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ENSO, volcanoes and record-breaking temperatures

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Abstract. Monthly-mean, near-surface temperatures are examined for records and trends after accounting for the influences of ENSO and the volcanic eruptions of Agung, El Chichón and Pinatubo. Of the 16 consecutive record-breaking months in 1997-98, at least six can be attributed to ENSO-associated warmth. The period is still unusual, but no more unusual than 1990-91 when an equal number of records occurred in the ENSO-adjusted data. The warming trend over the past two decades is also shown to be unusual, but is found (in the raw data) to be not significantly different from the warming trend of the 1910s–1930s. When ENSO and volcanic effects are removed, however, the recent warming trend increases (to 0.25°C/decade) and becomes highly significant compared to the earlier period.

Introduction

A recent paper by Karl et al. (1999) notes that, over the period May 1997 through August 1998 (16 months), each month broke the record as the warmest-ever value for that month in the Quayle et al. (1999) global-mean temperature time series. By analyzing the time series of monthly values from January 1880 through December 1998 as a set of four linear sections with Autoregressive Moving Average (ARMA) residuals, they show that the warmth of May 1997 through August 1998 is a statistically significant "event", possibly representing a change in the underlying low-frequency warming trend. This interval, however, coincided with a strong warm event in the El Niño/Southern Oscillation (ENSO). Since ENSO fluctuations are reflected in the global-mean temperature record, explaining some 30% of the high-frequency component in these data (Jones, 1989), it seems likely that the record-breaking sequence is at least partly a result of ENSO — indeed, this possibility has been noted by Karl (quoted by Stevens, 1999, p. 167). The main purpose of this paper is to quantify the ENSO influence.

Karl et al. do not ignore the possibility that ENSO is a factor, since they note that ARMA models "are capable of resolving...El Niño like oscillations". However, while an ARMA model can simulate the statistics of ENSO-like variability, it will not simulate the specific realization that actually occurred. It is only by accounting for this specific realization that one can determine how important ENSO was in explaining the sequence of record-breaking temperatures.

Factoring out ENSO

The most obvious way to assess the ENSO component in global-mean temperatures (T) is to regress the temperature data on an appropriate ENSO index (E):

$$\hat{T} = a + bE \qquad (1)$$

where the regression coefficient (b) may be referred to as the "ENSO sensitivity" and $\hat{T}$ is that part of the raw temperature record attributable to ENSO variability. Jones (1989, 1994a) used the Southern Oscillation Index (SOI) as an ENSO indicator (specifically, the record of Können et al., 1998). Christy and McNider (1994) used sea surface temperatures (SSTs) from the Pacific Niño3 and Niño4 regions. Here I will consider the SOI and Niño3.4 (5N–5S, 120–170W) SSTs as alternative ENSO indices.

One of the problems with relating global-scale temperatures to ENSO is that the relationship is not stable in time (Fig. 1): ENSO sensitivity was apparently much lower during and around the 1930s than either before or after. (Changes in ENSO-related teleconnections at this time are well known and have been documented, for example, by Trenberth, 1976, and reviewed by Allan et al., 1996.) There have also been marked changes in ENSO sensitivity in recent decades. The reasons for these changes are not entirely clear. The 1930s sensitivity breakdown was at least partly related to the general weakness of ENSO events at this time as defined

