RECENT CHANGES IN EL NIÑO - SOUTHERN OSCILLATION EVENTS AND THEIR IMPLICATIONS FOR SOUTHERN AFRICAN CLIMATE

By

S.J. MASON*

Climatology Research Group, University of the Witwatersrand, 2050 Wits,
South Africa

SUMMARY

Since the late 1970s, El Niño episodes have been unusually recurrent, while the frequency of strong La Niña events has been low. With the long El Niño sequence of 1991-1995, concern has been expressed about the possibility of climatic change in the equatorial Pacific. However, changes in the frequency of El Niño-Southern Oscillation events and earlier persistent El Niño and La Niña sequences can be detected in the historical and palaeoclimatic records. The recurrent warm event conditions of the first half of the 1990s are the result of the persistence of an anomalously warm pool near the date line which shifted the main centre of convection over Indonesia toward the centre of the equatorial Pacific Ocean. The eastward shift of the convection centre has allowed the penetration of westerly wind anomalies, associated with Madden-Julian wave activity, further into the western and central Pacific, thus initiating sequences of downwelling Kelvin waves. It has been suggested that the warm pool near the date-line may be a result of an abrupt warming trend in sea-surface temperatures throughout the tropical Indian and Pacific oceans. The abrupt warming has been attributed to the enhanced-greenhouse effect, but may equally be indicative of inter-decadal variability. The recent changes in El Niño events are therefore not necessarily an indication of climatic change. Although the generally dry conditions over parts of southern Africa over the last 15-20 years may be attributed in part to the relatively high ratio of warm to cold events, no long term change in the mean annual rainfall of the subcontinent can be implied at this stage.

INTRODUCTION

In recent years, there has been considerable interest in ocean-atmosphere variability in the equatorial Pacific Ocean. The interest has been focused largely on occasional basin-wide warming or cooling of equatorial sea-surface waters, known as El Niño and La Niña events, together with an associated oscillation of atmospheric pressure over the South Pacific Ocean, known as the Southern Oscillation. The coupled ocean-atmosphere system, including both El Niño and La Niña events, has come to be referred to as El Niño - Southern Oscillation (ENSO) (Allan *et al.*, 1996). The research focus is justified by theoretical and observational evidence indicating that ENSO events can have global climate repercussions, being associated with temperature and rainfall anomalies around the world (Ropelewski & Halpert, 1987, 1989; Halpert & Ropelewski, 1992). Over much of southern Africa droughts are frequently concurrent with Pacific warm events (Lindesay *et al.*, 1986; Janowiak, 1988; Lindesay, 1988; Jury *et al.*, 1994; Mason & Jury, 1997).

---

* Present address: Scripps Institution of Oceanography, University of California, San Diego, Mail code 0235, La Jolla CA 92093-0 285, United States of America. E-mail: simon@lacosta.ucsd.edu

ISSN 0035 919X – *Trans. Roy. Soc. S. Afr.*, 52(2). Pages 377-403, 1997.

El Niño - Southern Oscillation events have probably occurred over at least the last 5 000 years (Enfield, 1992), and although there are indications that their frequency has been variable, irregular oscillations between warm (El Niño) and cold (La Niña) conditions at periods of about 3 to 10 or more years may be considered typical (Trenberth & Shea, 1987; Trenberth, 1991; Ropelewski *et al.*, 1992). For most of the first half of the 1990s, however, El Niño conditions have been notably recurrent or persistent (Wuetrich, 1995; Trenberth & Hoar, 1996). Further, although each event has to be considered as unique in terms of the details of its timing and evolution (Diaz & Kiladis, 1992; Wang, 1995a), since the late 1970s the coupled ENSO system has exhibited a number of unusual characteristics when compared to its manifestations in the 1950s and 1960s. The 1977-1978 El Niño was followed by only weak La Niña conditions in 1981, but not evident in the Southern Oscillation Index (Allan *et al.*, 1996), and then by a second El Niño event in 1982-1983. The 1982-1983 El Niño, as measured by the Southern Oscillation Index, was the strongest in the period of instrumental records (Wright, 1989; Trenberth, 1991) and possibly over the last 500 years (Quinn *et al.*, 1987). Cold conditions in

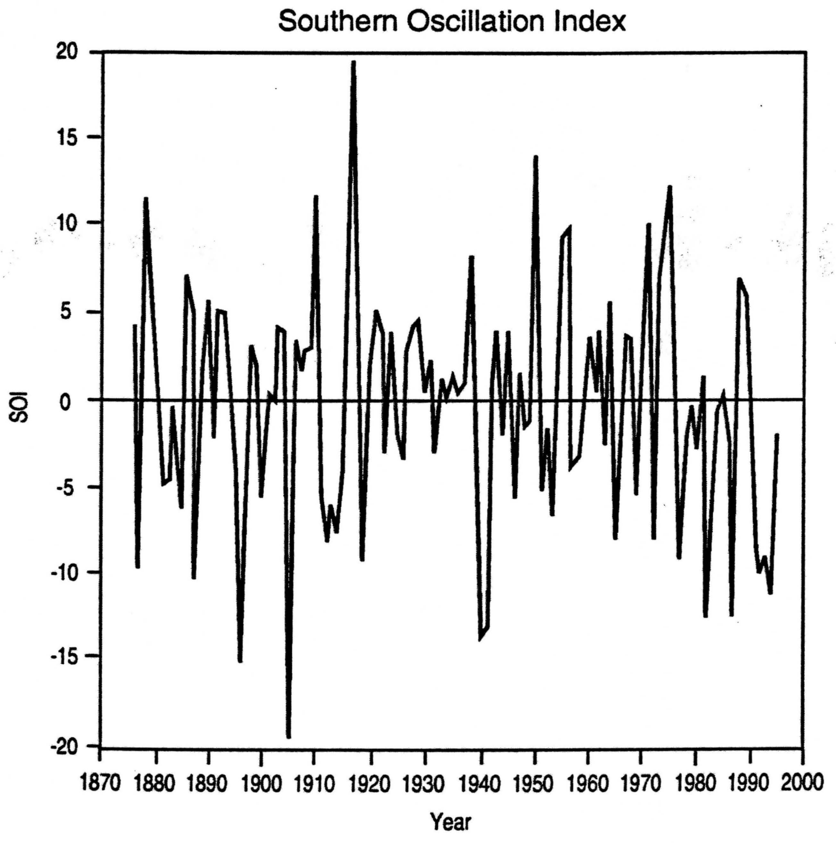
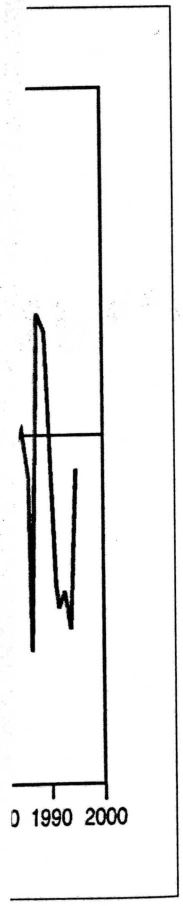


Figure 1. Annual mean Tahiti-Darwin Southern Oscillation Index, 1876 to 1995 (Allan, pers. comm.)

he last 5 000
een variable,
at periods of
7; Trenberth,
El Niño con-
Hoar, 1996).
; of its timing
ed ENSO sys-
ifestations in
ña conditions
and then by a
the Southern
Wright, 1989;
conditions in



m.)

1984-1985 were again not reflected in the Southern Oscillation Index, but a third El Niño occurred in 1986-1987 (Figure 1) (Trenberth, 1990; Kerr, 1992). After the La Niña event of 1988-1989 a further El Niño appears to have begun, but was aborted in 1990, only to develop a year later. It was linked to widespread drought conditions in southern Africa (Jury & Lutjeharms, 1993; Jury & Pathack, 1997). By the second half of 1992 this delayed El Niño had dissipated and most forecasts were for the development of cold conditions during the 1992-1993 season. In early 1993, however, a further El Niño regenerated and remained semi-persistent until early-1995.

An additional important change in the recent ENSO events is that their predictability appears to have decreased. The end of the 1991-1992 El Niño event was forecasted, but failed to occur, and the 1992-1993 warm event was not anticipated (Kerr, 1993). The 1992-1993 event is not even hindcasted successfully by most dynamical models of the coupled ocean-atmosphere system of the tropical Pacific Ocean such as the Cane-Zebiak model (Cane *et al.*, 1986). The forecast skill of the ocean-atmosphere system in the tropical Pacific during the 1990s has been poorer than during the 1970s and 1980s, and is matched by similar decreases in forecast skill for other atmospheric phenomena this decade such as North Atlantic tropical storms and Indian monsoon rains (Hastenrath, 1995). It is unclear whether the decrease in forecast skill is a reflection of model limitations or represents a decrease in predictability associated with a change in the climate system. Whatever the case, a deterioration in the operational forecast skill of ENSO events is of direct concern in the southern African region since ENSO-related indices are important inputs into operational and experimental seasonal forecast models (Jury *et al.*, 1994; Hastenrath *et al.*, 1995; Mason *et al.*, 1996) and are potentially important as direct input into agriculture- and industrial-related decision-making processes (Nicholls, 1988). Further, because ENSO events are generally associated with significant rainfall anomalies over most of southern Africa (Lindesay, 1988; Van Heerden *et al.*, 1988; Mason & Jury, 1997), long-term trends in their frequency and/or magnitude are of direct concern.

In this paper, evidence for long-term variability in the ENSO phenomenon is reviewed to provide a context for assessing the significance of its recent apparent changes in behaviour and predictability. The persistent warm event conditions during the 1990s are described and explained and compared to other prolonged events of the instrumental period. A review of simulated ENSO-like variability in a greenhouse-enhanced climate is included and implications for the southern African climate are assessed.

RECENT EL NIÑO EVENTS IN HISTORICAL AND PALAEOCLIMATIC CONTEXT

Although the ENSO phenomenon is intricately linked to the annual cycle (Barnett, 1991; Ropelewski *et al.*, 1992), it does display certain characteristics of a chaotic system (Chang *et al.*, 1994, 1995). Changes in the variability of the ocean-atmosphere system in the tropical Pacific are therefore an inherent part of its internal dynamics. Inter-decadal changes in the magnitude and frequency of ENSO events during the period of instrumental records have been detected (Reiter, 1978; Zhang & Casey, 1992; Gu & Philander, 1995) and probably have occurred over at least the last 5000 years (Enfield, 1992). As a result, persistent El Niño conditions are not unprecedented (Allan & D'Arrigo, 1996) and so are not necessarily an indication of long-term climatic change. Such changes in variability are evident not just from the observational data but also from modelling and theoretical studies.

Inter-Decadal Variability in the Frequency and Magnitude of El Niño - Southern Oscillation Events

Voluntary observing ship measurements of sea-surface temperatures are available from 1856 (Parker, 1987; Parker & Folland, 1988), but the quality of data before the late 1940s is questionable and observations are sparse over the Pacific Ocean even for recent years. The longest reliable instrumental records of ENSO variability are therefore obtainable from sea-level pressure data at Darwin and Tahiti (Troup, 1965; Wright, 1989). The difference between the standardised monthly sea-level pressure at Darwin and Tahiti is generally used as an index of the atmospheric counterpart of the oceanic El Niño signal. It is possible to reconstruct the Southern Oscillation Index using reliable instrumental records back to 1876 (Allan *et al.*, 1991; Young, 1993).

During the twentieth century, inter-decadal changes in the magnitude of the Southern Oscillation are evident (Figure 1). With the exception of the prolonged 1939-1942 El Niño the magnitude of ENSO events was relatively weak during the period 1920-1960, when the variability of atmospheric pressure at Darwin and of sea-surface temperatures in the equatorial Pacific Ocean decreased (Elliott & Angell, 1988). The frequency and intensity of ENSO episodes increased after the late 1960s, but the high intensity of events over the last approximately three decades is not exceptional: similar levels of sea-surface temperature variability and variability in the Southern Oscillation Index were evident before about 1920 (Trenberth & Shea, 1987; Gu & Philander, 1995).

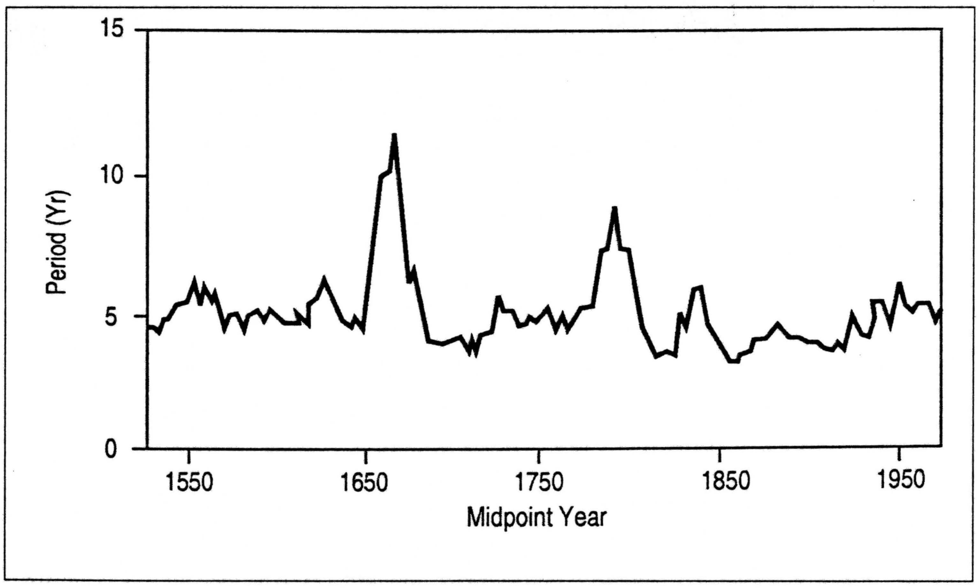


Figure 2. Mean recurrence interval of moderate or stronger El Niño events calculated for overlapping 19-year segments. Values have been smoothed with a 3-point binomial filter applied twice (after Diaz & Pulwarty, 1992).

