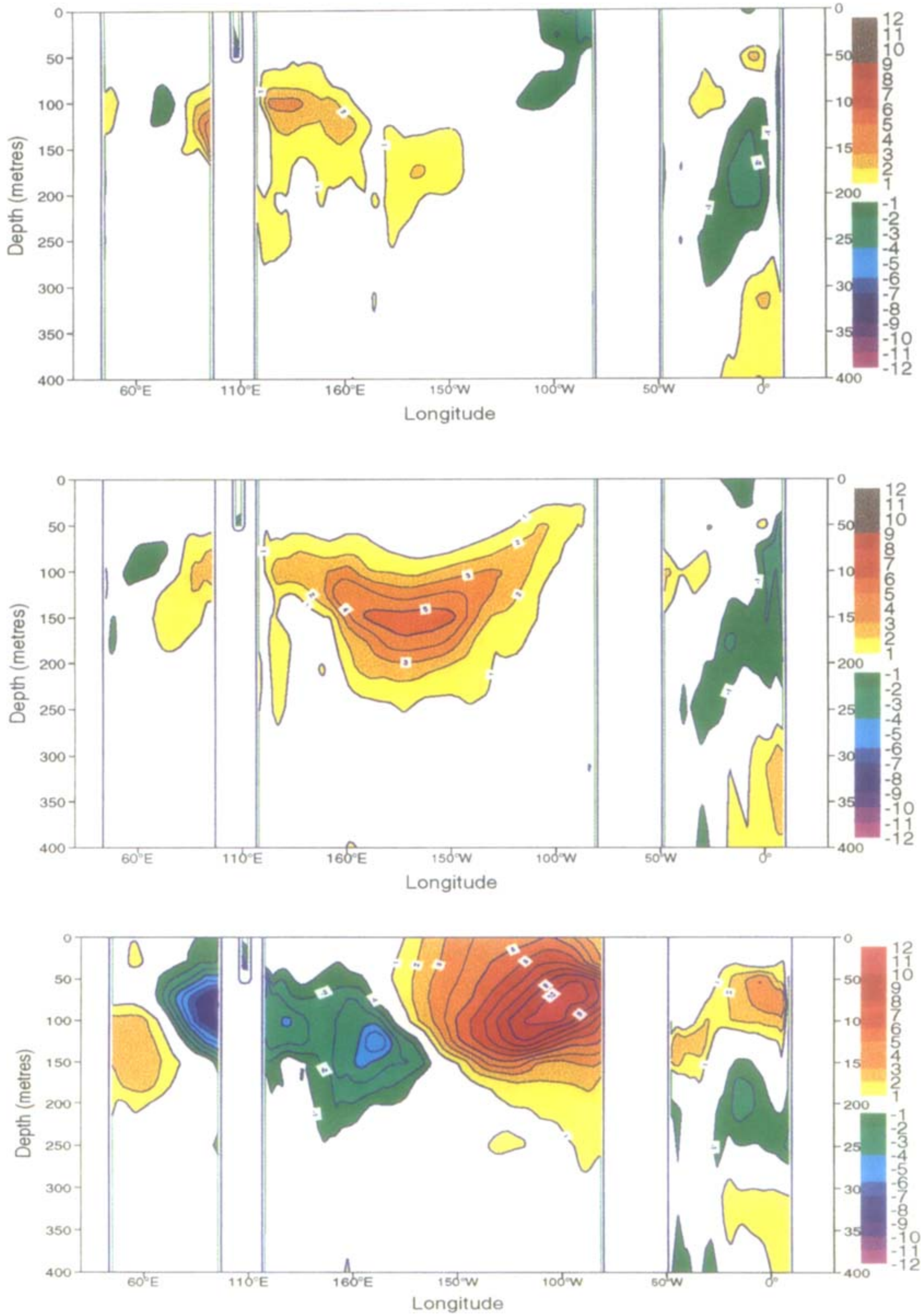

Fig. 8 Longitude–depth sections of equatorial upper ocean temperature anomalies (degC), for October, November, December 1996 (top), January, February, March 1997 (middle), and October, November, December 1997 (bottom). (See article on p. 295.)

(Fig. 4 – see also Jones and Thorncroft, this issue). These teleconnections with El Niño are well known and predictable, but were particularly marked in 1997 due to the intensity of the event.

As noted by Annamalai and Slingo (this issue), the Asian summer monsoon circulation was weaker than normal in 1997 – another well known impact of El Niño. However, the Indian monsoon rains were not particularly deficient. This has been related to the behaviour of the Pacific tropical cyclones which were particularly long-lived and intense during 1997, probably as a result of the abnormally extensive area of ocean with SSTs in excess of 28 °C. Indeed, tropical Pacific SSTs reached maxima in excess of 29.5 °C during much of the latter part of 1997.

From September onwards east Africa experienced exceptionally wet weather which can again be attributed to El Niño. The suppression of convection over Indonesia gave rise to persistent easterly anomalies in the lower tropospheric winds over the equatorial Indian Ocean (Fig. 3(b)). Figures 1(c) and (d) suggest that the local oceanic response to these wind anomalies was a reduction in the cold upwelling along the Somali coast and advection of the warm surface waters from the west to the east Indian Ocean. By the end of 1997, substantial warm SST anomalies had developed along the east African coast (Fig. 1(d)), triggering persistent convection which in turn served to maintain the low-level easterly wind anomalies and reinforce the SST anomaly pattern.

In the extratropics the main impact of El Niño is likely to be felt during the winter months. In the Southern Hemisphere the expected intensification of the subtropical westerly jet over the South Pacific occurred in the latter months of 1997, bringing wet and stormy conditions to parts of Chile and Uruguay. The impact of El Niño on the Northern Hemisphere has already brought wet conditions to California in association with a positive Pacific/North America anomaly pattern.

The strong intraseasonal activity in the zonal wind (Fig. 3(b)) and in the upper layers of the equatorial Pacific Ocean (Fig. 3(a)) were particular features of the winter and spring of 1996/97, but not of the previous year. The MJO displays substantial interannual variability in intensity. In some years it is very active, as in 1997, but in other years it is almost completely absent. The important question is whether the interannual variability in the activity of the MJO is related to changes in the mean state of the tropics and therefore to SST (such as the phase of El Niño), or whether it is purely stochastic and therefore inherently unpredictable. The evolution of the 1997/98 El Niño suggests that this question may have important implications for prediction on seasonal to interannual timescales.

Acknowledgement

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