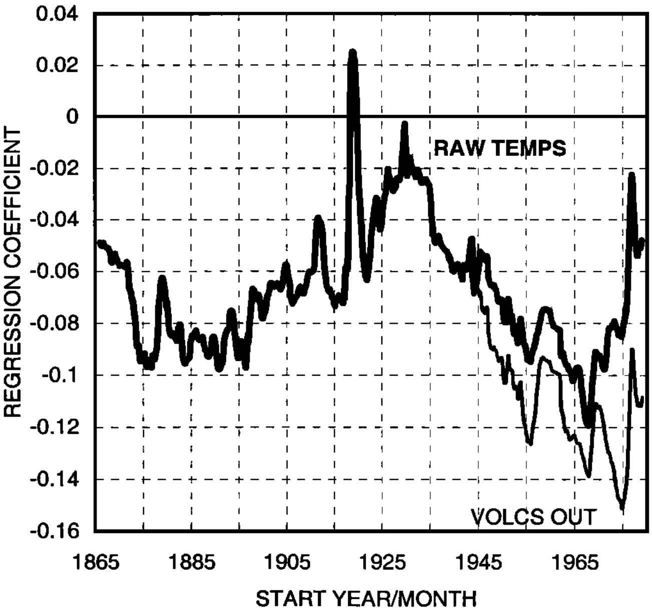

Figure 1. Running, maximally-overlapping 252-month regression coefficients (°C per SOI unit as defined by Können et al., 1998) between global-mean temperatures and the SOI, with SOI leading temperature by 7 months. Abscissa tick marks are on the Jan. of the year. Lower curve beginning in Jan. 1942 shows results when the effects of the eruptions of Agung, El Chichón and Pinatubo have been removed from the temperature data.

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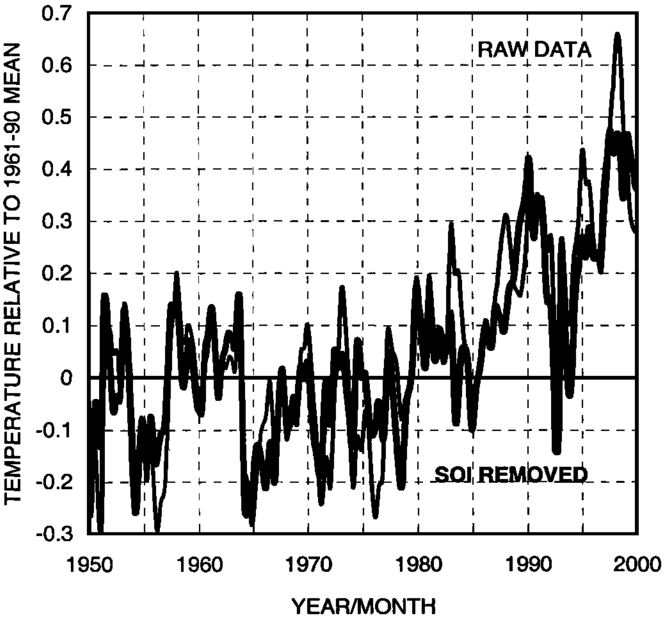

Figure 2. Raw (thin curve) and SOI-subtracted (thick curve) temperatures. The data have been smoothed with a low-pass (9-term, 12-month) Gaussian filter, with results plotted on the central year of the filter. Abscissa notation as in Fig. 1.

by the standard deviation of the SOI series or, almost equivalently, by the correlation between Tahiti and Darwin mean-sea-level pressures (Trenberth, 1976, 1984). This is not a causal explanation, however; all three items are presumably manifestations of some more fundamental change in the climate system that apparently occurred at this time. The more recent sensitivity breakdown, however, appears to be, at least in part, different: it is due largely to the obfuscating effects of the eruptions of El Chichón and Pinatubo (Wigley and Santer, 2000). For both eruptions, ENSO warm events occurred at almost the same time as the volcanic coolings, and these coolings obscure the ENSO influence. At the same time, the ENSO-related warmth obscured the volcanic coolings, especially in the case of El Chichón. Figure 1 shows that removing the volcanic effects (as described below) increases the ENSO sensitivity and makes it more stable over the past 40 years or so.

For the present analysis, sensitivity variations prior to the 1950s are not important, since our primary interest is in the most recent spate of record-setting temperatures. Calibration of the sensitivity is therefore performed only over the most recent 21 years of the data record (Jan. 1979–Dec. 1999), as in Wigley and Santer (2000); corresponding to the last "VOLCS OUT" point in Fig. 1.