Palaeoclimatic Variability in the Frequency and Magnitude of El Niño - Southern Oscillation Events

Proxy measurements of ENSO and its teleconnections have been reconstructed using data from sources such as tree rings, coral, marine sediments, fish catches, ice cores from high-altitude equatorial sites, streamflow data and anecdotal information on major floods or droughts (Diaz *et al.*, 1992). Indications are that significant changes in the frequency of ENSO events have occurred during at least the last approximately 500 years (Figure 2). These changes in frequency appear to have occurred independently of background changes in the mean climate state (Enfield & Cid, 1991; Diaz & Pulwarty, 1992; Enfield, 1992; Lough, 1992; Gu & Philander, 1995), such as are associated with the Little Ice Age for example (Quinn, 1992), thus supporting the contention that the non-stationarity is evidence of the chaotic nature of the coupled ocean-atmosphere system over the equatorial Pacific Ocean (Chang *et al.*, 1995). The Medieval Warm Period may provide an exception since there is some evidence to suggest that the frequency of ENSO events decreased during the period 1 000-1 400, when the background climatic state was warmer (Anderson, 1992). However, reconstruction of ENSO events from proxy data is difficult because of the need for high-resolution data (Allan & D'Arrigo, 1997) and so caution should be exercised in drawing conclusions about changes in ENSO variability before the period of instrumental records (Solow, 1995).

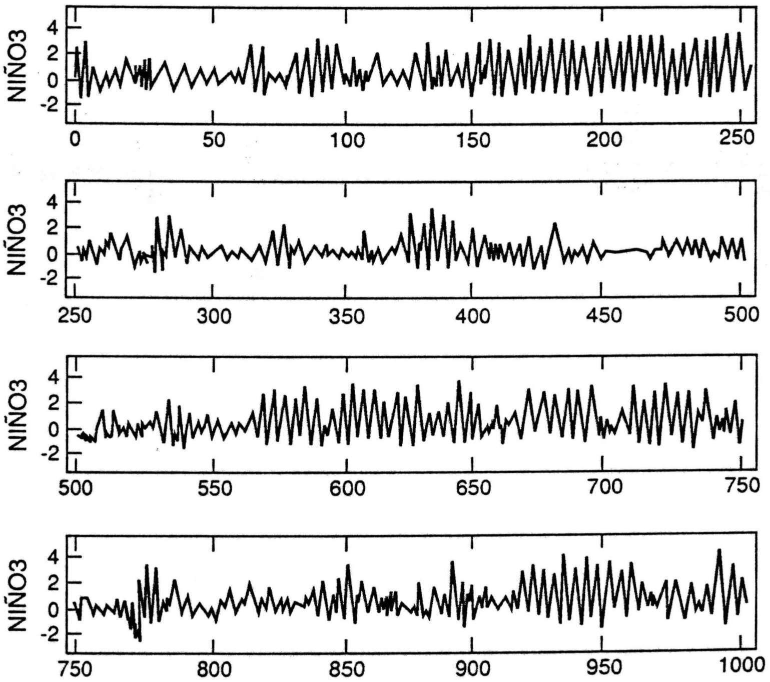


Figure 3. Simulated changes in sea-surface temperatures in the NIÑO3 region of the central Pacific (5°N to 5°S, 90°W to 150°W) obtained from a 1024-year integration of the Cane-Zebiak model (after Cane, 1992).

Modelling Evidence for the Non-Stationarity of El Niño Variability

Figure 3 presents simulated changes in sea-surface temperatures in the NIÑO3 region of the central Pacific (5°N to 5°S, 90°W to 150°W) obtained from a 1 024-year integration of the Cane-Zebiak model (Cane, 1992). Sea-surface temperatures in this area are often used as a measure of variability in the ENSO phenomenon as an alternative to the Southern Oscillation Index. The atmosphere is more sensitive to sea-surface temperature variability in the NIÑO3 region than other areas of the equatorial Pacific Ocean (Pan & Oort, 1983). Although the model variability tends to be more regular than observations, changes in variability are evident and result purely from the interaction between the atmosphere and the ocean in the absence of any external forcing or warming trend. For example, at about year 865-870 prolonged warm conditions combined with high-frequency variability are simulated and are followed in about year 880 by a stronger warm event without an intervening La Niña. In contrast, at about year 455 variability becomes minimal and near-average conditions persist for about a decade.

The Cane-Zebiak model involves a simplified atmospheric model and is constrained to the equatorial Pacific Ocean. Although the dynamics of ENSO variability are not modelled correctly by coupled ocean-atmosphere general circulation models (Chao & Philander, 1995), ENSO-like phenomena are reproduced. Inter-decadal, internal variability in these ENSO-like phenomena has been simulated by a number of coupled-ocean atmosphere general circulation models (e.g. Latif *et al.*, 1993; Knutson & Manabe, 1994).

Discussion

Inter-decadal changes in the variability of ENSO and ENSO-like events are evident from the instrumental data as well as from historical and palaeoclimatic observations and modelling and theoretical studies. Prolonged El Niño events of three to four years have been observed in the past and have been simulated by models of the equatorial Pacific Ocean. Coarser, but global, coupled ocean-atmosphere general circulation models additionally provide evidence of inter-decadal variability in the frequency and magnitude of ENSO-like events. The persistence and high-frequency of El Niño events relative to La Niña over the last 20 years is, therefore, perfectly possible in a stationary climate and so should not automatically be considered as evidence of a tropical climate response to global warming. It is important to consider the causes of the recent persistence of warm conditions and to compare the last 20 years with earlier persistent episodes in the period of instrumental records.

EXAMPLES OF EARLIER PROLONGED EL NIÑO SEQUENCES

Apart from the early 1990s, other prolonged El Niño sequences have been observed during the twentieth century in 1911-1915 and in the early 1940s (Figure 1). An additional prolonged event before 1900 is also detectable from the instrumental records in 1894-1897 (Allan & D'Arrigo, 1997). In general, however, the magnitude of ENSO events during most of the second half of the nineteenth century was relatively low (Lough, 1992). Prolonged La Niña sequences have occurred also and are evident in instrumental data for the periods 1878-1880, 1908-1911, 1916-1918, 1920-1923, 1954-1957 and 1973-1976 (Allan & D'Arrigo, 1997). Proxy records suggest that other prolonged warm event sequences have occurred over the past 500 years, including two 5-year periods (1782-1786 and 1835-1839) and an 8-year period (1790-1797) (Allan & D'Arrigo, 1997). The prolonged twentieth century events are considered in more detail below.

The 1911-1915 Episode

Given the poor data availability over the equatorial Pacific Ocean before the 1970s (Cane, 1991; cf. Posmentier *et al.*, 1989; Wu, 1995) it is not possible to reconstruct the evolution of events during these earlier persistent episodes in detail. Nevertheless, the general pattern of the evolution of events is inferable from changes in the Southern Oscillation Index and available sea-surface temperature data. The initial El Niño was preceded by prolonged cold conditions since 1908 (Allan & D'Arrigo, 1997) (marked A on Figure 4) that would have deepened the thermocline in the western equatorial Pacific Ocean. The evolution of the 1911-1912 El Niño seems to have been fairly typical, being initiated in the boreal spring of 1911 (B), reaching maturity early the following year (C) and decaying rapidly soon after (D). The Southern Oscillation Index remained almost consistently below average for the remainder of 1912 and into 1913 when an El Niño may have been aborted in the second half of the year (E). A second El Niño did occur in 1914 (F), decayed rapidly in early 1915 (G) and was followed by the strongest La Niña in the period of instrumental records in 1917 (H; cf. Figure 1).

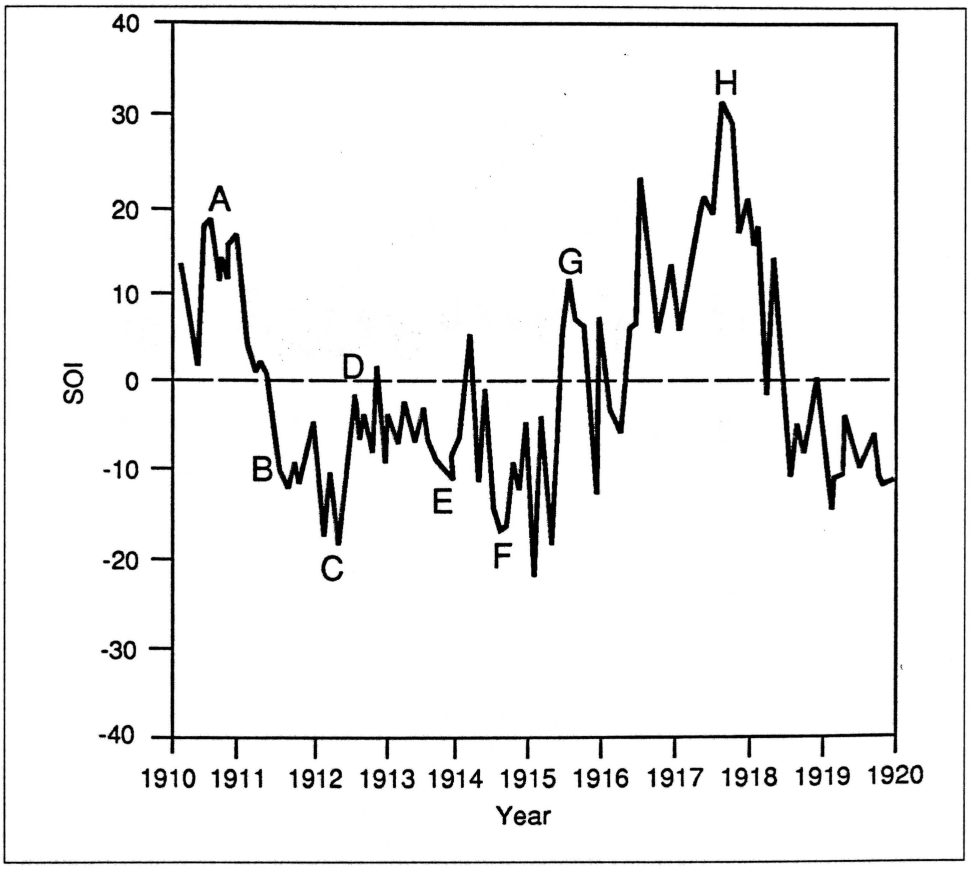


Figure 4. Monthly Tahiti-Darwin Southern Oscillation Index, January 1910 to December 1920, illustrating the prolonged 1911-1915 low-phase conditions.

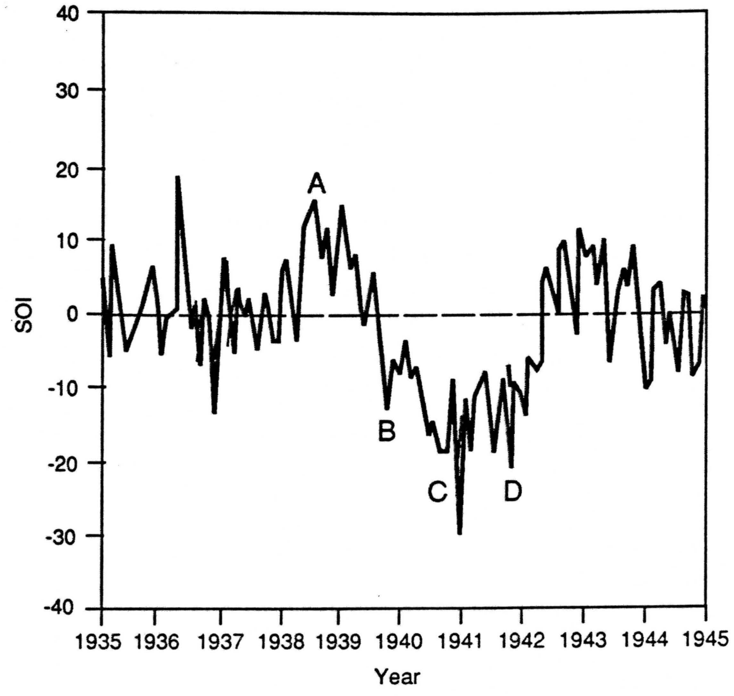


Figure 5. Monthly Tahiti-Darwin Southern Oscillation Index, January 1935 to December 1945, illustrating the prolonged 1939-1942 low-phase conditions.

The 1939-1942 Episode

The persistent El Niño conditions of 1939-1942 (Figure 5) occurred during a period of significant climatic anomalies in the equatorial Pacific, including large persistent zonal wind anomalies (Whysall *et al.*, 1987). A 7-year quiescent period after the previous warm event in 1932 (that occurred in the absence of any pronounced signal in the Darwin sea-level pressure and so is not readily detectable in the Southern Oscillation Index (Deser & Wallace, 1987)) preceded the event. The long period since the 1932 El Niño allowed time for a large reservoir of warm water above about 28°C to accumulate in the western equatorial Pacific (Bigg & Inoue, 1992). The build up of warm water was facilitated by a weak La Niña event during 1938-1939 (marked A on Figure 5). As a result, the thermocline in the western Pacific was exceptionally deep by the time of the initiation of the 1939-1942 El Niño (B). Modelling results suggest that differences in the morphology of the North and South Pacific Oceans resulted in the generation of two separate Kelvin waves responsible for the prolonged El Niño event. The weak preceding La Niña (A) generated an initial Kelvin wave in the eastern Pacific in early 1937. This was reflected at the eastern boundary forming oceanic Rossby waves that returned westward across the Pacific at about 10°-15° N and S. The Rossby wave in the southern hemisphere was reflected against Australia earlier than in the northern hemisphere where the western continental boundary is further to the west. Two separate equatorial Kelvin waves were accordingly generated. The first occurred in mid-1939 which initiated the first El Niño event (B), while the second, in early-1940, allowed for the prolongation of the 1939-40 event into 1941 (C) (Bigg & Inoue, 1992). Despite the prolonged El Niño conditions of 1939-1941, the warm pool in the western Pacific was not completely dissipated, thus leaving sufficient heat in the western Pacific for a successful regeneration of warm conditions later in 1941 (D) and an additional event that occurred in 1942, but which is not reflected by the Southern Oscillation Index (Deser & Wallace, 1987).

