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Weakening of the Walker Circulation and apparent dominance of El Niño both reach record levels, but has ENSO really changed?

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[1] Changes in El Niño-Southern Oscillation (ENSO) and the Walker Circulation can be routinely monitored using the Southern Oscillation Index (SOI). Here we show that the lowest 30-year average value of the June–December SOI just occurred (i.e. in 1977–2006), and that this coincided with the highest recorded value in mean sea-level pressure at Darwin, the weakest equatorial surface wind-stresses and the highest tropical sea-surface temperatures on record. We also document what appears to be a concurrent period of unprecedented El Niño dominance. However, our results, together with results from climate models forced with increasing greenhouse gas levels, suggest that the recent apparent dominance might instead reflect a shift to a lower mean SOI value. It seems that global warming now needs to be taken into account in both the formulation of ENSO indices and in the evaluation and exploitation of statistical links between ENSO and climate variability over the globe. This could very well lead to the development of more accurate seasonal-to-interannual climate forecasts. **Citation:** Power, S. B., and I. N. Smith (2007), Weakening of the Walker Circulation and apparent dominance of El Niño both reach record levels, but has ENSO really changed?, *Geophys. Res. Lett.*, *34*, L18702, doi:10.1029/2007GL030854.

1. Introduction

[2] The Walker Circulation is one of the world's most prominent and important atmospheric systems and is closely linked to the mean-state of the equatorial Pacific Ocean. It extends across the entire tropical Pacific Ocean, encompassing (1) the trade winds blowing from east to west, (2) air forced to rise over the western Pacific, south-east Asia and northern Australia through enhanced convection, (3) winds blowing counter to the trades aloft, and (4) air descending over the eastern Pacific Ocean [see e.g., *Gill*, 1982]. Changes in the Walker Circulation are linked to the El Niño-Southern Oscillation (ENSO), which drives major changes in rainfall [*Ropelewski and Halpert*, 1989; *Allan et al.*, 1996; *Power et al.*, 1999], river flow [*Kahya and Dracup*, 1993; *Merendo*, 1995; *Power et al.*, 1999], agricultural production [*Phillips et al.*, 1998; *Hammer et al.*, 2000; *Power et al.*, 1999], ecosystems [*Holmgren et al.*, 2001] and disease [*Nicholls*, 1993; *Bouma and Dye*, 1997] in many parts of the world.

[3] ENSO can be regarded as an irregular vacillation between two opposite phases: El Niño and La Niña. Threats associated with ENSO (e.g., drought in India) [*Allan et al.*, 1996] tend to increase or decrease depending on whether the event is an El Niño or a La Niña. The Walker Circulation weakens during El Niño years and strengthens during La Niña years [e.g., *Philander*, 1990].

[4] *Trenberth and Hoar* [1996] (hereinafter referred to as TH96) drew attention to anomalously protracted El Niño conditions over the period 1990 to 1995 and suggested that these were unusual in a historical context. This was subsequently challenged by *Harrison and Larkin* [1997] who claimed that, while unusual, (the then) recent conditions could plausibly be the result of natural variability. *Rajagopalan et al.* [1997] also argued that the event was not as rare as first thought. *Trenberth and Hoar* [1997] responded to these studies by reanalyzing Darwin monthly mean sea level pressure (MSLP) data up to early 1997 and maintained that recent ENSO behavior was "very unusual." Nevertheless *Wunsch* [1999] subsequently disagreed with the TH96 conclusion and *Solow and Huppert* [2003], in their study of changes in both NINO3 sea surface temperature anomalies and Darwin MSLP up to 2002 concluded that the changes were "…not inconsistent with overall stationarity."

[5] A weakening trend in the Walker Circulation during the 20th century and the early 21st century [*Tanaka et al.*, 2004; *Vecchi et al.*, 2006] and an apparent increase in the influence of El Niño towards the end of the 20th century [*Folland et al.*, 2001] have also been noted. *Fedorov and Philander* [2000] discussed the possibility that this apparent increase was linked to global warming.

[6] Here we will re-examine these issues using more recent data, and will show that the changes have persisted and have in fact reached record levels in 1977–2006. We will also show, however, that the changes are strongly interlinked and care is needed in their interpretation. We will provide a new, simple plausible interpretation that is consistent with both the observed changes and results from climate models forced with increasing greenhouse gas levels.

2. Results

2.1. Changes to the Mean Climate

[7] Changes in ENSO and the Walker Circulation are routinely monitored using the Southern Oscillation Index (SOI). The SOI is a measure of the difference in air pressure between Tahiti in the eastern Pacific and Darwin in northern Australia to the west of the Pacific Ocean.

