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Front cover CP © NASA/JPL/Caltech from the www site at http://www.jpl.nasa.gov/elnino

This image of the Pacific Ocean was produced using sea surface height measurements taken by the US/French TOPEX/Poseidon satellite. It shows sea surface height relative to normal ocean conditions on 1 December 1997. The white and red areas indicate unusual patterns of heat storage. Height anomalies shading includes the following: white +14 to +32 cm, red +10 cm, green – no anomaly, purple – at least 7 cm below normal.

Back cover is Fig. 4 from the article on p. 324

Anomalous August–September mean 500 mbar vertical motion (omega velocity, mbar day^{-1}) and 200 mbar wind vectors (m s^{-1}), derived from ECMWF analyses, for (a) 1983 and (b) 1997. Negative values indicate anomalous ascent, positive values anomalous descent.

back to 1951), 'nino' (the mean monthly SSTs for the Niño1+2, 3 and 4 regions back to 1970), 'olr' (equatorial Pacific OLR back to 1974), 'soi.his' (the SOI from 1882 to 1950) and many more.

With ENSO now recognised as having a global impact, it is also useful to keep up to date with global developments using monthly, on-line, climate summaries. Perhaps the most well known of these is the *Climate Diagnostics Bulletin* (M) from the Climate Prediction Center. The Climate Diagnostics Center also provides a variety of weekly, monthly and seasonal data on-line via its 'map room' site (N), while weekly weather highlights (of interest even without an El Niño) give an indication of weather extremes and conditions around the world (O).

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Measuring the strength of ENSO events:
How does 1997/98 rank?

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The 1997/98 El Niño event has been hailed as the 'El Niño of the century', pushing 1982/83 from its throne. Is this claim valid? How do we determine the strength of El Niño and La Niña events? This paper addresses these issues by comparing the temporal evolution of different El Niño Southern Oscillation (ENSO) indices for both events. The Multivariate ENSO Index (MEI) is favoured over conventional indices, since it combines the significant features of all observed surface fields in the tropical Pacific. Based on MEI data until May 1998, the current event is placed a close second both for its peak value and for the duration of front-runner status.

Background

The MEI is derived from tropical Pacific COADS (Comprehensive Ocean–Atmosphere Data Set) records and is a multivariate measure of the ENSO signal as expressed in the first principal component of six observed variables over the tropical Pacific (Wolter and Timlin 1993): sea-level pressure (P), surface zonal (U) and meridional (V) wind components, sea surface temperature (S), surface air temperature (A), and cloudiness (C). It is re-computed every month to monitor the strength of ENSO conditions for the preceding two months (our website http://www.cdc.noaa.gov/~kew/MEI/ discusses the MEI time-series and spatial patterns, and is updated during the first week of each following month).

The most commonly used ENSO indices are the Southern Oscillation Index (SOI – Ropelewski and Jones 1987), here computed from the Darwin minus Tahiti pressure difference, and mean sea surface temperature of Niño regions S12, S3, and S4 (see Fig. 1 for locations) as derived from Rasmusson and Carpenter (1982). Up-to-date monthly values of these ENSO indices can be found on the Web (http://nic.fb4.noaa.gov:80/data/cddb/). To make valid comparisons among all ENSO indices, they are normalised with respect to each sliding bimonthly season during the 1950–93 base period. As defined here, positive values of any ENSO index correspond to El Niño-like conditions. Using all seasons, correlations between the MEI and other indices range from 0.80 for S12 to 0.90 for S3, with the SOI and S4 in between. Correlations with the SOI reach 0.61 with S12, 0.73 with S3, and 0.79 with S4.

To better understand which parts of the MEI contribute to its observed behaviour, we select the most important features in each of its six

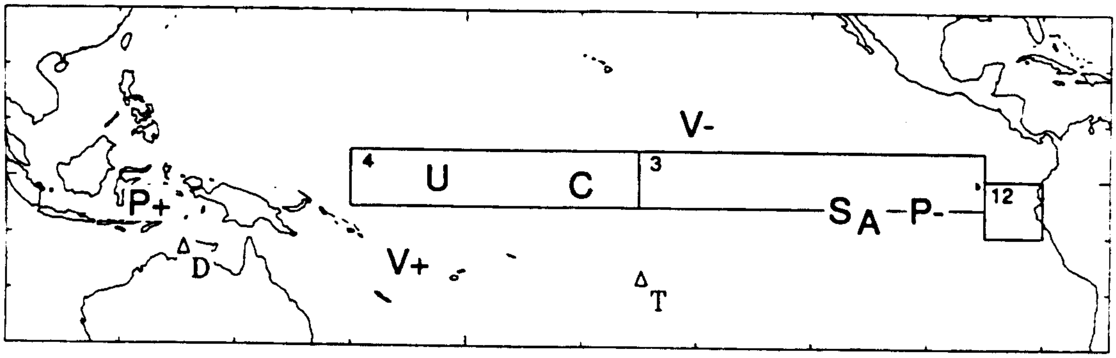


Fig. 1 Orientation map of the tropical Pacific basin. Bold capital letters denote the approximate centres of gravity of MEI key regions: P+ and P- are the western and eastern sea-level pressure dipoles (the difference between P+ and P- constitutes the see-saw index P), U represents westerly zonal wind anomalies in the central Pacific, V+ (V-) indicate southerly (northerly) meridional wind anomalies in the south-western (northern) portion of the domain (V+ minus V- is symbolised by V in this paper), S and A denote the average locations of the sea surface and surface air temperature anomalies, and C represents anomalous cloudiness over the central Pacific during ENSO events. Rectangular boxes marked 4, 3, and 12 denote locations of Niño regions S4, S3 and S12, respectively. Darwin and Tahiti are denoted by open triangles and the letters D and T.