Removing the volcano influences requires iteration, since these influences themselves are uncertain. The procedure is described further in Wigley and Santer (2000). First, a trial volcanic-influence time series (V(t)) is subtracted from the data (to give $X = T - V$). Second, X is regressed against an ENSO index, E, where E is appropriately low-pass filtered (Trenberth, 1984; Wigley and Santer, 2000); $\hat{X} = \alpha + \beta E$. Lagged values of E are used, with the lag chosen to optimize the X,E correlation, usually with E leading X by 6 or 7 months; cf Jones (1989). The ENSO sensitivity (β) is then used to adjust the original temperatures (step 3; $Y = T - \beta E$ with E appropriately lagged). Then (step 4), the apparent volcanic signals in the residuals Y are compared with the originally-assumed signals. If they agree, the iteration ceases. If not, V(t) is modified based on Y, and the process is repeated until stable volcanic signal and ENSO sensitivity results are obtained. Sensitivities based on the full 252-month period are: using SOI as the ENSO index, −0.109°C/index unit; using Niño3.4 SSTs, 0.130°C/°C.

Records in ENSO-subtracted temperatures

The temperature data used here (and above) are the data used by the Intergovernmental Panel on Climate Change (IPCC), updated, as described in Jones et al. (1999) and based on the work of Jones (1994b) and Parker et al. (1994). At the

Table 1. Year and month in which a new high temperature record for that particular month was set. Temperatures are anomalies relative to 1961–90 means (°C). Three decimals are given to facilitate ranking only; this does not reflect the accuracy of the data.

Raw data		SOI removed		Niño3.4 removed	
Yr(mo)	**Temp**	**Yr(mo)**	**Temp**	**Yr(mo)**	**Temp**
1953(4)	0.224	1953(4)	0.215	1989(2)	0.350
1957(11)	0.134	1987(2)	0.338	1989(3)	0.379
1963(11)	0.167	1989(3)	0.333	1989(4)	0.336
1973(3)	0.202	1989(4)	0.282	1989(5)	0.344
1979(12)	0.393	1989(5)	0.274	1989(6)	0.358
1980(11)	0.192	1989(6)	0.272	1989(7)	0.459
1981(3)	0.231	1989(7)	0.366	1989(8)	0.430
1983(2)	0.398	1989(8)	0.345	1989(11)	0.271
1983(3)	0.281	1989(11)	0.273	1990(2)	0.431
1983(11)	0.285	1990(2)	0.439	1990(3)	0.629
1987(7)	0.298	1990(3)	0.624	1990(4)	0.415
1988(3)	0.305	1990(4)	0.400	1990(11)	0.374
1988(4)	0.321	1990(6)	0.305	1994(11)	0.381
1988(5)	0.269	1990(11)	0.400	1995(2)	0.553
1988(6)	0.278	1991(6)	0.356	1996(5)	0.345
1990(3)	0.582	1995(2)	0.459	1997(5)	0.346
1990(4)	0.380	1995(8)	0.355	1997(6)	0.485
1990(5)	0.273	1997(5)	0.362	1997(7)	0.499
1990(6)	0.329	1997(6)	0.488	1997(8)	0.515
1990(10)	0.412	1997(7)	0.495	1997(9)	0.533
1990(11)	0.420	1997(8)	0.505	1997(10)	0.551
1991(4)	0.421	1997(9)	0.509	1997(11)	0.392
1991(5)	0.313	1997(10)	0.513	1997(12)	0.416
1991(6)	0.394	1998(2)	0.644	1998(2)	0.613
1991(7)	0.360	1998(4)	0.504	1998(12)	0.430
1994(11)	0.438	1998(5)	0.434		
1995(1)	0.501	1998(7)	0.520		
1995(2)	0.641	1998(12)	0.431		
1995(7)	0.398	1999(2)	0.713		
1995(8)	0.440	1999(12)	0.471		
1997(5)	0.318	1999(2)	0.693		
1997(6)	0.451	1999(4)	0.477		
1997(7)	0.465	1999(5)	0.406		
1997(8)	0.493	1999(12)	0.504		
1997(9)	0.536				
1997(10)	0.592				
1997(11)	0.481				
1997(12)	0.557				
1998(1)	0.530				
1998(2)	0.852				
1998(3)	0.600				
1998(4)	0.691				
1998(5)	0.613				
1998(6)	0.634				
1998(7)	0.719				
1998(8)	0.695				

Table 2. Number of record-breaking months for different intervals.