[8] The average value of the SOI in each month before, during and after the June–December SOI > +5 is shown in

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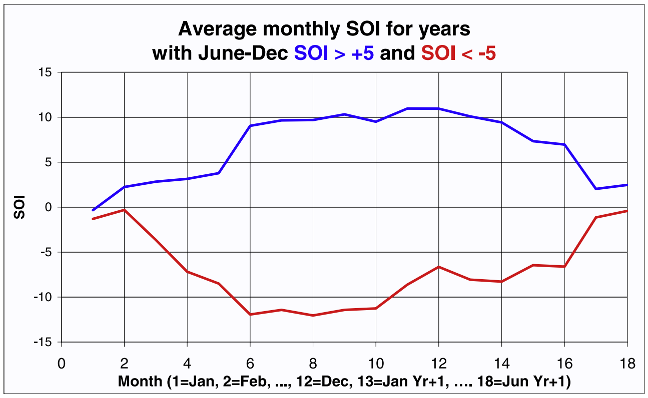

Figure 1. Average value of the SOI in each month in years during and after the June–December SOI exceeds +5 (blue) and drops below −5 (red).

Figure 1. The monthly SOI tends to exceed a value of 8 between June, and February in the following calendar year. Maximum values tend to occur in November and December. The average value of the SOI in each month before, during and after years in which the June–December SOI < −5 is shown in Figure 1. The SOI tends to drop below −6 from April through to April in the following year. The largest drops tend to occur between June and September. Thus in Figure 1 the largest excursions from zero occur between June and December. The average value of the SOI over the period June–December is therefore a useful indicator of change.

[9] A time series of the June–December SOI is depicted in Figure 2. The average over the period 1876–1976 is −0.1, whereas the average for 1977–2006 is −3.0. A t-test for the difference between these two values (i.e. a test which takes year-to-year variability and the magnitude of the change into account - c.f. *Trenberth and Hoar* [1996]) indicates that the recent 30-year (1977–2006) average is both the lowest 30-year value on record and is unusually low (significant at the 95% level). This corresponds to a record (30-year) high value for mean sea-level pressure (MSLP) at Darwin during 1977–2006 (also shown in Figure 2) and a (non-record) low value at Tahiti. This is reassuring because it has been suggested that the Tahitian record may be less reliable than the Darwin record before 1935 and Darwin MSLP alone is sometimes used as an index for ENSO variability [*Trenberth and Hoar*, 1997, and references therein]. 1976/1977 also appears as a breakpoint with the 1977–2006 period characterized by a mean value close to +0.4 hPa higher than the 1876–1976 value (the difference is significant at the 99% level).

[10] The time series for June to December average NINO4 values (1871–2006) is also shown in Figure 2 and 1976/1977 again stands out as a clear breakpoint, with values 0.4°C higher over the subsequent 30 years than previously (significant above 99.9% level). In this case recent changes in the NINO4 index exhibit a more gradual increase, rather than step-like, over time. The equivalent time series for NINO3 values (not shown) is characterized by a breakpoint in 1975/76 (significant at 93% level).

[11] Since the SOI is an indicator of pressure difference and pressure difference is a major driver of equatorial winds, the changes strongly suggest that the equatorial winds should have weakened. Figure 2 also includes two time series of June to December average surface wind stresses across the equatorial Pacific region (149°E to 271°E, 5.3°S to 5.3°N) from two analyses – ERA40 [*Gibson et al.*, 1997] and NCEP [*Kalnay et al.*, 1996]. Both time series show a weakening as anticipated. In the case of the ERA values over the period 1958 to 2001, a breakpoint occurs at 1975/76 where the average over 1976–2001 is −.034 compared to −0.040 over the period 1958 to 1975. This represents a 15% weakening of the easterly surface wind stresses (significant above 95% level). The values based on NCEP analyses over the longer period 1948 to 2006 also have a breakpoint at 1975/76 but with a highly significant reduction in strength of close to −30% (−0.037 to −0.25). The lowest 30-year value of the NCEP easterly wind-stress on record occurred during 1977–2006. *Wu and Xie* [2003] suggest that there may be an artificial trend in the NCEP wind stresses over the eastern equatorial Pacific but the data set they use for comparison (corrected COADS winds) also shows an overall increase in the equatorial average westerly wind component after 1977.