THE PROLONGED EL NIÑO CONDITIONS OF THE 1990s

During the 1990s prolonged warm event conditions have been experienced. However, the oceanographic processes involved during this decade have differed, at least from the 1939-1942 event. The evolution of the 1991-1995 episode is outlined below.

The 1991-1992 El Niño

After the La Niña event of 1988-1989 (marked A on Figure 6) westerly wind anomalies in late 1990 initiated an El Niño (Mo, 1993; Ropelewski *et al.*, 1993) that was soon aborted (B) (Chelliah, 1993; Wang, 1995a; Boulanger & Menkes, 1996). The aborted El Niño was responsible, however, for a reduced build up of warm water in the western Pacific and a shoaling of the thermocline before the 1991-1992 event (Bigg, 1995; Kessler & McPhaden, 1995), which may have been weakened slightly as a result, since perturbations in the thermocline depth are crucial in determining the evolution of ENSO events (Kleeman, 1993). Although the

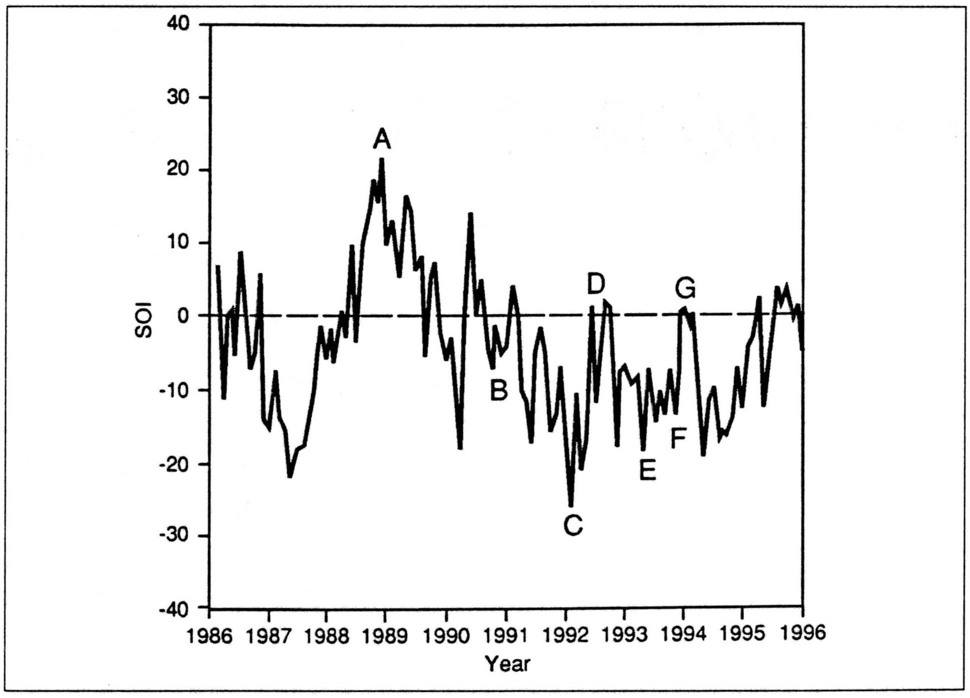


Figure 6. Monthly Tahiti-Darwin Southern Oscillation Index, January 1986 to December 1995, illustrating the prolonged 1991-1995 low-phase conditions.

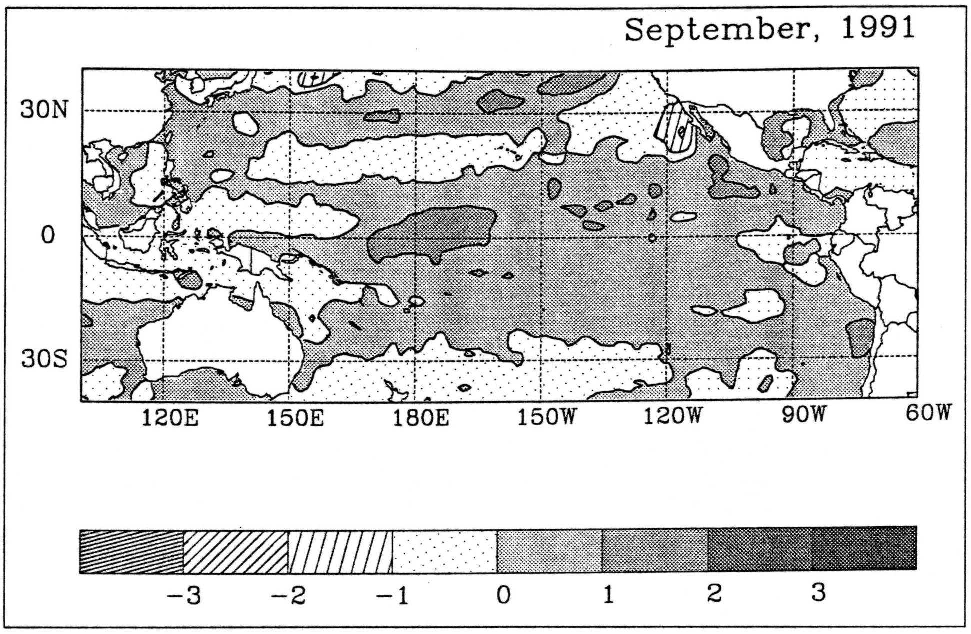


Figure 7. Sea-surface temperature anomalies in the Pacific Ocean during the onset of the 1991-1992 El Niño event. Anomalies are for September 1991 and are with reference to the 1951-1980 mean.

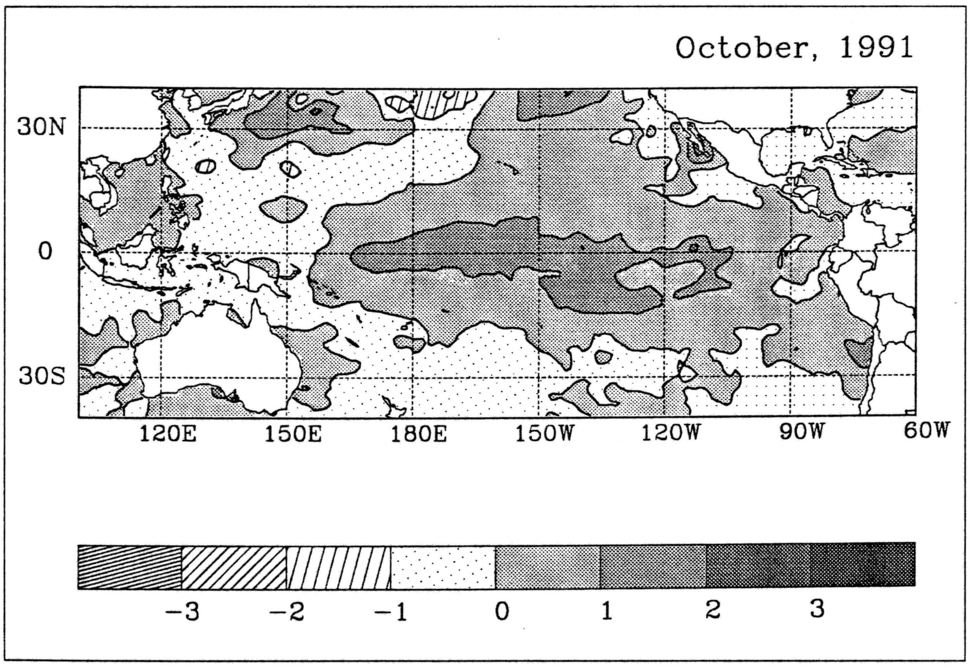
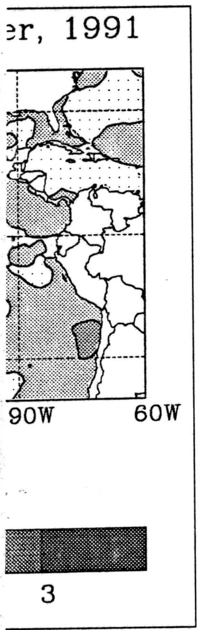
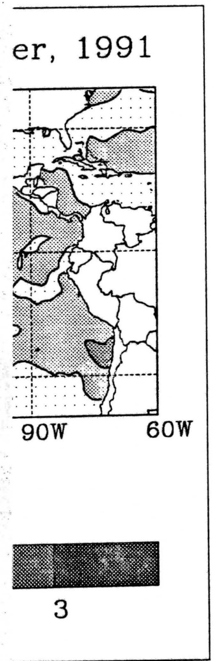


Figure 8. Sea-surface temperature anomalies in the Pacific Ocean during the onset phase of the 1991-1992 El Niño event. Anomalies are for October 1991 and are with reference to the 1951-1980 mean.



)1-1992 El Niño event.



the 1991-1992 El Niño

Cane-Zebiak model was successful in forecasting the delayed onset, it is not clear why, but one effect of the shoaling may have been to allow for a rapid onset in 1991. Warm event conditions began to redevelop (Bell & Halpert, 1993; Delcroix *et al.*, 1993; Halpert & Bell, 1993; Boulanger & Menkes, 1996) and positive sea-surface temperature anomalies appeared across the equatorial Pacific Ocean between September and October 1991 faster than an oceanic Kelvin wave could propagate (Kessler & McPhaden, 1995) (compare Figures 7 and 8). Weakened easterlies in the central Pacific in October-November of 1991 intensified the event (Janowiak, 1993) so that by January 1992 sea-surface temperature anomalies had reached a maximum (Figure 9, C on Figure 6) (Kousky, 1993). Mature conditions persisted into May (Wang, 1993), but by July the event had almost died out (Figure 10, D on Figure 6) (Mo & Wang, 1994). With the appearance of negative temperature anomalies in the eastern equatorial Pacific there were signs of the development of a La Niña event by September (Figure 11) (Kerr, 1993), although weak warm conditions were persistent in the central and eastern Pacific (Bell & Basist, 1994; Chelliah, 1994).

The 1993 El Niño

The boreal spring El Niño event in 1993 occurred after an apparent return to cool conditions in the second half of 1992 that were the result of a strengthening of the South Equatorial Current, producing equatorial upwelling through Ekman divergence (Lukas *et al.*, 1995). Warm events are often preceded by at least a year of stronger than average trade winds allowing a build up of a deep layer of warm water in the western Pacific (Ho *et al.*, 1995). With the initiation of an El Niño, this warm water is drained eastward by an equatorially-trapped Kelvin wave and is largely responsible for the typically positive sea-surface temperature anomalies observable in the central and eastern Pacific during El Niño events. The Kelvin wave is initiated by westerly wind anomalies in the western and central Pacific, which, at the same time, generate westward propagating, upwelling, off-equatorial Rossby waves (Schopf & Suarez, 1988; Suarez & Schopf, 1988). These Rossby waves are thought to be reflected at the western boundary in the form of an upwelling Kelvin wave that becomes responsible for the decay of the warm conditions (Graham & White, 1988).

Although the failure of the upwelling Rossby waves to reverse the sign of an El Niño have already been observed in the case studies of the earlier twentieth century prolonged warm episodes, the 1993 event was unusual in that the western Pacific thermocline was about 30 m shallower than average in late 1992 and early 1993. The anomalously warm pool remaining at the date-line through 1992 was therefore of crucial importance, drawing attention away from the western Pacific by causing a shift of convection and westerly wind stress into the central part of the Ocean (Bell & Basist, 1994; Kessler & McPhaden, 1995). By December 1992, therefore, the negative surface temperature anomalies in the eastern Pacific had effectively disappeared (Figure 12). With the eastward shift of the western Pacific convective centre, westerly wind bursts associated with Madden-Julian wave activity could penetrate further into the Pacific Ocean during December 1992 and January 1993 (Bell & Basist, 1994; Gutzler *et al.*, 1994). This high amplitude phase of the Madden-Julian wave thus spawned another train of downwelling Kelvin waves (Busalacchi *et al.*, 1994) and was responsible for a deepening of the thermocline in the eastern Pacific and further shoaling in the west in early 1993 (Boulanger & Menkes, 1996). The timing of the this highly active phase of the Madden-Julian oscillation

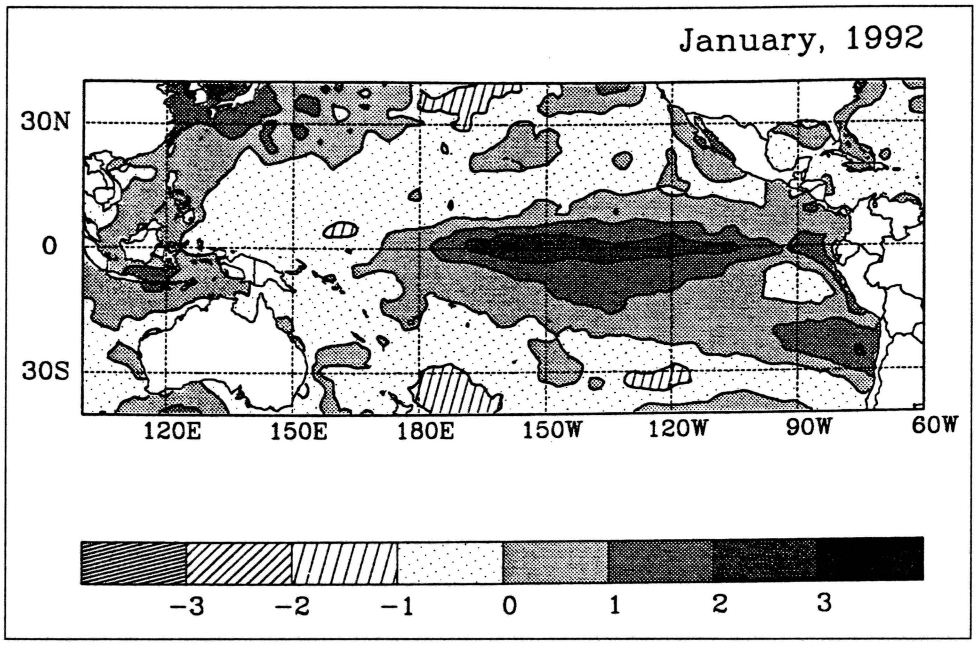


Figure 9. Sea-surface temperature anomalies in the Pacific Ocean during the mature phase of the 1991-1992 El Niño event. Anomalies are for January 1992 and are with reference to the 1951-1980 mean.