Start mo.	1/50	1/89	5/90	9/91	1/96	5/97	9/98
End mo.	12/88	4/90	8/91	12/95	4/97	8/98	1/00
Length (mos)	468	16	16	52	16	16	16
Raw data	15	2	8	5	—	16	—
SOI removed	3	10	3	2	—	10	3
Niño3.4 removed	1	11	1	2	1	9	5

monthly timescale, these data show only small differences from the Quayle et al. (1999) data set.

Figure 2 shows the raw and ENSO-subtracted temperatures for the case where the SOI is used as the ENSO index (for 1950 onwards; earlier results may be obtained from the author). The same (1979–99) ENSO sensitivity has been used throughout. If the ENSO-sensitivity variations shown in Fig. 1 are real (rather than artifacts of statistical noise and/or data quality problems), then using the same sensitivity throughout will lead to some spurious results in the pre-1979 period.

The raw data show a striking peak in 1998. From Fig. 2, however, the character of this recent warmth changes markedly when the ENSO influence is removed. The signals from El Chichón and Pinatubo also become more well-defined when ENSO is removed — indeed, the influence of El Chichón cannot be seen at all in the raw data. The analysis suggests peak global-mean coolings of 0.4 ± 0.1°C for Agung, 0.2 ± 0.1°C for El Chichón and 0.5 ± 0.1°C for Pinatubo.

To analyze record temperatures on the monthly timescale, the full temperature time series back to Jan. 1861 was employed. Only the most recent decades, however, are of interest. Table 1 shows sequences of record-breaking temperatures for the raw data and for data from which ENSO influences have been removed, beginning in Jan. 1940. Table 2 gives a breakdown of the number of records set over different time intervals. Table 3 shows the current records.

It is clear from Tables 1 and 2 that the frequency with which records are set varies markedly, and that the frequency is highly dependent on the ENSO phase. Very few records were set during the 1950–88 interval, and most of those that appear in the raw data can be attributed to warm ENSO events (Table 2). The 52-month interval 9/91 through 12/95 is also notable for a dearth of records (a result of cooling associated with Pinatubo — see below). The interval noted by Karl et al. (5/97–8/98) remains anomalous even when ENSO effects are removed from the data (with either 9 or 10 records being set in the 16-month period). However, for ENSO-removed data, 1/89–4/90 (also 16 months) was equally unusual (masked in the raw data by the occurrence of a La Niña event).

Table 3. Existing records by month (value in °C, with year in parentheses). Three decimals are given to facilitate ranking only; this does not reflect the accuracy of the data.

Month	Raw data	SOI removed	Niño3.4 removed
1	.530(1998)	.497(1944)	.515(1944)
2	.852(1998)	.693(1999)	.613(1998)
3	.600(1998)	.624(1990)	.629(1990)
4	.691(1998)	.406(1999)	.415(1990)
5	.613(1998)	.477(1999)	.346(1997)
6	.634(1998)	.488(1997)	.485(1997)
7	.719(1998)	.520(1998)	.499(1997)
8	.695(1998)	.505(1997)	.515(1997)
9	.536(1997)	.509(1997)	.533(1997)
10	.592(1997)	.513(1997)	.551(1997)
11	.481(1997)	.400(1990)	.392(1997)
12	.557(1997)	.504(1999)	.430(1998)

Table 4. Number of records per calendar year since Jan. 1980.