fields, and include all regions with loadings of at least 80 per cent of the highest values. These regions vary with the seasonal cycle (Wolter and Timlin 1993), reaching their greatest coherence and size around boreal winter, and their minimum in late spring. Figure 1 shows their approximate centres of gravity, as well as the locations of conventional ENSO indices.

Historic El Niño events since 1950

The instrumental record of ENSO events is unreliable during the two World Wars. Furthermore, the 1940s saw a revision of virtually every observational technique aboard ships. Therefore, this paper focuses on the period from 1950 onwards. Table 1 classifies all MEI seasons from December/January 1949/50 to November/December 1997 into seven categories: strong, moderate, weak El Niño/La Niña, and neutral. Of the 60 strong El Niño seasons, 90 per cent are associated with the seven leading El Niño events since 1950: 1957/58, 1965/66, 1972/73, 1982/83, 1986/87, 1991/92 and 1997/98. In fact, 1982/83 remained strong for 13 months in a row (this duration is now matched by 1997/98). Analogous rankings for S12 and S3 yield the same number of seasons in the top seven El Niño events, while SOI and S4 harbour only 75 per cent of their strongest rankings in these events.

One of the more interesting aspects of ENSO is the lack of La Niña events since 1976 (Table 1). It has been noted elsewhere (*e.g.* Trenberth and Hurrell 1994) that general circulation changes in the Pacific basin have taken place in association with tropical Pacific sea surface temperature shifts in the mid-to-late-1970s. Is there a systematic difference between El Niño events prior to 1976 and since then? We present evidence for this in Fig. 2, which illustrates the typical evolution of the three main El Niño events before and after 1976 in the MEI, SOI, S12, and S4, as compared to 1997/98.

For the MEI (Fig. 2(a)), average El Niño behaviour before 1976 can be characterised by a rapid onset phase from March/April to June/July, mature conditions (>80 per cent of maximum value) until January/February, and a rapid decline by May/June of Year 1. The mature phase often features two separate peaks around July and December of Year 0. More recent events have taken much longer to mature, resulting in a delayed peak around March/April of Year 1, a shorter duration of the mature stage, and a slow decline towards the end of Year 1 (Fig. 2(a)). The evolution of 1997/98 matches pre-1976 events very well throughout most of 1997, followed by more affinity towards post-1976 behaviour until March 1998, and a more rapid decline since then (Fig. 2(a)).

For the SOI, the average life cycle of pre- and post-1976 El Niño events (Fig. 2(b)) follows the MEI mould (Fig. 2(a)), albeit in a jagged fashion (SOI users often resort to five-month

Table 1 Classification of each bimonthly season into either El Niño of highest strength (7), moderate strength (6), or weak strength (5), or La Niña of same (1, 2 and 3), or in between (4) for 1950–97. El Niño and La Niña categories refer to five cases each (strong = rank 1–5, moderate = rank 6–10, and weak = rank 11–15) and the neutral category includes 18 cases (rank 16–33).