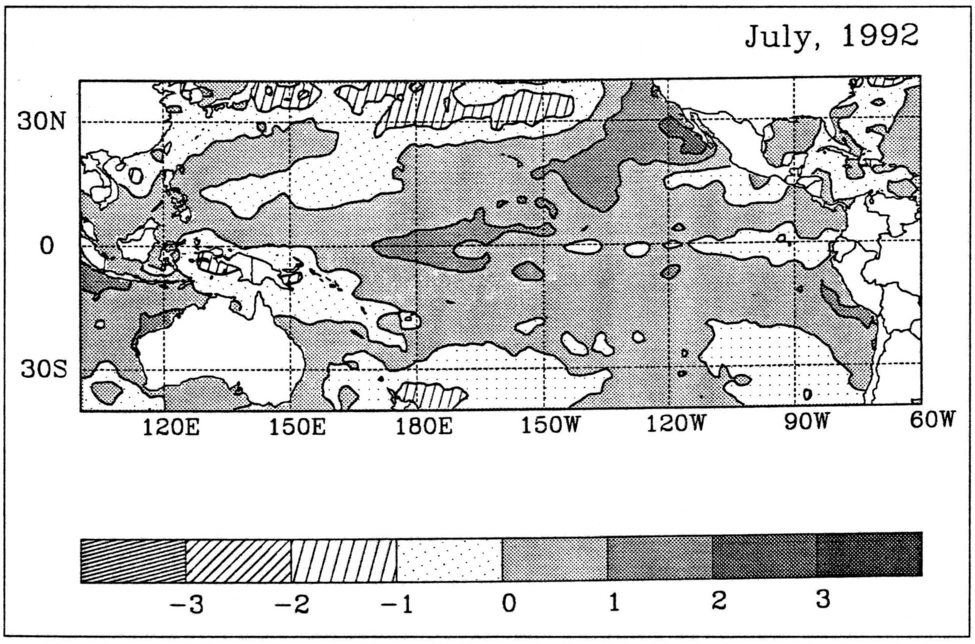
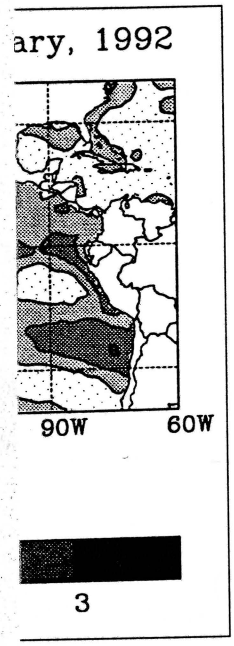
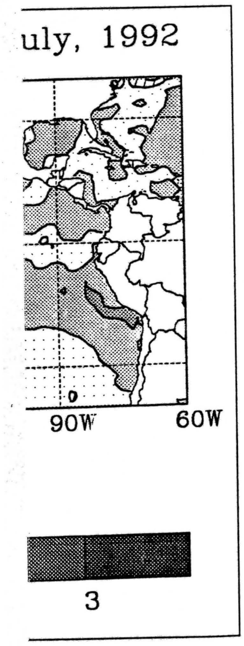


Figure 10. Sea-surface temperature anomalies in the Pacific Ocean at the end of the 1991-1992 El Niño event. Anomalies are for July 1992 and are with reference to the 1951-1980 mean.



f the 1991-1992 El Niño



991-1992 El Niño event.

may have been crucial, since its effect was to amplify the annual cycle; the amplification being expressed as an El Niño event (Boulanger & Menkes, 1996). This second, but weaker, El Niño reached maturity by May (Figure 13, E on Figure 6) (Bigg, 1995).

The 1993 El Niño decayed fairly rapidly after May, but again a warm pool near the date line remained (Kerr, 1993) and the far western Pacific remained slightly cooler than normal (Figure 14) so that enhanced convection continued to occur in the central Pacific. The Southern Oscillation Index accordingly remained negative into late 1993 (F on Figure 6). However, Madden-Julian wave activity was weak in September – October 1993 so that in the absence of any strong wind-stress anomalies, oceanographic conditions across the equatorial Pacific tended back toward average (G on Figure 6). Cool conditions began to develop again in the eastern Pacific during early 1994 as a result of cold upwelling (Figure 15), but because of persistent warm conditions over the previous two years, the thermocline in the western Pacific was shallower than average. With pronounced Madden-Julian wave activity in the western Pacific during May - August 1994, atmospheric conditions were unfavourable for the continued development of a La Niña and so the eastern equatorial Pacific cooling trend reversed.

The 1994-1995 El Niño

The central Pacific warm pool redeveloped in mid-1994 and the development of a further El Niño was clearly evident by about August. Although sea-surface temperatures in the western Pacific had returned to normal by about April 1994 (Figure 15), temperatures below the surface were still colder than average. With only a small shoaling of the thermocline, surface temperatures in the west could cool rapidly. Convective activity was able to penetrate as far as the date line. The thermocline in the eastern Pacific deepened rapidly and El Niño conditions returned late in 1994, persisting into early 1995, but decaying rapidly. The thermocline shoaled across the Pacific during the first few months of 1995, except at the central Pacific warm pool which did not cool until the second quarter of the year.

Conditions during 1995-1996

The 1994-1995 El Niño dissipated in the early part of 1995 and slightly lower than average sea-surface temperatures returned to most of the eastern and central equatorial Pacific Ocean. Of critical importance was the disappearance of the central Pacific warm pool during the middle of 1995 and the warming of the western Pacific (Figure 17). By about June or July 1995, with cold sub-surface waters across the central and eastern Pacific, prospects for the development of a modest cold event were becoming promising. In August the outgoing longwave radiation (OLR) in the central Pacific was the highest it had been for four years, indicating the westward shift of convection back toward Indonesia. A weak cold event reached maturity by November 1995, but decayed slowly thus persisting well into 1996.

Discussion

Given the different timing of events between the prolonged El Niño sequences of the twentieth century, it seems likely that they can be caused in different ways, but some general hypotheses can be suggested based on the instrumental data for the 1911-1915, 1939-1942 and 1991-1995 sequences. During a prolonged sequence the initial El Niño apparently evolves fairly typically. Upwelling Rossby waves, generated by the westerly wind anomalies associated

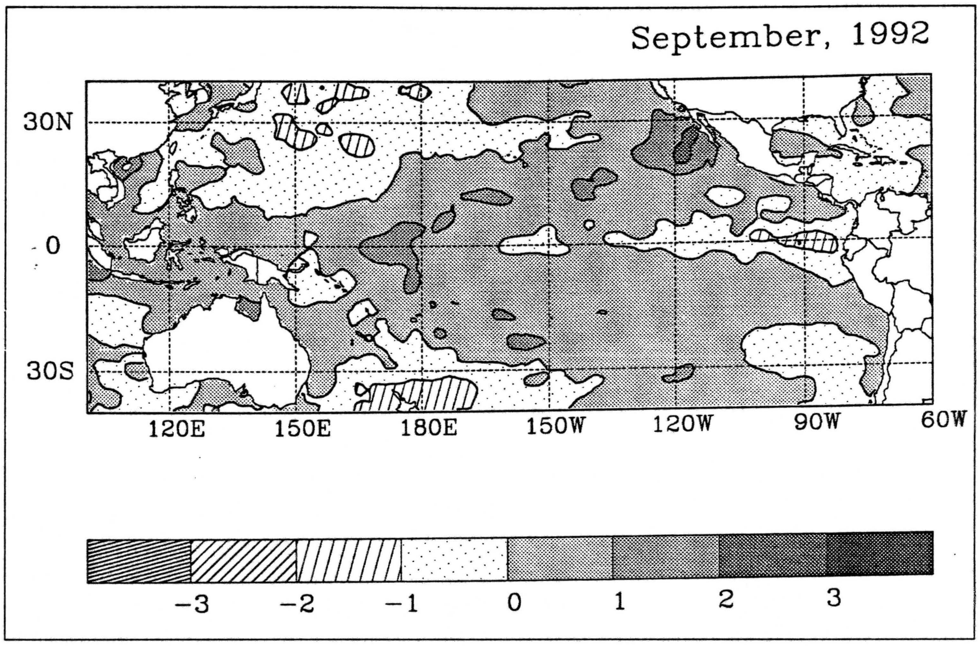


Figure 11. Sea-surface temperature anomalies in the Pacific Ocean during September 1992 indicating signs of the initiation of a La Niña event. Anomalies are with reference to the 1951-1980 mean.

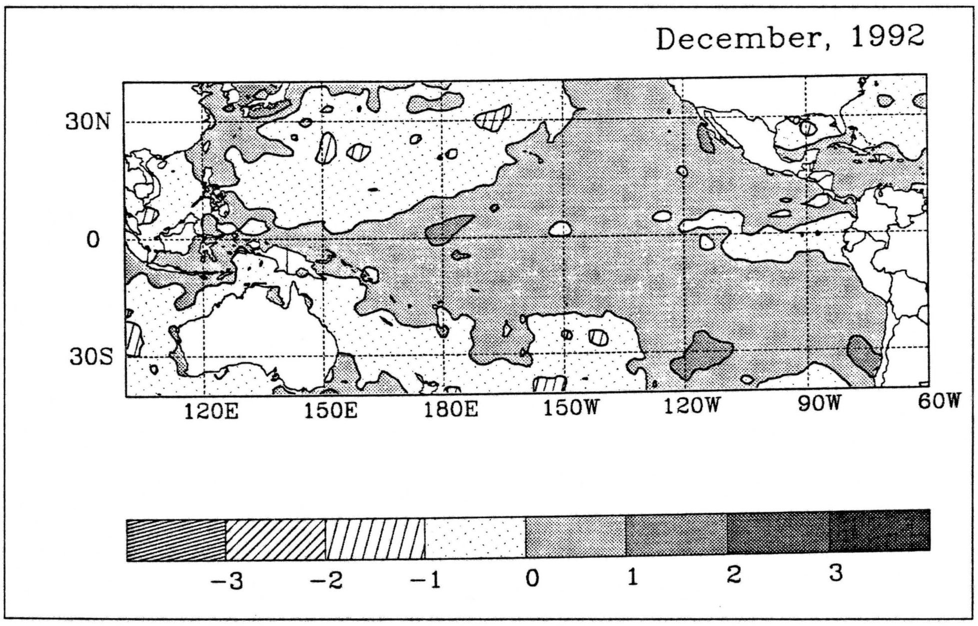
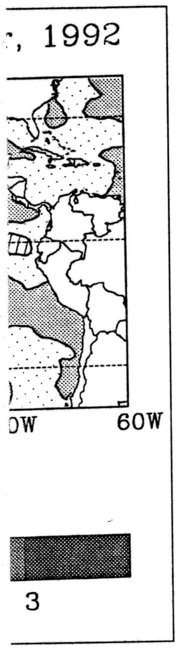
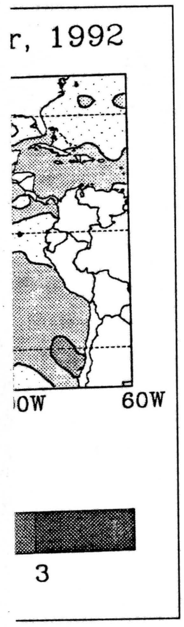


Figure 12. Sea-surface temperature anomalies in the Pacific Ocean during December 1992 indicating the warm pool near the date line and the disappearance of negative anomalies in the east. Anomalies are with reference to the 1951-1980 mean.



ng signs of the initi-



ating the warm pool
ference to the 1951-

with this first El Niño, for some reason fail to reflect at the western boundary in the form of upwelling Kelvin waves, which are an essential component of the delayed oscillator mechanism of ENSO variability (Graham & White, 1988; Allan *et al.*, 1996). Instead, if pronounced Madden-Julian wave activity penetrates into the central Pacific Ocean, further downwelling Kelvin waves can be initiated that maintain or redevelop warm conditions in the eastern equatorial Pacific.

In the abortion of the 1993-1994 La Niña and redevelopment of the 1994-1995 El Niños, the persistence of anomalously warm conditions near the date line and cool conditions in the western Pacific appear to have been fairly crucial. Both sea-surface temperature anomalies displaced the Indonesian low toward the central Pacific and thus allowed the intrusion of westerly wind anomalies associated with Madden-Julian wave activity into the western Pacific. The Madden-Julian wave activity was notably stronger than average during late boreal summer in both 1992 and 1994. The resultant westerly wind anomalies generated further downwelling Kelvin waves that were responsible for warming in the eastern Pacific Ocean.