Year	Raw data	SOI and volcanoes removed	Niño3.4 and volcanoes removed
1980	1	—	—
1981	1	—	1
1982	—	—	—
1983	3	1	2
1984	—	1	1
1985	—	—	—
1986	—	—	—
1987	1	1	—
1988	4	1	—
1989	—	5	6
1990	6	4	3
1991	4	1	—
1992	—	5	5
1993	—	5	5
1994	1	4	4
1995	4	3	2
1996	—	1	—
1997	8	5	6
1998	8	4	—
1999	—	2	1

A more even distribution of record-setting months is obtained if both ENSO and volcanic influences are subtracted from the raw data. Table 4 shows the number of months per

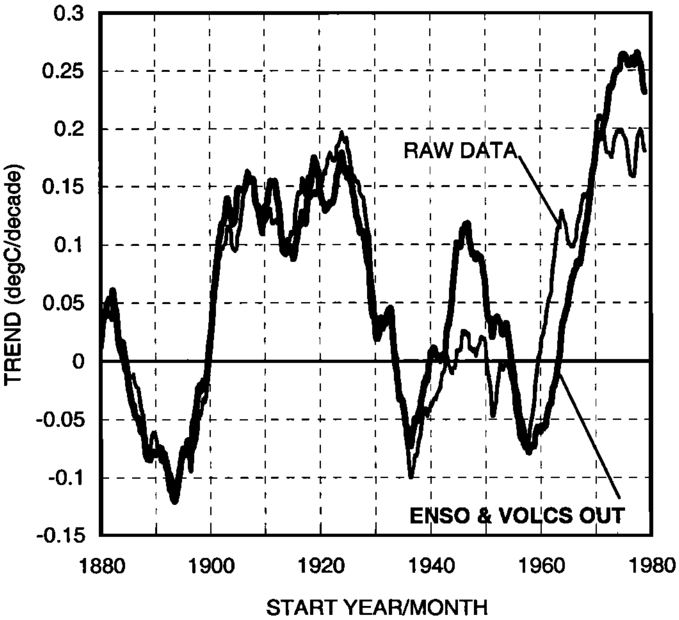

Figure 3. Running, maximally-overlapping 252-month trends for raw (thin curve) temperatures and temperatures with both ENSO and volcanic effects (Agung, El Chichón and Pinatubo only) removed (thick curve). Abscissa notation as in Fig. 1.

year in which records were set over the past 20 years. The masking effect of Pinatubo is clear with 16 or 17 of the months in the interval 9/91–12/95 setting records when both ENSO and Pinatubo are subtracted, compared with only 2 when ENSO only is subtracted (see Table 2).

Analysis of trends

Karl et al. suggest is that the record-breaking years, 1997-98, may be explained by a discontinuous change in the global-mean warming trend that occurred around 1976. The credibility of this claim rests on the subjective choice of method used to support it. An alternative view is presented here. Figure 3 shows running 252-month linear trends for the raw temperature data, and for the data with both ENSO (SOI) and volcanic effects (Agung, El Chichón and Pinatubo only) removed. The trend changes evident in this Figure clearly reflect the apparent step-like behavior evident in the original temperature time series. For the raw data, the current warming trend of around 0.2°C/decade has been quite stable since 1970, prior to which the warming trend was much less (at least back to the mid 1940s). This result is consistent with Karl et al.'s description of the data. When ENSO and volcanic effects are removed from the data, the most recent warming trend becomes greater, and trend acceleration continues through to 1975. In other words, the data characteristics to which Karl et al. attribute the record-breaking sequence of monthly-mean temperatures in 1997-98 are even more pronounced when the data are adjusted by removing ENSO and volcanic influences. In spite of this (see Table 4) the number of record-breaking months in 1997-98 is *less* in the adjusted data than in the raw data. This must cast some doubt on Karl et al.'s interpretation.

Conclusions

When ENSO and/or ENSO-plus-volcanic influences are subtracted from monthly-mean temperature data, a number of record months in the sequence of 16 consecutive record-breaking temperatures noted by Karl et al. are no longer records. The interval 5/97–8/98 is still unusual in terms of the number of records, but no more unusual than the earlier 16-month interval spanning Jan. 1989 through April 1990.