Year	D/J	J/F	F/M	M/A	A/M	M/J	J/J	J/A	A/S	S/O	O/N	N/D
1950	2	2	1	2	1	1	1	2	3	3	2	1
1951	2	1	2	3	4	4	5	6	6	5	5	4
1952	4	4	4	4	4	3	4	4	4	4	4	4
1953	4	4	4	6	6	4	4	4	4	4	4	4
1954	4	4	4	3	1	1	1	1	2	2	2	2
1955	3	3	2	1	1	1	1	1	1	1	1	1
1956	1	1	1	1	1	1	2	2	2	1	2	2
1957	2	4	4	4	6	5	6	6	6	6	6	6
1958	7	7	7	6	6	6	5	4	4	4	4	5
1959	5	6	5	4	4	4	4	4	4	4	4	4
1960	4	4	4	4	4	4	4	4	3	4	4	4
1961	4	4	4	4	4	4	4	4	4	3	3	3
1962	1	2	3	2	2	2	3	3	3	3	3	3
1963	2	2	3	3	3	4	4	5	5	5	6	5
1964	6	5	3	3	2	2	1	1	2	2	2	2
1965	3	4	4	4	5	6	6	7	7	6	7	7
1966	7	6	5	5	4	4	4	4	4	4	4	4
1967	4	3	2	2	3	4	3	3	2	3	3	4
1968	3	2	3	2	2	2	3	4	4	4	4	4
1969	5	6	5	6	6	5	4	4	4	4	5	4
1970	4	4	4	4	4	3	2	2	2	2	3	2
1971	1	1	1	1	1	1	2	2	1	1	1	2
1972	4	4	4	4	5	6	7	7	7	7	7	7
1973	7	7	6	5	4	2	2	1	1	1	1	1
1974	1	1	1	1	2	3	3	3	3	2	2	3
1975	4	4	2	2	2	2	1	1	1	1	1	1
1976	1	1	1	1	3	4	4	5	6	5	4	4
1977	4	4	4	6	4	5	5	5	5	5	6	5
1978	6	6	6	4	4	3	4	4	4	4	4	4
1979	5	4	4	4	4	4	4	5	5	5	5	6
1980	5	5	6	7	6	5	5	4	4	4	4	4
1981	4	4	5	6	4	4	4	4	4	4	4	4
1982	4	4	4	4	4	6	7	7	7	7	7	7
1983	7	7	7	7	7	7	7	6	4	4	4	4
1984	4	4	4	5	4	4	4	4	4	4	4	3
1985	3	3	3	4	3	4	4	3	3	4	4	4
1986	4	4	4	4	4	4	4	5	6	6	5	6
1987	6	7	7	7	7	7	7	7	7	7	7	7
1988	6	5	5	4	4	3	2	2	1	2	1	1
1989	2	2	2	3	3	4	3	3	4	4	4	4
1990	4	5	6	4	5	4	4	4	4	4	4	4
1991	4	4	4	4	5	6	6	6	5	6	6	6
1992	7	7	7	7	7	7	6	4	4	4	4	5
1993	5	6	7	7	7	7	6	6	6	6	5	5
1994	4	4	4	5	5	5	5	4	5	7	6	6
1995	6	5	6	4	4	4	4	4	4	3	3	3
1996	3	3	4	4	4	4	4	4	4	4	4	4
1997	4	3	4	5	7	7	7	7	7	7	7	7

running means to get rid of noise). After a very good fit with pre-1976 events until May/June 1997, the 1997/98 El Niño charted its own course through 1997, and then switched over to match post-1976 events until April/May 1998 (Fig. 2(b)).