The 1993 El Niño was not anticipated by either the Cane-Zebiak model or statistical forecasting models. The statistical models probably failed partly because of the uniqueness of the event, but the failure of the dynamical predictions is of greater concern. Because of the weak ocean-atmosphere coupling of the ENSO system in the boreal spring (thus allowing for a rapid decay of ENSO events after achieving maturity in boreal winter), there is generally a poor forecastability at this time of year, referred to as the "springtime barrier" (Webster, 1995; Moore & Kleeman, 1996). The failure of the Cane-Zebiak model predictions is therefore all the more surprising since the unexpected evolution of events occurred in the late part of the calendar year and in the boreal winter. The problem is possibly the result of systematic failures in the model which is unable to simulate adequately the observed variability in the Pacific Ocean west of about 160°W (Cane, 1991, 1992). With an eastward shift of the Australian-Indonesian quasi-permanent low pressure centre, systematic errors in the model western Pacific would become of greater significance because of a failure to simulate accurately the important westerly wind bursts to the west of the convective centre when located near the date line (Gutzler *et al.*, 1994). Early estimates of the forecast skill of the Cane-Zebiak (Cane, 1991, 1992) and other dynamical models (e.g. Barnett *et al.*, 1993) illustrating forecastability up to 18 months are therefore probably overly optimistic (Webster, 1995).

It is certain that the dynamics of prolonged El Niño (and La Niña) sequences are poorly understood and require further investigation. Improvements in the forecast model performance during such sequences should then be attainable, although if the timing and intensity of Madden-Julian wave activity is crucial, as suggested in this paper, significant improvements in lead-times may not be easily attainable.

RECENT CHANGES IN THE ENSO PHENOMENON

Changes in the Background Mean State

Since the late 1970s, the ENSO system has moved into a period of predominantly warm event (El Niño) conditions, whilst maintaining a high level of inter-annual variability (Kerr, 1992). Only one strong La Niña event occurred in the 19-year period 1977-1995, whereas El Niños have occurred in 1982-1983, 1986-1987 and for most of 1991-1995. In comparison, strong La Niñas equalled the number of El Niños during the period 1876-1976. The recent shift

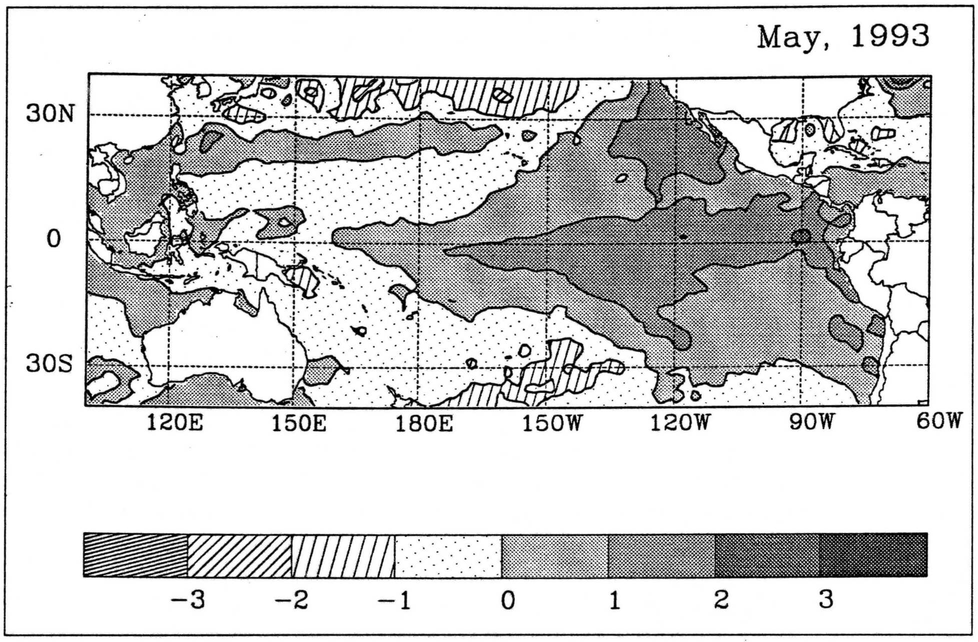


Figure 13. Sea-surface temperature anomalies in the Pacific Ocean during May 1993 indicating the return to weak El Niño conditions during the boreal spring. Anomalies are with reference to the 1951-1980 mean.

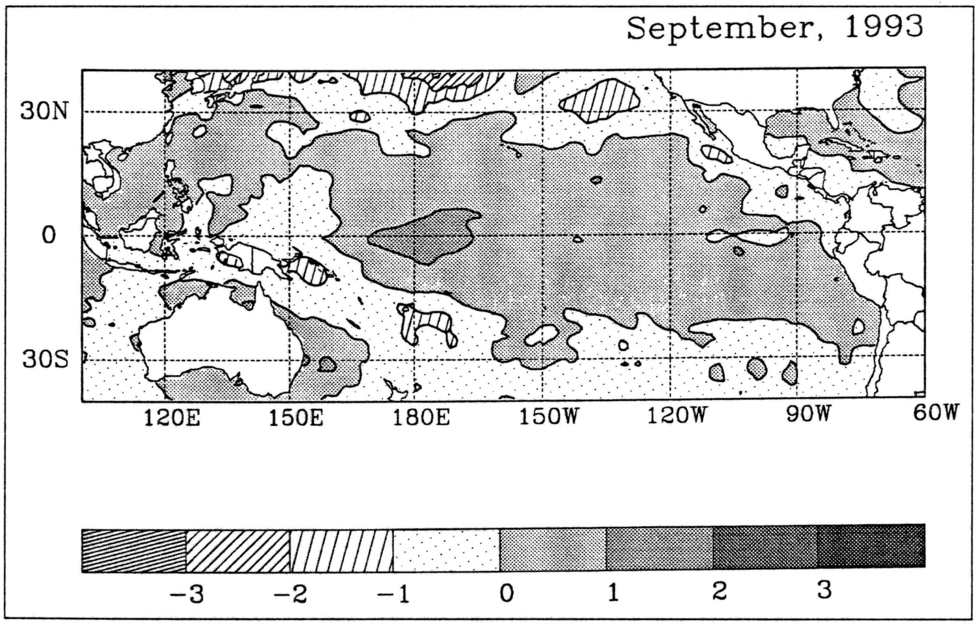
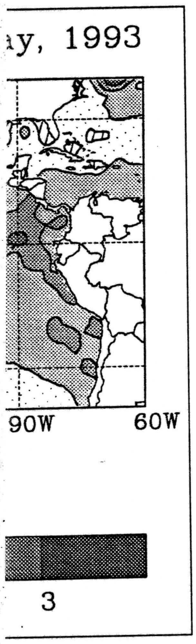
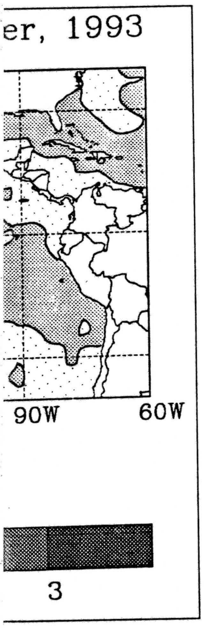


Figure 14. Sea-surface temperature anomalies in the Pacific Ocean during September 1993 indicating the persistence of the central Pacific warm pool. Anomalies are with reference to the 1951-1980 mean.



the return to weak El



cating the persistence of

toward the predominance of El Niño-type conditions is reflected in a significant decrease in the mean value of the Southern Oscillation Index (Trenberth & Hoar, 1996; cf. Solow, 1995), as illustrated in Figure 18. The downward shift in the mean may not simply be a reflection of an increase in the frequency and/or magnitude of low-phase (El Niño) events, but may reflect a change in the background climate state (Graham, 1994). The change is associated with a fairly abrupt increase in sea-surface temperatures in the Indian and Pacific Oceans that occurred in the late 1970s (Figure 19) (Trenberth, 1990; Kerr, 1992; Allan *et al.*, 1995; Graham, 1995; Wang, 1995b), resulting in mean sea-surface temperatures that are more reminiscent of an El Niño. The warming has been attributed to the enhanced greenhouse effect (Kerr, 1993), although the possibility of inter-decadal variability cannot be ruled out (Miller *et al.*, 1994; Trenberth & Hurrell, 1994; Allan *et al.*, 1995; Reason *et al.*, 1996a,b). This shift toward predominantly warm conditions is consistent with an observed decrease in the sea-level difference between the east and west equatorial Pacific Ocean (Posmentier *et al.*, 1989). Although the onset and evolution of ENSO events is highly sensitive to small changes in the mean annual cycle, there is no particular reason to expect that the higher sea-surface temperatures will result in a continuation in the recent imbalance in the frequencies of El Niños and La Niñas.

Recent Changes in the Onset of El Niños

As a result of the post-1977 changes in the background mean state, consequent changes in the onset of El Niño events have been detected (Wang, 1995b). Prior to the abrupt increase in sea-surface temperatures in 1977, east coast warming, in response to weakened south-east trade winds, occurred about three months before warming in the central Pacific. Since the change in the mean state, the central Pacific warming has been occurring first, implying that anomalous westerly winds in the western Pacific may be more important. Changes in oceanic waves will also have occurred, influencing the timing of events (Kleeman, 1993; Wang & Weisberg, 1994; Nagai *et al.*, 1995). The differences in the onset may have important implications for forecasting skill, although it would be incorrect to assert that the change is responsible for the recent decrease in forecastability: the 1982-1983 El Niño, for example, is successfully hindcasted using data for early 1981, and the delayed onset of the 1991-1992 event was similarly forecasted successfully.

EL NIÑOS IN A GREENHOUSE-ENHANCED CLIMATE

Since the late-1980s the coupling of oceanic and atmospheric general circulation models has enabled sensitivity studies relating to the ocean-atmosphere system as a whole, rather than to the atmosphere in isolation, often linked to passive climatological or other prescribed ocean characteristics. Largely because of the generally coarse resolution of coupled models, there are a number of systematic errors that result in poorer performances than some of the high-resolution oceanic models (Meehl, 1995). One important restriction is that the control ENSO-like variability in coupled models is typically about a half of the observed variability, although the simulated frequencies of events are generally more realistic (Meehl, 1991, 1993, 1995; Schneider & Kinter, 1994; Nagai *et al.*, 1995; Tett, 1995). The underestimation of the ENSO-like variability in the coupled models appears to be a result of the coarse model resolution (Schneider & Kinter, 1994), which results in an excessive damping of Kelvin waves (Tett, 1995), although the atmospheric response to tropical sea-surface temperature anomalies in

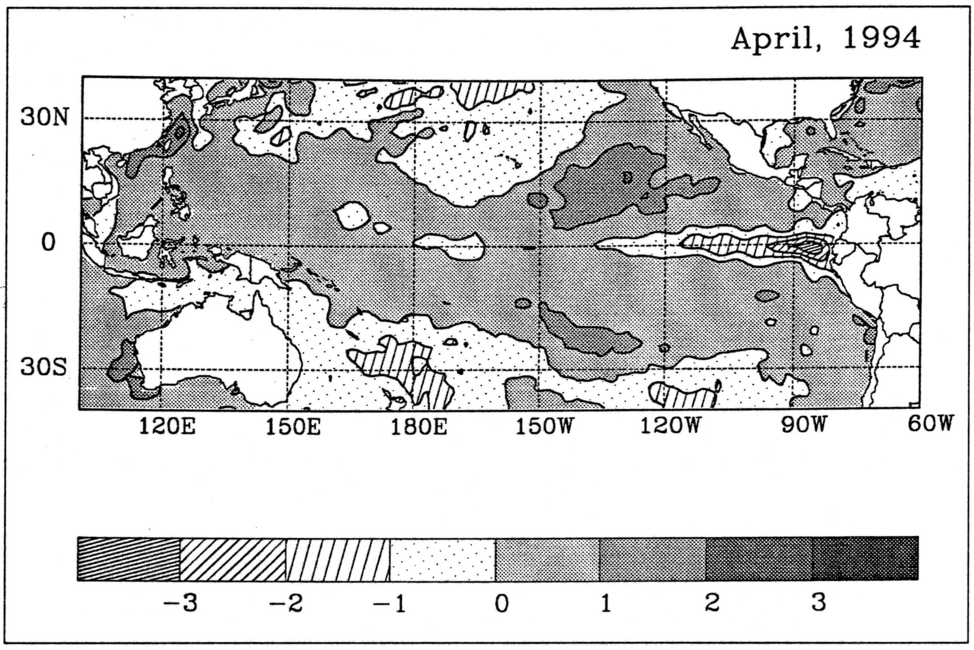


Figure 15. Sea-surface temperature anomalies in the Pacific Ocean during April 1994 indicating the initiation of weak La Niña conditions. Anomalies are with reference to the 1951-1980 mean.