2.2. Apparent Changes to ENSO Variability

[12] There is no universally accepted criterion to classify El Niño or La Niña years. Here we use the following simple, objective classification: an El Niño event is defined as a year in which the June–December SOI is less than −5, and a La Niña event as a year in which the June–December SOI exceeds +5. This gives a total of 35 El Niño events, 36 La Niña events, and 60 neutral years over the period 1876–2006. In the 21st century (i.e., from 2001 onwards) there have been 3 El Niño years (in 2002, 2004 and 2006),

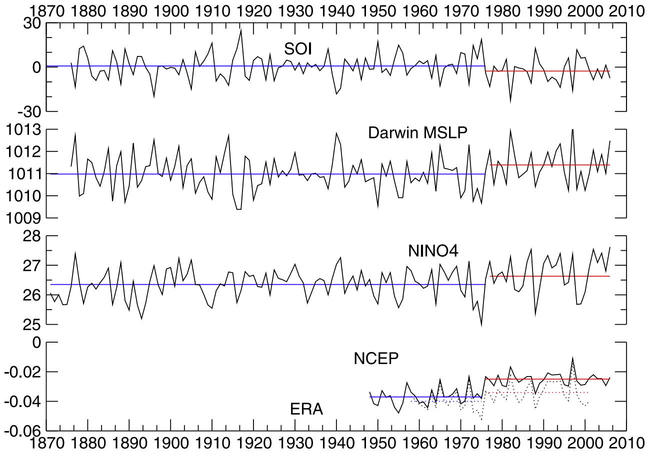

Figure 2. June to December averages. From top to bottom: SOI (1876–2006), Darwin MSLP (1876–2006), NINO4 (1871–2006), and equatorial Pacific (149°E to 271°E, 5.3°S to 5.3°N) surface wind stress from ERA (1958–2001) and NCEP analyses (1948–2006). The SOI represents the standardised anomaly of MSLP difference [*Troup*, 1965] between Tahiti and Darwin: SOI = 10[ΔP − ΔPave]/SD(ΔP), where ΔP = (average Tahiti MSLP for the month) - (average Darwin MSLP for the month), ΔPave = long-term average of ΔP for the month in question, and SD(ΔP) = long-term standard deviation of ΔP for the month in question.

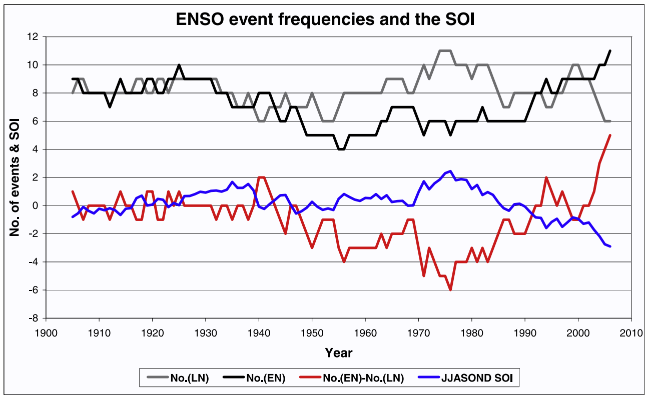

Figure 3. Thirty year running averages of various indices relating to El Niño-Southern Oscillation (ENSO). From top to bottom: the number of La Niña events in all 30 year periods from 1876–1905 through to 1977–2006 (N(LN), grey), the number of El Niño events in each 30-year period (N(EN), black), the difference Δ = N(EN) − N(LN) (red), and the 30-year running average of the June–December Southern Oscillation Index (SOI, blue).

3 neutral years and no La Niña years. The SOI was negative in five of the six 21st century years.

[13] The number of El Niño and La Niña events in each 30 year block is an important statistic because it can play a major role in determining climatic conditions and risks in ENSO-affected regions. Our interest here is in long-term change, and so 30-year average values are shown in Figure 3. Thirty years is the minimum period recommended by the World Meteorological Organisation (WMO) to calculate climatological averages [*World Meteorological Organization*, 1983]. The proportion of El Niño events was the highest on record (11) in the most recent 30-year period, while the proportion of La Niña events was low (6). The difference between these two values, Δ, is also shown. Variability in Δ tends to be out-of-phase with the 30-year running average of the SOI (correlation coefficient is −0.8).

[14] The largest value of Δ (5) occurred in 1977–2006. If ENSO events are defined in terms of Darwin MSLP instead of the SOI the conclusions remain the same, i.e., the frequency of El Niño events and Δ reach their maximum values in the most recent 30-year block. This result is not sensitive to the choice of SOI threshold used in the definition of ENSO events (i.e., ±5) – provided the threshold has the same magnitude for both El Niño and La Niña events - because Δ attains a maximum value during 1977–2006 for SOI threshold values ranging from ±2 to ±8.