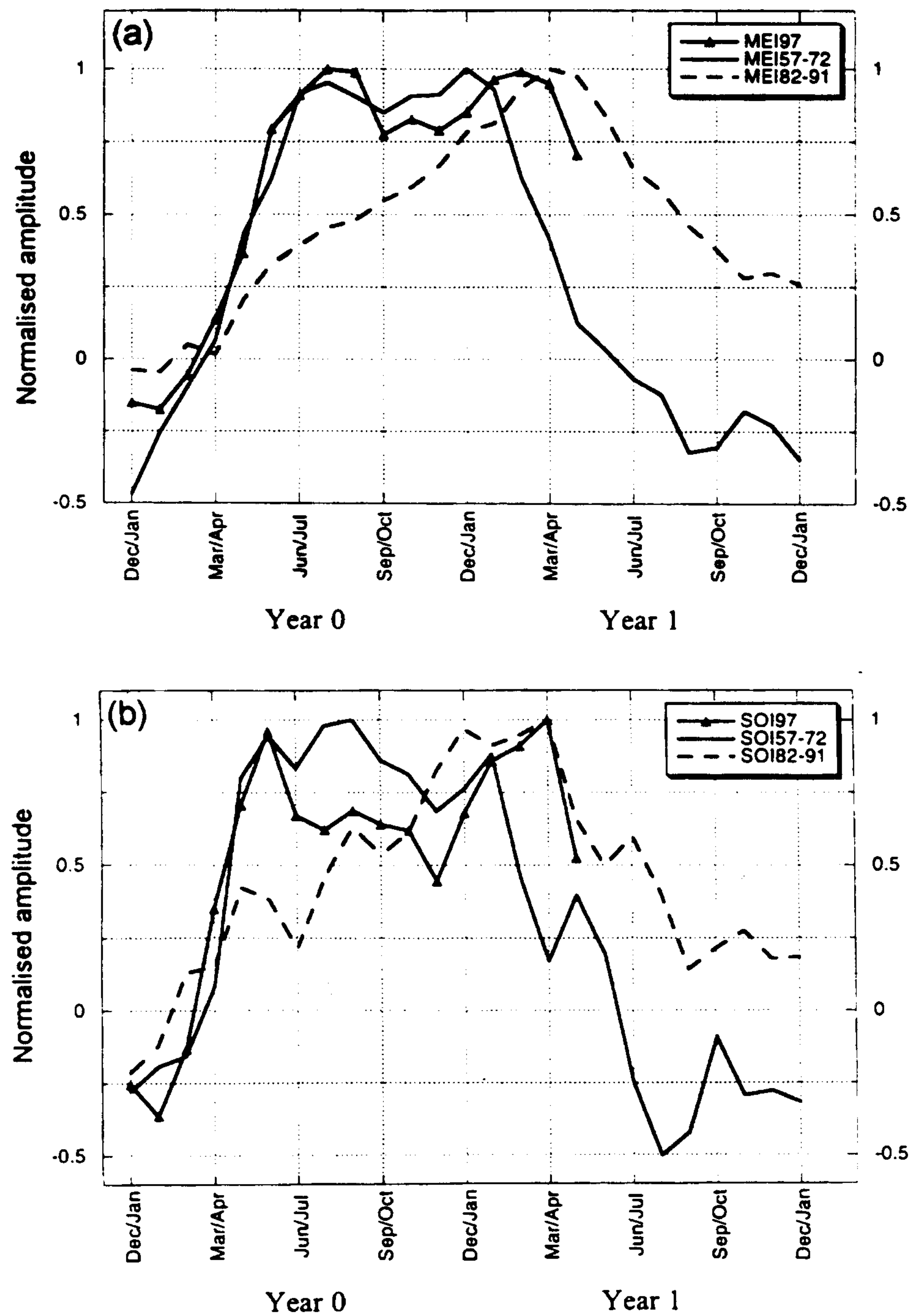
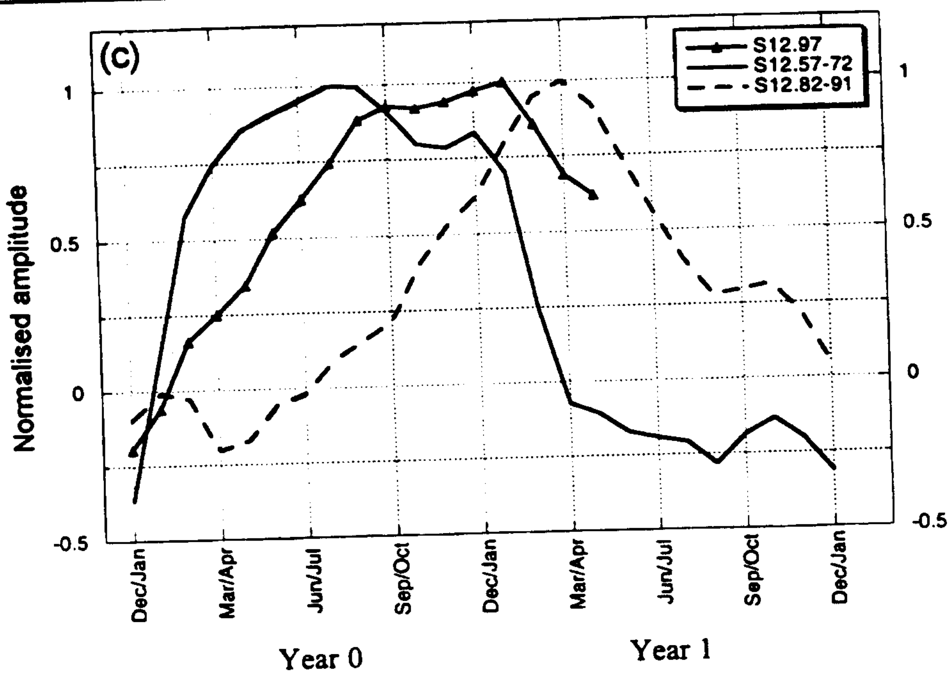


Fig. 2 Normalised amplitude plots comparing the average evolution of the three El Niño events of 1957/58, 1965/66 and 1972/73 (solid line) versus 1982/83, 1986/87 and 1991/92 (dashed line) and 1997/98 (solid triangles). Each El Niño time-series was divided by its highest positive value first and then averaged among the three cases to generate the average evolutions for early and recent events. Shown are bimonthly sliding time-series of the MEI(a), SOI(b), S12(c) and S4(d).

Differences between early and recent El Niños are most dramatic in S12 (Fig. 2(c)): the onset phase used to be completed by April/May versus the beginning of Year 1, while the decline back to 'normal' (by March/April of Year 1 for early events) has recently been delayed until the end of Year 1. During the 1997/98 El Niño, S12 has tracked a course between early and recent events. In fact, the correlation between 1997/98 and the average of the early and recent composites reaches +0.96 from December/January of Year 0 to April/May of Year 1.

Finally, S4 shows more subtle differences between pre- and post-1976 behaviour. The