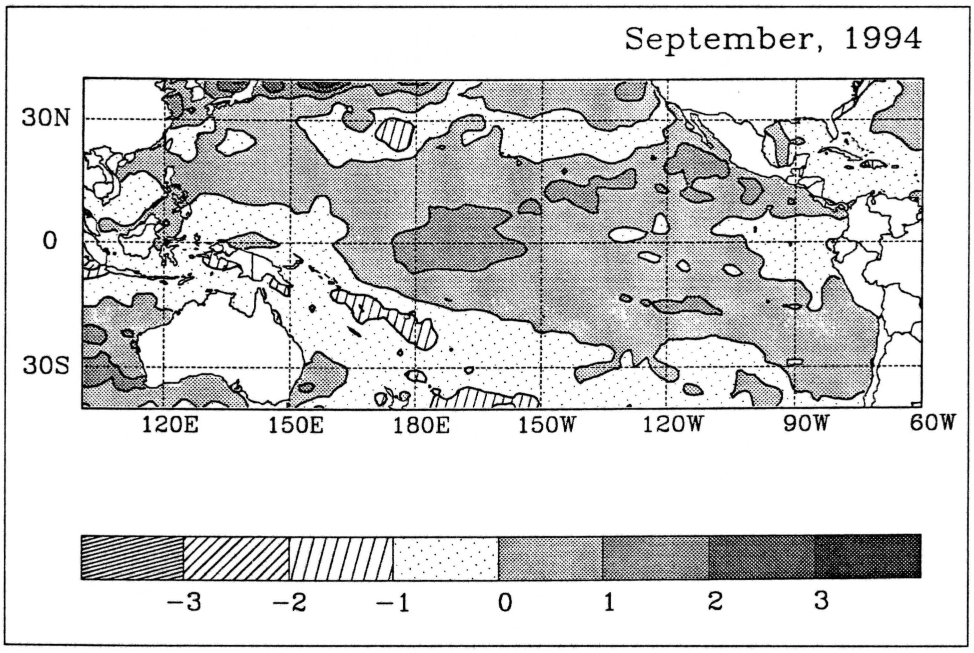
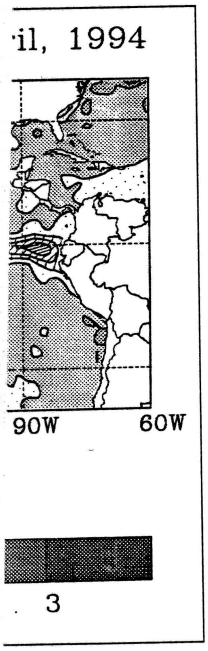
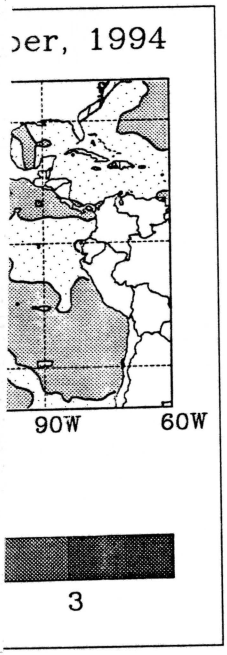


Figure 16. Sea-surface temperature anomalies in the Pacific Ocean during September 1994 indicating the persistence of the central Pacific warm pool. Anomalies are with reference to the 1951-1980 mean.



ng the initiation of weak



ndicating the persistence of

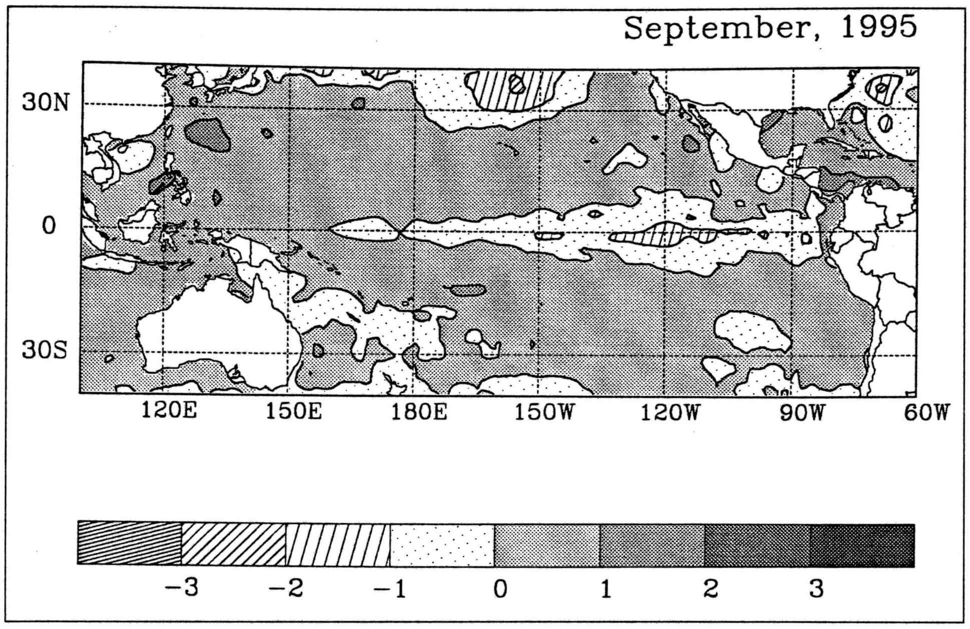


Figure 17. Sea-surface temperature anomalies in the Pacific Ocean during September 1995 indicating the disappearance of the central Pacific warm pool and the heating of the western Pacific. Anomalies are with reference to the 1951-1980 mean.

general circulation models is known to be too weak anyway (Latif *et al.*, 1994; Smith, 1995). A further complication is that the systematic errors are regime specific; that is the model errors vary under differing sea-surface temperature fields (Mo & Wang, 1995). As a result the interpretation of the model output cannot be adjusted simply by correcting for the time-averaged systematic error. Sensitivity studies of changes in ENSO and ENSO-related variability therefore have to be approached with caution.

There are some indications that ENSO variability has been greater during periods when the climatic sea-surface temperatures have been higher than average (Wang & Ropelewski, 1995), although the relationship is certainly not a simple linear one (Allan *et al.*, 1996). In a doubled-CO_2 climate mean sea-surface temperatures are expected to be higher than at present and yet there is no simulated increase in ENSO variability by general circulation models (Knutson & Manabe, 1994, 1995; Tett, 1995). The lack of any significant change in variability is attributed to an increase in atmospheric static stability, a decrease in the time-mean zonal sea-surface temperature gradient across the equatorial Pacific (because of a larger warming in the east) and to enhanced evaporative damping of sea-surface temperature anomalies as a result of the tropical evaporation constraint (Hoffert *et al.*, 1983; Hartmann & Michelson, 1993). Even without an increase in variability, however, atmospheric anomalies in the tropics are expected to strengthen in response to ENSO events in a greenhouse-enhanced climate because of the warmer background climatic state. In the mid-latitudes, significant changes in extra-tropical teleconnections may occur, with possible changes in the sign of correlations between the atmosphere in the southern hemisphere and the Southern Oscillation (Meehl & Branstator, 1992; Meehl *et al.*, 1993). Given the inability of the coupled models to reproduce

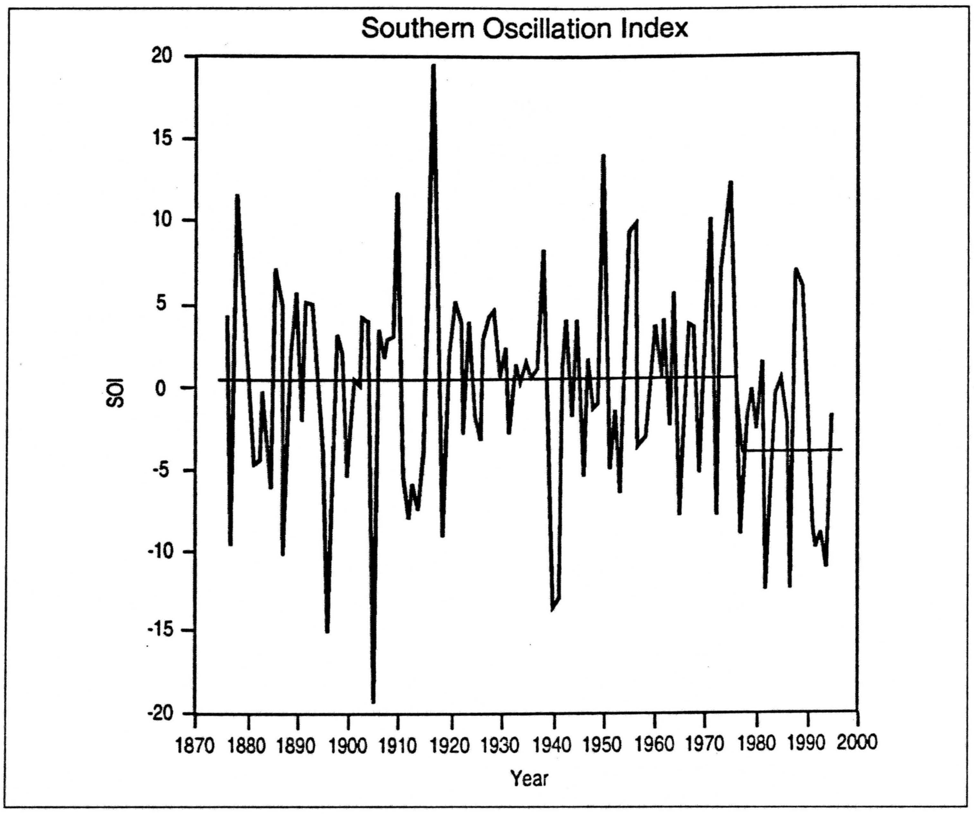
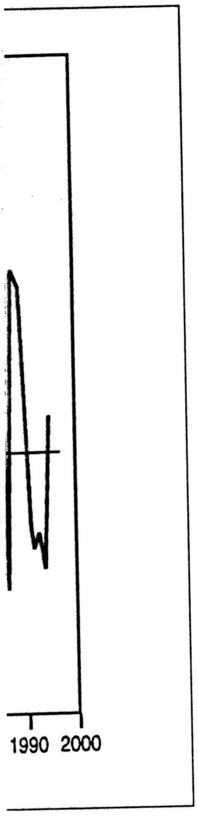


Figure 18. Annual mean Tahiti-Darwin Southern Oscillation Index, January 1876 to December 1995. The pre- and post-1977 long-term mean is superimposed.

adequately the dynamics of the ENSO phenomenon, scenarios for changes in ENSO variability in a greenhouse-enhanced climate should be approached with caution.

IMPLICATIONS FOR SOUTHERN AFRICA

The El Niño-Southern Oscillation phenomenon is one of the major influences on interannual rainfall variability over southern Africa (Lindesay *et al.*, 1986; Lindesay, 1988; Van Heerden *et al.*, 1988; Lindesay & Vogel, 1990; Matarira, 1990; Jury *et al.*, 1994; Moron *et al.*, 1995; Shinoda & Kawamura, 1996; Mason & Jury, 1997). Usually, although not always (Mason & Mimmack, 1992; Mason & Lindesay, 1993), La Niña and El Niño events are associated with the occurrence of wet and dry years, respectively. The abrupt warming in 1977 in the tropical Indian and Pacific oceans may be partly responsible for the generally dry conditions that have been experienced over the country for much of the last 20 years. Although there is no evidence for a decrease in annual rainfall over most of South Africa, the changes in the tropical climate system of the Pacific Ocean are synchronous with a changepoint in the annual rainfall over the Lowveld (Mason, 1996). The correlation between the Southern Oscillation Index, however, is weaker in the north-eastern part of the country than for areas further west



995. The pre- and post-

in ENSO variabil-

ıfluences on inter-
ndesay, 1988; Van
994; Moron *et al.*,
hough not always
io events are asso-
arming in 1977 in
nerally dry condi-
ars. Although there
the changes in the
epoint in the annu-
uthern Oscillation
areas further west

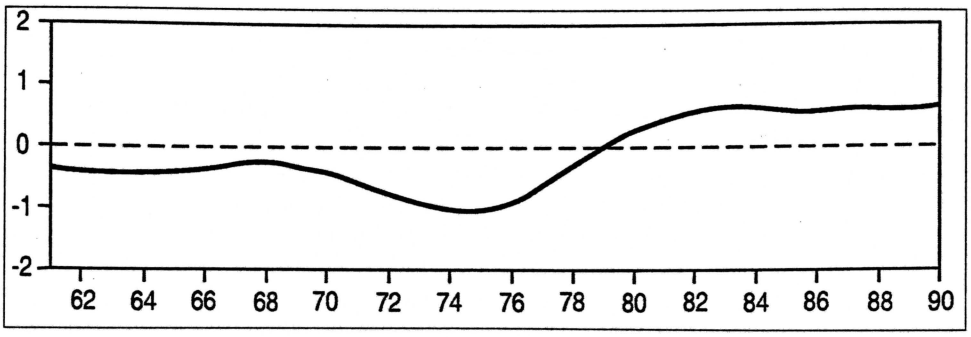


Figure 19. The temporal coefficient of the most important EOF mode of the interdecadal component of low-pass filtered monthly mean sea-surface temperature anomalies in the Indian and Pacific Oceans (after Wang, 1995b).

(Lindesay *et al.*, 1986; Lindesay, 1988; Van Heerden *et al.*, 1988) and so it is likely that the desiccation over the Lowveld is related more to the increases in sea-surface temperatures in the Indian Ocean. Higher than average sea-surface temperatures in the western and central equatorial Indian Ocean are generally associated with drier than average conditions over southern Africa (Jury & Pathack, 1991, 1993; Jury, 1995; Mason, 1995; Mason & Jury, 1997).

Because the generally dry conditions over the subcontinent over the last two decades is attributable in part to the recent predominance of El Niño conditions, future prospects for ENSO variability are of direct interest. It has been shown above that palaeoclimatic and modelling studies indicate that ENSO events are not expected to change significantly in frequency or magnitude in a warmer climate associated with an enhanced greenhouse effect. However, if possible changes in the teleconnection patterns in the mid-latitudes occur in a warmer climate, rainfall over southern Africa may be affected. The rainfall response over southern Africa to ENSO events occurs largely as a result of adjustments in the tropical atmospheric circulation, which is dominant over the region in the peak rainfall months of the austral summer, but responses of the temperate atmospheric circulation are important also (Harrison, 1986; Mason & Jury, 1997). The high rainfall associated with La Niña events is the result of the development of a continental heat low over the subcontinent coupled with the leading-edge of a westerly trough to the south. During El Niño events the easterly low and westerly trough are both displaced to the east and geopotential heights increase over the subcontinent (Lindesay, 1988; Taljaard, 1989; Jury *et al.*, 1994; Shinoda & Kawamura, 1996). Any change in the temperate atmospheric response to ENSO events in the southern African region may affect this current association with rainfall, although it is not possible to say in which way without precise knowledge of how the teleconnection pattern in the mid-latitudes is likely to react.