[15] While the recent values of Δ and the frequency of El Niño events are records, the corresponding values are within the bounds of what could be expected by random variation alone. For example, Δ was equal to −6 earlier in the century, during a period that was more heavily dominated by La Niña than the most recent 30-year period was dominated by El Niño. The recent changes in Δ and the frequency of El Niño could therefore represent natural fluctuations in the climate system. Indeed natural variability alone can drive substantial interdecadal variability in ENSO and ENSO impacts in climate models [*Power et al.*, 2006].

[16] The changes are, nevertheless, interesting – if ENSO events are defined in terms of exceeding SOI thresholds (e.g., ±5), then the dominance of El Niño appeared to reach an unprecedented level in 1977–2006. However, if we assume that the mean-state of the climate system has changed and the 1977–2006 value of the SOI value has become a better reference value for defining ENSO events, then the threshold for an El Niño event has become −8 and the new threshold for La Niña events is +2. This then gives 8 "El Niño" years (1977, 1982, 1987, 1991, 1993–94, 1997 and 2002) and 7 "La Niña" years (1981, 1988–89, 1996, and 1998–2000) during 1977–2006. So the apparent dominance of El Niño might instead reflect a decline in the long-term average value of the SOI.

3. Discussion and Conclusions

[17] The SOI, Darwin MSLP, NINO3, and the equatorial zonal wind-stress all reached record values in 1977–2006. Statistical tests show that the recent values are unlikely to have come from the same "population" as the earlier values. The Walker Circulation tends to weaken in climate models forced with increasing greenhouse gases [*Tanaka et al.*, 2004; *Vecchi et al.*, 2006; *Meehl et al.*, 2007]. As global warming has accelerated in recent decades [*Alley et al.*, 2007] its effects could reasonably be expected to be most clearly evident in the most recent decades.

[18] On the other hand, there is currently no consensus amongst climate models concerning change in the behaviour of ENSO in response to global warming [*Cane*, 2005; *Collins et al.*, 2005; *Guilyardi*, 2006; *Nyenzi and Lefale*, 2006; *Philip and van Oldenborgh*, 2006; *van Oldenborgh et al.*, 2005; *Zelle et al.*, 2005; *Meehl et al.*, 2007]. Yet if ENSO events are defined as years in which the magnitude of the June–December SOI exceeds 5 then El Niño events appear to have been more dominant in 1977–2006 than in any other 30 year period on record.

[19] However, if global warming is largely responsible for the observed decline in the average value of the SOI over the period 1977–2006 then the threshold values used to define ENSO events need to be lowered (by approximately 3 SOI units). Under the new thresholds the apparent dominance of El Niño disappears. This simple interpretation gives a result that is consistent with modelling results: global warming weakens the Walker Circulation and warms the tropical Pacific Ocean, but has little impact on tropical ENSO-driven variability about the new mean-state [*Meehl et al.*, 2007]. While plausible, further research is needed to help quantify the extent to which global warming has in fact driven the unprecedented recent decline in the 30-year average value of the SOI.

[20] Global warming has very likely driven changes in mean rainfall, temperature, stream-flow and other important climatic variables [*Hegerl et al.*, 2007; *Alley et al.*, 2007; *Meehl et al.*, 2007] in many countries. ENSO events are responsible for some of the variability about these means in some locations, so climatic conditions experienced during ENSO events have very likely changed. Consequently, past experiences of ENSO impacts, and past inter-relationships underpinning statistical forecast systems, have probably become less accurate guides to the future. Taking these changes into account has the potential to increase the accuracy of seasonal-to-interannual climate forecasts.

[21] **Acknowledgments.** The SOI was made available by the Australian National Climate Centre. The Tahiti data originates from Meteo-France, the Darwin data from the Northern Territory Office of the Australian Bureau of Meteorology. The wind-stress data were obtained from G.J. van Oldenborgh via the KNMI web-site (http://climexp.knmi.nl). One of the wind-stress data-sets originates from the European Centre for Medium Range Prediction, the other from both the National Centers for Environmental Prediction and Atmospheric Research (NCEP/NCAR) in the U.S. The NINO sea-surface temperature indices were obtained from NOAA. We also wish to thank Penny Whetton for useful discussions, and anonymous reviewers for helpful comments. This research was partially supported by the Australian Climate Change Science Program, which is administered by the Australian Greenhouse Office.

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