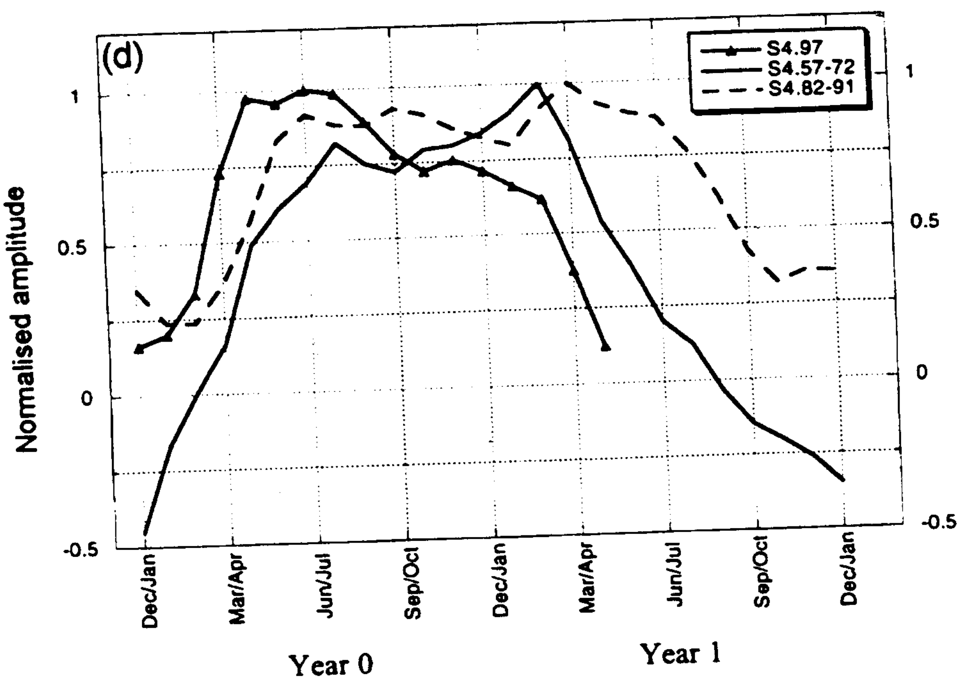


Fig. 2 *Continued.*

lack of recent La Niña events leaves El Niño onsets ill-defined, but the remaining onset and mature phases look similar for both periods, followed by a tendency towards earlier declines in the pre-1976 events (Fig. 2(d)). Note that the S4 composites for the early and recent El Niño events are less representative of individual cases than the composites of other ENSO indices. The early peak of S4 in the 1997/98 El Niño and its subsequent relative decline match the individual events of 1972/73 and 1982/83 better than the composite behaviour of early and recent events.

The El Niño events of 1982/83 and 1997/98

By any measure, the 1982/83 and 1997/98 El Niño events are in a league of their own, probably going back to 1877/78 (Kiladis and

Table 2 Bimonthly comparison of 1982/83 and 1997/98 for various ENSO indicators, starting with the first season that any of them ranks highest for the season in Year 0 (May/June), and ending 12 seasons later in Year 1 (April/May). If the highest value for the season (since 1950) does not occur in these two events, the table entry is underlined. If the standardised departure of the leading value exceeds 2 standard deviations above the mean, it is flagged with an asterisk. Summary statistics at the end of this table include a count of the front-runner seasons, the peak standardised values for each ENSO indicator, and an overall 'winner' for each ENSO measure (in **bold** letters if by both criteria).

Season	MEI	P	U	V	S	A	C	SOI	S12	S3	S4
Year 0											
May/June	1997*	1997	1997	1997	1997*	1997	1997	1997*	1997*	1997*	1982*
June/July	1997*	1997*	1982*	1997*	1997*	1997*	1982	1982	1997*	1997*	1982*
July/Aug.	1997*	1997*	1982*	1997*	1997*	1997*	1982	1982*	1997*	1997*	1997
Aug./Sept.	1997*	1997*	1982*	1997*	1997*	1997*	1997	1982*	1997*	1997*	1997
Sept./Oct.	1997*	1997*	1982*	1997*	1997*	1997*	1997	1982*	1997*	1997*	1982
Oct./Nov.	1982*	1997*	1982*	1982*	1997*	1997*	1982*	1982*	1997*	1997*	1982
Nov./Dec.	1982*	1982*	1982*	1982*	1997*	1997*	1982*	1982*	1997*	1997*	1997
Year 1											
Dec./Jan.	1983*	1983*	1983*	1983*	1998*	1998*	1983*	1983*	1998*	1998*	1998
Jan./Feb.	1983*	1983*	1983*	1998*	1983*	1983*	1998*	1983*	1998*	1983*	1998
Feb./Mar.	1983*	1983*	1983*	1983*	1998*	1983*	1983*	1983*	1998*	1983*	1983
Mar./Apr.	1983*	1983*	1983*	1983*	1983*	1983*	1998*	1998*	1998*	1983*	1983
Apr./May	1983*	1983*	1983	1998*	1983*	1983*	1983	1998	1983*	1983*	1983
Total number of occurrences											
1982/83	7	6	11	5	3	4	7	9	1	4	7
1997/98	5	6	1	7	9	8	5	3	11	8	5
Peak 1982+	3.2	3.6	3.5	3.5	2.8	2.9	3.2	3.3	4.0	3.6	2.1
Peak 1997+	2.9	3.0	2.3	3.6	3.1	2.9	2.9	2.6	4.8	3.7	1.8
'Winner'	**1982+**	1982+	**1982+**	**1997+**	**1997+**	1997+	**1982+**	**1982+**	**1997+**	**1997+**	**1982+**

Diaz 1986). In the following, let us compare the time-series of key regions and variables of the MEI (and of conventional ENSO indices) for both El Niño events. Table 2 summarises these direct comparisons from May/June of Year 0 to April/May of Year 1, while Fig. 3 documents the time-series of MEI components for both years.