SUMMARY AND CONCLUSIONS

Since the late 1970s the frequency of strong La Niña events has been low, while El Niño episodes have been unusually recurrent, culminating in the long El Niño sequence of 1991-1995. Prolonged El Niño conditions are, however, not unprecedented during the period of instrumental records: persistent warm conditions in the equatorial Pacific Ocean and negative values of the Southern Oscillation Index were experienced in 1911-1915 and 1939-1942. It is difficult to isolate the causes of these earlier events, but it seems likely that prolonged warm events can have very different causes. During the 1990s, the persistence of an anomalously warm pool near the date line has shifted the main centre of convection over Indonesia toward the centre of the ocean, allowing for the penetration of westerly wind anomalies into the western Pacific, responsible for the generation of successive downwelling Kelvin waves. It has been postulated that the warm pool may be a result of an increasing trend in sea-surface temperatures, possibly associated with the enhanced greenhouse effect, although the effects of inter-decadal variability are probably of greater importance.

The abrupt increase in sea-surface temperatures in the equatorial Indian and Pacific oceans has been responsible for changes in the dynamics of the inter-annual variability in the Pacific Ocean and globally. The warming may be partly responsible for a decrease in forecast skill of ENSO events during the 1990s, since variability in the western Pacific Ocean has become more important in the initiation and development of El Niños, and this area is relatively poorly represented in the Cane-Zebiak model. However, ENSO episodes during the 1980s were successfully forecasted as was the delayed onset of the 1991-1992 event. Nevertheless, earlier estimates of forecastability of useful skill with more than 18 months lead-time are probably overly optimistic. The boreal spring, when ocean-atmosphere coupling over the equatorial Pacific Ocean is weak, is likely to remain a significant forecast barrier for a few years still. Additionally, the modelling of the influence of Madden-Julian wave activity in the western Pacific on ocean dynamics needs to be improved.

It is of interest that the abrupt increase in sea temperatures was synchronous with a decrease in annual mean rainfall over the Lowveld of South Africa, although the desiccation cannot be attributed solely to the increase in warm events in the Pacific Ocean; warming in the Indian Ocean, associated with dry conditions over much of South Africa, may be at least as important. Nevertheless, the frequency of El Niño events compared to La Niñas since the late 1970s has probably been partly responsible for the generally dry conditions of the 1980s and early 1990s over most of the country. Long-term prospects for ENSO variability are therefore of crucial significance. Palaeoclimatic and modelling studies suggest that ENSO events are not likely to change significantly in frequency or magnitude in a warmer climate associated with an enhanced greenhouse effect. In a doubled-CO_2 climate, however, changes in ENSO teleconnection patterns in the mid-latitudes may occur. Since the response to ENSO events of rainfall over southern Africa occurs as a result of both tropical and temperate atmospheric teleconnections, the association between rainfall of the region and sea temperatures in the Pacific Ocean may be affected. However, the tropical atmospheric response is of greater significance and so changes in the association are not likely to be highly significant.

ACKNOWLEDGEMENTS

This research was funded by Technology Research and Investigations, a division of the Technology Group of Eskom. P. Stickler drew the diagrams. Oceanographic information for 1991-1995 were obtained from the Climate Monitoring Bulletin published by the Australian Bureau of Meteorology. R.J. Allan supplied the Southern Oscillation Index data. Useful comments by R.J. Allan and M.H. Glantz are gratefully acknowledged.

REFERENCES

ALLAN, R.J. & D'ARRIGO, R.D. (submitted). 'Persistent' ENSO sequences: how unusual was the recent El Niño? *Holocene*.

ALLAN, R.J., NICHOLLS, N., JONES, P.D. & BUTTERWORTH, I.J. 1991. A further extension of the Tahiti-Darwin SOI, early

ENSO events and Darwin pressure. *Journal of Climate* **4**: 743-749.

ALLAN, R.J., LINDESAY, J.A. & REASON, C.J.C. 1995. Multidecadal variability in the climate system over the Indian Ocean region during the austral summer. *Journal of Climate* **8**: 1853-1873.

ALLAN, R.J., LINDESAY, J.A. & PARKER, D.E. 1996. *El Niño Southern Oscillation and Climatic Variability*. CSIRO Publishing, Collingwood. pp. 405.

ANDERSON, R.Y. 1992. Long-term changes in the frequency of occurrence of El Niño events. In Diaz, H.F. & Markgraf, V. (Eds) *El Niño: Historical and Palaeoclimatic Aspects of the Southern Oscillation*. Cambridge, Cambridge University Press. pp. 193-200.

BARNETT, T.P. 1991. The interaction of multiple time scales in tropical climate system. *Journal of Climate* **4**: 269-285.

BARNETT, T.P., LATIF, M., GRAHAM, N., FLUGEL, M., PAZAN, S. & WHITE, W. 1993. ENSO and ENSO-related predictability. Part I: prediction of equatorial Pacific sea surface temperature with a hybrid coupled ocean-atmosphere model. *Journal of Climate* **6**: 1545-1566.

BELL, G.D. & BASIST, A.N. 1994. The global climate of December 1992 - February 1993. Part I: warm ENSO conditions continue in the tropical Pacific; California drought abates. *Journal of Climate* **7**: 1581-1605.

BELL, G.D. & HALPERT, M.S. 1993. The global climate of March - May 1991: anomalous low-frequency fluctuations dominate the midlatitudes; ENSO becomes established in the tropics. *Journal of Climate* **6**: 1413-1433.

BIGG, G.R. 1995. El Niño and the Southern Oscillation. *Weather* **45**: 2-8.

BIGG, G.R. & INOUE, M. 1992. Rossby waves and El Niño during 1935-46. *Quarterly Journal of the Royal Meteorological Society* **118**: 125-152.

BOULANGER, J.P. & MENKES, C. 1996. Propagation and reflection of long equatorial waves in the Pacific Ocean during the 1992-1993 El Niño. *Journal of Geophysical Research* **100**: 25041-25059.

BUSALACCHI, A.J., MCPHADEN, M.J. & PICAUT, J. 1994. Variability in equatorial Pacific sea surface topography during the verification phase of the TOPEX/POSEIDON mission. *Journal of Geophysical Research* **99**: 24725-24738.

CANE, M.A. 1991. Forecasting El Niño with a geophysical model. In Glantz, M.H., Katz, R.W. & Nicholls, N. (Eds) *Teleconnections Linking Worldwide Climate Anomalies: Scientific Basis and Societal Impact*. Cambridge, Cambridge University Press, pp. 345-369.

CANE, M.A. 1992. Tropical Pacific ENSO models: ENSO as a mode of the coupled system. In Trenberth, K.E (Ed.) *Climate System Modeling*. Cambridge, Cambridge University Press. pp. 583-614.

CANE, M.A., ZEBIAK, S.E. & DOLAN, S.C. 1986. Experimental forecasts of El Niño. *Nature* **321**: 827-832.

CHANG, P., WANG, B., LI, T. & JI, L. 1994. Interactions between the seasonal cycle and the Southern Oscillation - frequency entrainment and chaos in a coupled ocean-atmosphere model. *Geophysical Research Letters* **21**: 2817-2820.

CHANG, P., JI, L., WANG, B. & LI, T. 1995. Interactions between the seasonal cycle and El Niño-Southern Oscillation in an intermediate coupled ocean-atmosphere model. *Journal of the Atmospheric Sciences* **52**: 2353-2372.

CHAO, Y. & PHILANDER, S.G. 1993. On the structure of the Southern Oscillation. *Journal of Climate* **6**: 450-469.

CHELLIAH, M. 1993. The global climate for December 1990 - February 1991: strong temperature and precipitation contrasts over North America and Eurasia; mixed ENSO conditions in the tropics. *Journal of Climate* **6**: 1392-1412.

CHELLIAH, M. 1994. The global climate for September - November 1992: weak warm ENSO episode conditions linger in the tropical Pacific. *Journal of Climate* **7**: 1565-1580.

DELCROIX, T., ELDIN, J.M., MCPHADEN, M.J. & MORLIÈRE, A. 1993. Effects of westerly wind bursts upon the western equatorial Pacific Ocean, February - April 1991. *Journal of Geophysical Research* **92**: 14189-14196.

DESER, C. & WALLACE, J.M., 1987. El Niño events and their relation to the Southern Oscillation: 1925-1986. *Journal of Geophysical Research* **92**: 14189-14196.

DIAZ, H.F. & KILADIS, G.N., 1992. Atmospheric teleconnections associated with the extreme phases of the Southern Oscillation. In Diaz, H.F. & Markgraf, V. (Eds) *El Niño: Historical and Palaeoclimatic Aspects of the Southern Oscillation*. Cambridge, Cambridge University Press. pp. 7-28.

DIAZ, H.F. & PULWARTY, R.S. 1992. A comparison of Southern Oscillation and El Niño signals in the tropics. In Diaz, H.F. & Markgraf, V. (Eds) *El Niño: Historical and Palaeoclimatic Aspects of the Southern Oscillation*. Cambridge, Cambridge University Press. pp. 175-192.

DIAZ, H.F. & PULWARTY, R.S. 1994. An analysis of the time scales of variability in centuries-long ENSO-sensitive records in the last 1000 years. *Climatic Change* **26**, 317-342.

DIAZ, H.F., MARKGRAF, V. & HUGHES, M.K. 1992. Synthesis and future prospects. In Diaz, H.F. & Markgraf, V. (Eds) *El Niño: Historical and Palaeoclimatic Aspects of the Southern Oscillation*. Cambridge, Cambridge University Press. pp. 463-471.

ELLOTT, W.P. & ANGELL, J.K. 1988. Evidence for changes in Southern Oscillation relationships during the last 100 years. *Journal of Climate* **1**: 729-737.

ENFIELD, D.B. 1992. Historical and prehistorical overview of El Niño/Southern Oscillation. In Diaz, H.F. & Markgraf, V. (Eds) *El Niño: Historical and Palaeoclimatic Aspects of the Southern Oscillation*. Cambridge, Cambridge University Press. pp. 95-117.

Enfield, D.B. & Cid, S.L. 1991. Low-frequency changes in El Niño-Southern Oscillation. *Journal of Climate* **4**: 1137-1146.

Graham, N.E. 1994. Decadal-scale climate variability in the tropical and North Pacific during the 1970s and 1980s: observations and model results. *Climate Dynamics* **10**: 135-162.

Graham, N.E. 1995. Simulation of recent global temperature trends. *Science* **267**: 666-671.

Graham, N.E. & White, W.B. 1988. The El Niño cycle: a natural oscillator of the Pacific Ocean atmosphere system. *Science* **240**: 1293-1302.

Gu, D. & Philander, S.G.H. 1995. Secular changes of annual and interannual variability in the tropics during the past century. *Journal of Climate* **8**: 864-876.

Gutzler, D.S., Kiladis, G.N., Meehl, G.A., Weickmann, K.M. & Wheeler, M. 1994. The global climate of December 1992 - February 1993. Part II: large-scale variability across the tropical western Pacific during TOGA COARE. *Journal of Climate* **7**: 1606-1622.

Halpert, M.S. & Bell, G.D. 1993. The global climate of June - August 1991: tropical Pacific warm episode conditions evolve; new base period means established. *Journal of Climate* **6**: 1434-1456.

Halpert, M.S. & Ropelewski, C.F. 1992. Surface temperature patterns associated with the Southern Oscillation. *Journal of Climate* **5**: 577-593.

Harrison, M.S.J. 1986. A synoptic climatology of South African rainfall variability. Unpublished Ph.D. Thesis, University of the Witwatersrand, 341pp.

Hartmann, D.L. & Michelsen, M.L. 1993. Large-scale effects on the regulation of tropical sea surface temperatures. *Journal of Climate* **6**: 2049-2062.

Hastenrath, S. 1995. Recent advances in tropical climate prediction. *Journal of Climate* **8**: 1519-1532.

Hastenrath, S., Greischar, L. & Van Heerden, J. 1995. Prediction of the summer rainfall over South Africa. *Journal of Climate* **8**: 1511-1518.

Ho, C.-R., Yan, X.-H. & Zheng, Q. 1995. Satellite observations of upper-layer variabilities in the western Pacific warm pool. *Bulletin of the American Meteorological Society* **76**: 669-679.

Hoffert, M.I., Flannery, B.P., Callegari, A.J., Hsieh, C.T. & Wiscombe, W. 1983. Evaporation-limited tropical temperatures as a constraint on climate sensitivity. *Journal of the Atmospheric Sciences* **40**: 1659-1668.

Janowiak, J.E. 1988. An investigation of interannual rainfall variability in Africa. *Journal of Climate* **1**: 240-255.

Janowiak, J.E. 1993. The global climate for September - November 1991: warm (ENSO) episode conditions strengthen. *Journal of Climate* **6**: 1616-1638.

Jury, M.R. 1995. A review of research on ocean-atmosphere interactions and South African climate variability. *South African Journal of Science* **91**: 289-294.

Jury, M.R. & Lutjeharms, J.R.E. 1993. Die struktuur en moontlike aandrywingskragte van die 1991-1992-droogte in suidelike Afrika. *Suid-Afrikaanse Tydskrif vir Natuurwetenskap en Tegnologie* **12**: 8-16.

Jury, M.R. & Pathack, B.M.R. 1991. A study of climate and weather variability over the tropical southwest Indian Ocean. *Meteorology and Atmospheric Physics* **47**: 37-48.

Jury, M.R. & Pathack, B.M.R. 1993. Composite climatic patterns associated with extreme modes of summer rainfall over southern Africa: 1975-1984. *Meteorology and Atmospheric Physics* **47**: 137-145.

Jury, M.R. & Pathack, B.M.R. 1997. Climatic patterns associated with the 1992 drought over southern Africa: observations and GCM results. *Journal of the African Meteorological Society*, in press.

Jury, M.R., McQueen, C. & Levey, K. 1994. SOI and QBO signals in the African region. *Meteorology and Atmospheric Physics* **50**: 103-115.