Both of these record-breaking intervals occurred during a period of unusually-large warming trend which appears to have been relatively stable since the early 1970s. Record-breaking is obviously more likely the larger the warming trend. One should not over-interpret this result. The behavior of trends over the past 120 years has been quite erratic. Associating this erratic character with either external forcing and/or internally-generated effects is not straightforward. For the raw data, the recent trend is not significantly different from the trend that was observed during the 1910s–1930s (the trend difference is around 0.02°C/decade, compared with trend standard errors (SEs) calculated after accounting for autocorrelation in the data of 0.03–0.05°C/decade). When ENSO and volcanic effects are removed, the recent trend is approximately 0.10°C/decade greater than that for the earlier period. This difference is statistically significant; trend SEs are 0.025–0.045°C/decade. It would be even greater and more significant if volcanic influences prior to Agung had been removed, since part of the early 20th century warming has been attributed to volcanoes (e.g. Tett et al., 1999). The combined influence of ENSO and volcanic effects has clearly masked the signature of anthropogenic forcing on the climate system in recent years. Similar statistical removal of other modes of internal variability (such as the Arctic Oscillation) might further enhance insights into the causes of observed temperature changes and the frequency of record-breaking extremes.

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References

Allan, R.J., J. Lindesay, and D.E. Parker, *El Niño, Southern Oscillation and Climatic Variability,* CSIRO Publishing, Collingwood, Vic., 1996, 405pp.

Christy, J.R., and R.T. McNider, Satellite greenhouse signal, *Nature* **367**, 325, 1994.

Jones, P.D., The influence of ENSO on global temperatures, *Climate Monitor* **17**, 80–89, 1989.

Jones, P.D., Recent warming in global temperature series, *Geophys. Res. Lett.* **21**, 1149–1152, 1994a.

Jones, P.D. Hemispheric surface air temperatures: A reanalysis and an update to 1993, *J. Climate* **7**, 1794–1802, 1994b.

Jones, P.D., M. New, D. E. Parker, S. Martin, and I. G. Rigor, Surface air temperature and its changes over the past 150 years. *Rev. Geophys.* **37**, 173–199, 1999.

Karl, T.R., R.W. Knight, and B. Baker, The record-breaking global temperatures 1997 and 1998: Evidence for an increase in the rate of global warming? *Geophys. Res. Lett.* **27**, 719–722, 1999.

Können, G.P., P.D. Jones, M.H. Kaltofen, and R.J. Allan, Pre-1866 extensions of the Southern Oscillation Index using early Indonesian and Tahitian meteorological readings, *J. Climate* **11**, 2325–2339, 1998 (updated).

Parker, D.E., P.D. Jones, C.K. Folland, and A. Bevan, Interdecadal changes in surface temperatures since the late 19th century, *J. Geophys. Res.* **99**, 14373–14399, 1994.

Quayle, R.G., T.C. Peterson, A.N. Basist, and C.S. Godfrey, An operational near-real-time global temperature index, *Geophys. Res. Lett.* **26**, 333-335, 1999.

Stevens, W.K., *The Change in the Weather: People, Weather, and the Science of Climate*, Delacorte Press, New York, 1999, 357 pp.

Tett, S.F.B., P.A. Stott, M.R. Allen, W.J. Ingram and J.F.B. Mitchell, Causes of twentieth-century temperature change near the Earth's surface. *Nature* **399**, 569–572, 1999.

Trenberth, K.E., Spatial and temporal variations of the Southern Oscillation, *Q. J. Roy. Met. Soc.* **102**, 639–653, 1976.

Trenberth, K.E., Signal versus noise in the Southern Oscillation, *Mon. Wea. Rev.* **112**, 326–332, 1984.

Wigley, T.M.L., and B.D. Santer, Differential ENSO and volcanic effects on surface and tropospheric temperatures (submitted, 2000).

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