As recorded in the MEI (Fig. 3(a)), the most recent El Niño event commenced around March 1997, rose rapidly above 2σ (two standard deviations above the mean), and continued above 2σ from May/June 1997 to April/May 1998 – the longest such run on record. Although unprecedented in its growth and early size, the initial sequence fits the onset and early mature phase of the early El Niño events very well (see Fig. 2(a)). However, after its first peak around August 1997, the MEI dropped below 1982/83 levels from October/November 1997 onwards (Fig. 3(a)), staying in a close second place through early 1998 despite a secondary peak in February/March 1998. Overall, the MEI features both the most front-runner seasons and the highest seasonal value during the 1982/83 event, but the lead ahead of 1997/98 is small (see Table 2).

Since the Southern Oscillation is the most important atmospheric component of the ENSO phenomenon, it is not surprising that P tracks the MEI very well (correlating at 0.94 for all seasons). However, the two onset phases in P resemble each other more than in the overall MEI. On the other hand, the early peak in July/August 1997 is followed by only a minor secondary rally into 1998, while the 1982/83 peak in March/April 1983 is distinctly higher than Year 0 values (Fig. 3(b)). The highest individual value occurred in 1982/83, while the number of front-runner seasons is identical for both events (Table 2). By comparison, the SOI would clearly favour 1982/83 (Table 2), highlighting differences between P and SOI not further explored here.

Key components of El Niño behaviour in the surface wind field are westerly anomalies near the date line and the equator in U (Fig. 3(c), correlating at 0.83 with the MEI), and a southward shift in the intertropical convergence zone, along with an eastward shift in the South Pacific convergence zone, as captured in V (Fig. 3(d), correlating at 0.90 with the MEI). The onset of El Niño conditions in late boreal spring of 1982 was rapid and well matched between U and V (compare Fig. 3(c) with 3(d)), followed by slower growth into the mature phase until early 1983, still reasonably similar in both fields. However, decline phases in mid-1983 were quite dissimilar, with a secondary peak in V around July (Fig. 3(d)). By comparison, the evolution of the 1997/98 event is divergent for U and V from June 1997 onwards, with U breaking the 2σ barrier only once in early 1998, far behind its counterpart in 1982/83 (Fig. 3(c)), while V reaches historic proportions already in June/July 1997 and again in early 1998 when 1983 and 1998 values run neck and neck for three months in a row (Fig. 3(d)). Therefore, 1982/83 remains the largest El Niño event in both duration and peak values of U, while 1997/98 comes out ahead for V (Table 2).

At the most basic level, El Niño events can be understood as long-lasting positive sea surface temperature anomalies in the eastern tropical Pacific, and were indeed named in this fashion long before the atmospheric portion of this coupled phenomenon was recognised (*e.g.* Philander 1990). The S core region correlates better (at 0.96) with the overall MEI time-series than any other component. The 1997/98 time-series for S (Fig. 3(e)) documents its breathtaking increase from negative values in early 1997 to above 2σ by April/May 1997. After its peak in August/September 1997, it has become more comparable with 1982/83 levels (especially in early 1998), but retains an advantage over the older El Niño both in length of frontrunner status and highest values (Table 2). Among conventional sea surface temperature-based ENSO indices, S12 and S3 feature clear leads of 1997/98 over 1982/83, while S4 favours 1982/83 over 1997/98 but usually denies either event the leading position since 1950 (see Table 2). The evolution of the main air temperature (A) signal in both El Niño events is very similar to S (not included in Fig. 3, correlating at 0.95), more so than during weaker El Niño events.

Enhanced cloudiness over the central equatorial Pacific is the weakest supporting link of the MEI (correlating at 0.76), perhaps due to its qualitative nature (cloudiness is the only variable still exclusively estimated by eye), and relatively low spatial coherence (Wolter 1987). The onset phase of both El Niño events displays rather erratic behaviour in C, but both 1982/83 and 1997/98 feature a massive increase late in Year 0, followed by almost identical amplitudes through March/April of Year 1 (Fig. 3(f)). Both in duration and peak values of C, 1982/83 appears slightly stronger than 1997/98 (Table 2), but only the peak sequence from late Year 0 through early Year 1 is not overshadowed by other events.

Discussion

Determining the strength of ENSO events is not just an academic exercise. Given their worldwide impacts, it is of crucial importance to ascertain the magnitude of El Niño events in particular, given the recent dearth of La Niña events. Even if the global climate response is somewhat nonlinear, it is not unreasonable to expect the largest responses to the largest ENSO anomalies. Furthermore, we have now witnessed two so-called '100-year' events within 16 years of each other. Is this linked to global warming (if only through their impact on global temperatures)? In this context, we need to ascertain the strength of ENSO events just as we need to know the surface temperature of our planet.