Kerr, R.A. 1992. Unmasking a shifty climate system. *Science* **255**: 1508-1510.

Kerr, R.A. 1993. El Niño metamorphosis throws forecasters. *Science* **262**: 656-657.

Kessler, W.S. & McPhaden, M.J. 1995. Oceanic equatorial waves and the 1991-93 El Niño. *Journal of Climate* **8**: 1757-1774.

Kleeman, R. 1993. On the dependence of hindcast skill on ocean thermodynamics in a coupled ocean-atmosphere model. *Journal of Climate* **6**: 2012-2033.

Knutson, T.R. & Manabe, S. 1994. Impact of increased CO_2 on simulated ENSO-like phenomena. *Geophysical Research Letters* **21**: 2295-2298.

Knutson, T.R. & Manabe, S. 1995. Time-mean response over the tropical Pacific to increased CO_2 in a coupled ocean-atmosphere model. *Geophysical Research Letters* **21**: 2295-2298.

Kousky, V.E. 1993. The global climate of December 1991 - February 1992: mature-phase warm (ENSO) episode conditions develop. *Journal of Climate* **6**: 1639-1655.

Latif, M., Sterl, A., Maier-Reimer, E. & Junge, M.M. 1993. Climate variability in a coupled GCM. Part I: the tropical Pacific. *Journal of Climate* **6**: 5-21.

Latif, M., Sterl, A., Assenbaum, M., Junge, M.M. & Maier-Reimer, E. 1994. Climate variability in a coupled GCM. Part II: the Indian Ocean and monsoon. *Journal of Climate* **7**: 1449-1462.

Lindesay, J.A. 1988. South African rainfall, the Southern Oscillation and a southern hemisphere semi-annual cycle.

Journal of Climatology **8**: 17-30.

LINDESAY, J.A. & VOGEL, C.H. 1990. Historical evidence for Southern Oscillation-southern African rainfall relationships. *International Journal of Climatology* **10**: 679-689.

LINDESAY, J.A., HARRISON, M.S.J. & HAFFNER, M.P. 1986. The Southern Oscillation and South African rainfall. *South African Journal of Science* **82**: 196-189.

LOUGH, J.M. 1992. An index of the Southern Oscillation reconstructed from western North American tree-ring chronologies. In Diaz, H.F. & Markgraf, V. (Eds) *El Niño: Historical and Palaeoclimatic Aspects of the Southern Oscillation*. Cambridge, Cambridge University Press. pp. 215-226.

LUKAS, R., WEBSTER, P.J., JI, M. & LEETMA, A. 1995. The large-scale context for the TOGA coupled ocean-atmosphere response experiment. *Meteorology and Atmospheric Physics* **56**: 3-18.

MASON, S.J. 1995: Sea-surface temperature - South African rainfall associations, 1910-1989. *International Journal of Climatology* **15**, 119-135.

MASON, S.J. 1996: Rainfall trends over the Lowveld of South Africa. *Climatic Change* **32**, 35-54.

MASON, S.J. & JURY, M.R. 1997: Climatic variability and change over southern Africa: a reflection on underlying processes. *Progress in Physical Geography* **21**: 23-50.

MASON, S.J. & LINDESAY, J.A. 1993: A note on the modulation of Southern Oscillation-southern African rainfall associations with the Quasi-biennial Oscillation. *Journal of Geophysical Research* **98**, 8847-8850.

MASON, S.J. & MIMMACK, G.M. 1992: The use of bootstrap confidence intervals for the correlation coefficient in climatology. *Meteorology and Atmospheric Physics* **45**, 229-233.

MASON, S.J., JOUBERT, A.M., COSIJN, C. & CRIMP, S.J. 1996: Review of the current state of seasonal forecasting techniques with applicability to southern Africa. *WaterSA* **22**: 203-209.

MATARIRA, C.H. 1990: Drought over Zimbabwe in a regional and global context. *International Journal of Climatology* **10**, 609-625.

MEEHL, G.A. 1991. The Southern Oscillation in a coupled GCM: implications for climate sensitivity and climate change. In Schlesinger, M.E. (Ed.) *Greenhouse-Gas-Induced Climatic Change: A Critical Appraisal of Simulations and Observations*. Amsterdam, Elsevier. pp. 111-128.

MEEHL, G.A. 1993. A coupled air-sea biennial mechanism in the tropical Indian and Pacific regions: role of the ocean. *Journal of Climate* **6**: 31-41.

MEEHL, G.A. 1995. Global coupled general circulation models. *Bulletin of the American Meteorological Society* **76**: 951-957.

MEEHL, G.A. & BRANSTATOR, G.W. 1992. Coupled climate model simulation of El Niño/Southern Oscillation: implications for paleoclimate. In Diaz, H.F. & Markgraf, V. (Eds) *El Niño: Historical and Palaeoclimatic Aspects of the Southern Oscillation*. Cambridge, Cambridge University Press. pp. 69-91.

MEEHL, G.A., BRANSTATOR, G.W. & WASHINGTON, W.M. 1993. Tropical Pacific interannual variability and CO_2 climate change. *Journal of Climate* **6**: 42-63.

MILLER, A.J., CAYAN, D.R., BARNETT, T.P., GRAHAM, N.E. & OBERHUBER, J.M. 1994. Interdecadal variability of the Pacific Ocean: model response to observed heat flux and wind stress anomalies. *Climate Dynamics* **9**: 287-302.

MO, K.C. 1993. The global climate of September - November 1990: ENSO-like warming in the western Pacific and strong ozone depletion over Antarctica. *Journal of Climate* **6**: 1375-1391.

MO, K.C. & WANG, X.L. 1994. The global climate of June - August 1992: warm ENSO episode decays and colder than normal conditions dominate the northern hemisphere. *Journal of Climate* **7**: 335-357.

MO, K.C. & WANG, X.L. 1995. Sensitivity of the systematic error of extended range forecasts to sea surface temperature anomalies. *Journal of Climate* **8**: 1533-1543.

MORON, V., BIGOT, S. & ROUCOU, P. 1995. Rainfall variability in subequatorial America and Africa and relationships with the main sea-surface temperature modes (1951-1990). *International Journal of Climatology* **15**: 1297-1322.

MOORE, A.M. & KLEEMAN, R. 1996. The dynamics of error growth and predictability in a coupled model of ENSO. *Quarterly Journal of the Royal Meteorological Society* **122**: 1405-1446.

NAGAI, T., KITAMURA, Y., ENDOH, M. & TOKIOKA, T. 1995. Coupled atmosphere-ocean model simulations of El Niño/Southern Oscillation with and without an active Indian Ocean. *Journal of Climate* **8**: 3-14.

NICHOLLS, N. 1988. El Niño - Southern Oscillation impact prediction. *Bulletin of the American Meteorological Society* **69**: 173-176.

PAN, Y.H. & OORT, A.H. 1983. Global climate variations connected with sea surface temperature anomalies in the eastern equatorial Pacific Ocean for the 1958-73 period. *Monthly Weather Review* **111**: 1244-1258.

PARKER, D.E. 1987. The Meteorological Office historical sea surface temperature data set. *Meteorological Magazine* **116**: 250-254.

PARKER, D.E. & FOLLAND, C.K. 1988. The Meteorological Office historical sea surface temperature data set. In Gregory, S. (Ed.) *Recent Climatic Change*. London, Belhaven Press. pp. 41-50.

POSMENTIER, E.S., CANE, M.A. & ZEBIAK, S.E. 1989. Tropical Pacific climate trends since 1960. *Journal of Climate* **2**: 731-736.

Quinn, W.H. 1992. A study of Southern Oscillation-related climatic activity for A.D. 622-1900 incorporating Nile River flood data. In Diaz, H.F. & Markgraf, V. (Eds) *El Niño: Historical and Palaeoclimatic Aspects of the Southern Oscillation*. Cambridge, Cambridge University Press. pp. 119-149.

Quinn, W.H., Neal, V.T. & Antunez de Mayolo, S.E. 1987. El Niño occurrences over the past four and a half centuries. *Journal of Geophysical Research* **92**: 14449-14461.

Reason, C.J.C., Allan, R.J. & Lindesay, J.A. 1996a. Dynamical response of the oceanic circulation and temperature to interdecadal variability in the surface winds over the Indian Ocean. *Journal of Climate* **9**: 97-114.

Reason, C.J.C., Allan, R.J. & Lindesay, J.A. 1996b. Evidence for the influence of remote forcing on interdecadal variability in the southern Indian Ocean. *Journal of Geophysical Research* **101**: 11867-11882.

Reiter, E.R. 1978. Long-term variability in the tropical Pacific, its possible causes and effects. *Monthly Weather Review* **106**: 324-330.

Ropelewski, C.F. & Halpert, M.S. 1987. Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Monthly Weather Review* **115**: 1606-1626.

Ropelewski, C.F. & Halpert, M.S. 1989. Precipitation patterns associated with the high index phase of the Southern Oscillation. *Journal of Climate* **2**: 268-284.

Ropelewski, C.F., Halpert, M.S. & Wang, X. 1992. Observed tropospheric biennial variability and its relationship to the Southern Oscillation. *Journal of Climate* **5**: 594-614.

Ropelewski, C.F., Lamb, P.J. & Portis, D.H. 1993. The global climate for June - August 1990: drought returns to sub-Saharan Africa and warm Southern Oscillation episode conditions develop in the central Pacific. *Journal of Climate* **6**: 2188-2212.

Schneider, E.K. & Kinter, J.L. 1994. An examination of internally generated variability in long climate simulations. *Climate Dynamics* **10**: 181-204.

Schopf, P.S. & Suarez, M.J. 1988. Vacillations in a coupled ocean-atmosphere model. *Journal of the Atmospheric Sciences* **45**: 549-566.

Shinoda, M. & Kawamura, R. 1996. Relationships between rainfall over semi-arid southern Africa and geopotential heights and sea surface temperatures. *Journal of the Meteorological Society of Japan* **74**: 21-36.

Smith, I.N. 1995. A GCM simulation of global climate interannual variability: 1950-1988. *Journal of Climate* **8**: 709-718.

Solow, A.R. 1995. Testing for change on the frequency of El Niño events. *Journal of Climate* **8**: 2563-2566.

Suarez, M.J. & Schopf, P.S. 1988. A delayed action oscillator for ENSO. *Journal of the Atmospheric Sciences* **45**: 3283-3287.

Taljaard, J.J. 1989. Climate and circulation anomalies in the South African region during the summer of 1982/83. *South African Weather Bureau Technical Paper* **21**: 45pp.

Tett, S. 1995. Simulation of El Niño - Southern Oscillation-like variability in a global AOGCM and its response to CO2 increase. *Journal of Climate* **8**: 1473-1502.

Trenberth, K.E. 1990. Recent observed interdecadal climate changes in the Northern Hemisphere. *Bulletin of the American Meteorological Society* **71**: 988-993.

Trenberth, K.E. 1991. General characteristics of El Niño - Southern Oscillation. In Glantz, M.H., Katz, R.W. & Nicholls, N. (Eds) *Teleconnections Linking Worldwide Climate Anomalies: Scientific Basis and Societal Impact*. Cambridge, Cambridge University Press, pp. 13-42.

Trenberth, K.E. & Hoar, T.J. 1996. The 1990-1995 El Niño-Southern Oscillation event: longest on record. *Geophysical Research Letters* **23**: 57-60.

Trenberth, K.E. & Hurrell, J.W. 1994. Decadal atmosphere-ocean variations in the Pacific. *Climate Dynamics* **9**: 303-319.

Trenberth, K.E. & Shea, D.J. 1987. On the evolution of the Southern Oscillation. *Monthly Weather Review* **115**: 3078-3096.

Troup, A.J. 1965. The Southern Oscillation. *Quarterly Journal of the Royal Meteorological Society*, **91**: 490-506.

Van Heerden, J., Terblanche, D.E. & Schulze, G.C. 1988. The Southern Oscillation and South African summer rainfall. *Journal of Climatology* **8**: 577-597.

Wang, B. 1995a. Transition from a cold to a warm state of the El Niño - Southern Oscillation cycle. *Meteorology and Atmospheric Physics* **56**: 17-32.

Wang, B. 1995b. Interdecadal changes in El Niño onset in the last four decades. *Journal of Climate* **8**: 267-285.

Wang, C. & Weisberg, R.H. 1994. On the "slow mode" mechanism in ENSO-related coupled ocean-atmosphere models. *Journal of Climate* **7**: 1657-1667.

Wang, X. 1993. The global climate for March - May 1992: mature phase warm episode continues in the tropical Pacific. *Journal of Climate* **6**: 2465-2485.

Wang, X.L. & Ropelewski, C.F. 1995. An assessment of ENSO-scale secular variability. *Journal of Climate* **8**: 1584-1599.

Webster, P.J. 1995. The annual cycle and the predictability of the tropical coupled ocean-atmosphere system.

Meteorology and Atmospheric Physics **56**: 33-55.

WHYSALL, K.D.B., COOPER, N.S. & BIGG, G.R. 1987. Long-term changes in the tropical Pacific surface wind field. *Nature* **327**: 216-219.

WRIGHT, P.B. 1989. Homogenised long-period Southern Oscillation indices. *International Journal of Climatology* **9**: 33-54.

WU, J. 1995. Sea surface winds - a critical input to oceanic models, but are they accurately measured? *Bulletin of the American Meteorological Society* **76**: 13-19.

WUETRICH, B. 1995. El Niño goes critical. *New Scientist* **1963**: 32-35.

YOUNG, K.C. 1993. Detecting and removing inhomogeneities from long-term monthly sea level pressure time series. *Journal of Climate* **6**: 1205-1220.

ZHANG, X.-G. & CASEY, T.M. 1992. Long-term variations in the Southern Oscillation and relationships with Australian rainfall. *Australian Meteorological Magazine* **40**: 211-225.