The ranking of the current El Niño is dependent not only on the measure used, but also on the definition of rank – is it the highest value that counts, or is it the longest stretch on top? How about the longest duration above a certain threshold, say 2σ? For the MEI, the first two criteria keep 1982/83 ahead, while the record-breaking duration above 2σ in 1997/98 is three months longer than in 1982/83. In terms of MEI components, meridional wind and temperatures favour 1997/98, while sea-level pressure, zonal wind, and cloudiness favour 1982/83. In conventional ENSO indices, the SOI and S4 render 1982/83 as the strongest El Niño, while S12 and S3 keep 1997/98 on top. This is a confusing picture. At least we are certain that no other El Niño comes even close

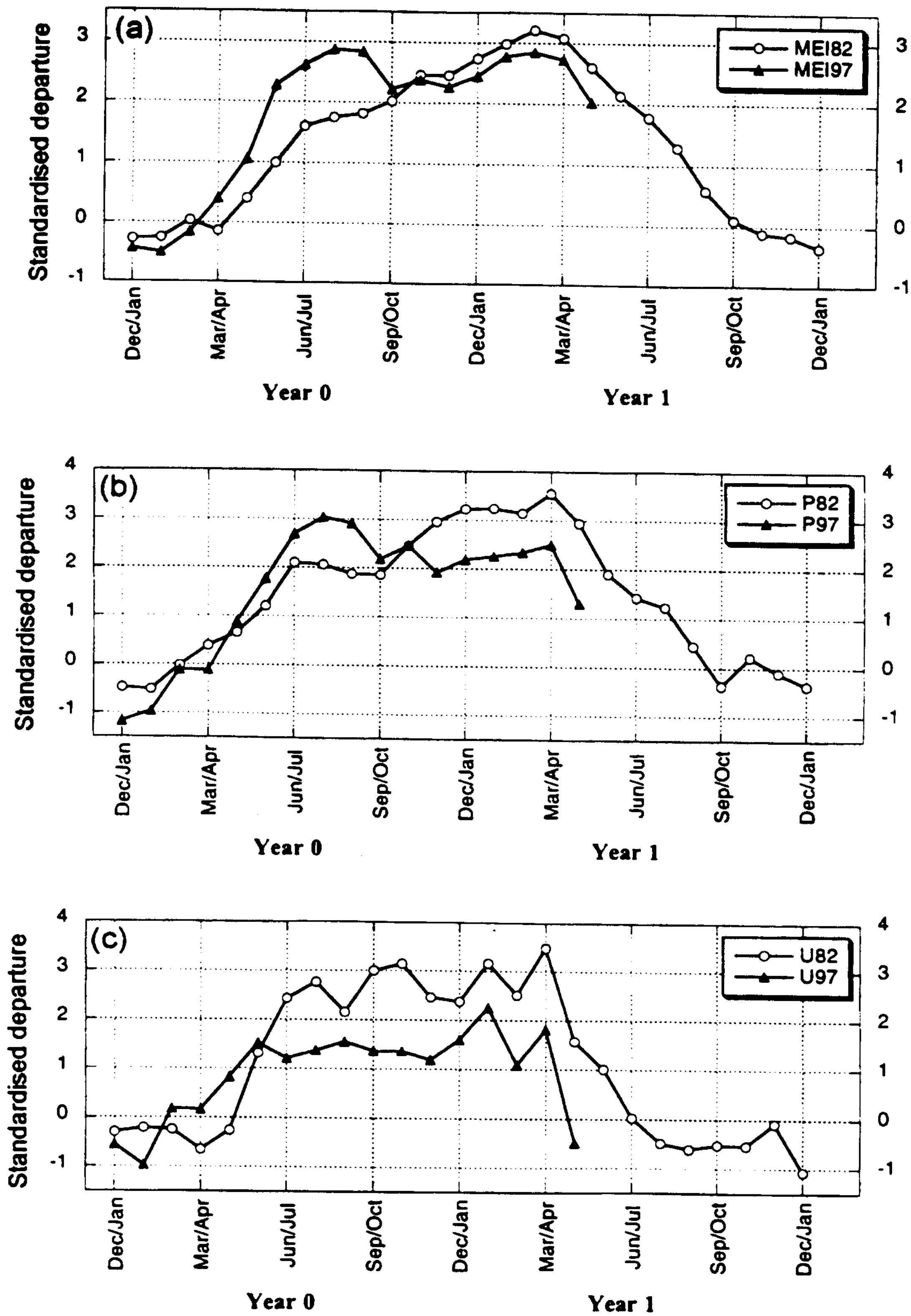


Fig. 3 Comparison plots of the 1982/83 and 1997/98 El Niño events for the MEI(a) and its key regions/differences: P(b), U(c), V(d), S(e) and C(f). Shown are bimonthly sliding time-series for the available record, in open circles for the earlier event and in solid triangles for the most recent event. Standardisation was performed on each season and the common base period of 1950–93. Vertical axes denote the value in units of standard deviations from the mean.

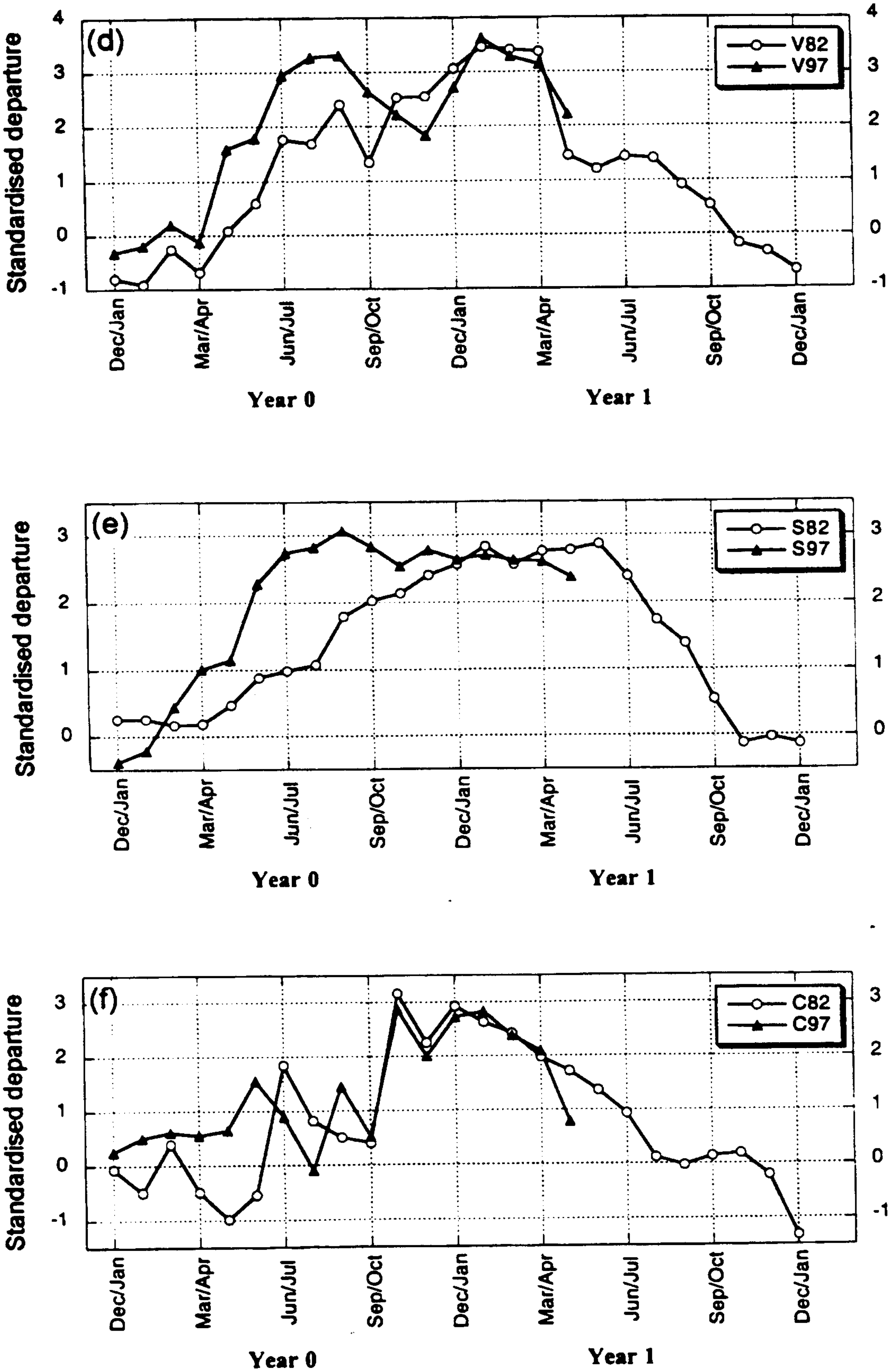


Fig. 3 Continued.

to either event since 1950. If the recent decline of the 1997/98 event continues into boreal summer, most temperature-based ENSO indices will end up favouring 1982/83 over 1997/98, since the former event lasted throughout the summer of 1983. Therefore, the overall verdict should be more definitely in favour of 1982/83 by late 1998.

For the first time in more than two decades, we have witnessed an El Niño with Year 0 coastal warming and a rapid onset. In many aspects, the 1997/98 event has matched the prototypical ENSO sequence described in Rasmusson and Carpenter (1982). In a parallel analysis, we are exploring the impact of ENSO on world-wide seasonal temperatures and precipitation, and comparing the MEI further against the most commonly used ENSO indices: SOI and Niño3. We update the MEI and post related information on all MEI research projects at http://www.cdc.noaa.gov/~kew/MEI/.

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The rôle of El Niño in Atlantic tropical cyclone activity

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The tropical cyclone is one of the most spectacular and destructive weather systems on our planet. It can cause considerable loss of life and billions of dollars of damage to property and infrastructure (Legett 1993). Understandably, there is a lot of interest in furthering our understanding of these systems and in particular what determines the year-to-year variation in their number and intensity. Knowledge of this will have implications for seasonal forecasting of Atlantic tropical cyclone activity (Gray 1984b).