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The record breaking global temperatures of 1997 and 1998: Evidence for an increase in the rate of global warming?

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Abstract. During the time between May of 1997 and September of 1998, for sixteen consecutive months, each month broke the previous monthly all-time record high temperature. Using auto-regressive intervention moving average (ARMA) models in a series of Monte Carlo experiments the probability of such an event was analyzed for various rates of temperature change. The string of record-breaking global temperatures could not be readily explained by the best fit linear increase of temperature since the late 1970's (2°C/Century), although the event was not implausible (probabilities slightly less than 5%). The 1997-98 event could signal yet another change point in the rate of global temperature increase, but the warming rate over the past few decades is already comparable to that projected during the 21st Century based on IPCC business as usual scenarios of anthropogenic climate change (Kattenberg et al., 1996).

1. Introduction

There are many facets to the problem of understanding the sensitivity of the climate system to both natural and anthropogenic changes. An important piece of information related to this issue is the rate of global temperature change. The second assessment report (SAR) of the IPCC [*Nicholls et al.*, 1996] reported that there has been a 0.3 to 0.6°C temperature increase in the instrumental temperature record (late nineteenth and twentieth centuries), but new data since the SAR indicates that the increase is now closer to 0.6°C (Fig.1a). The SAR also noted that some of the warmest years on record have occurred during the 1990's, e.g., 1995, 1990. Since the SAR (1996), three additional years have been added to the record. Two of these three years have again broken previous all-time record high global mean annual temperatures. Included in the recent two years was a string of 16 consecutive months from May of 1997 to August of 1998 where each monthly mean global temperature broke all of the previous records (Fig. 1b). In fact, during much of 1998, records were broken that had just been set in the previous year.

The question arises whether such a string of record high temperatures is consistent with an "average" rate of warming of 0.6°C per Century. Alternatively, do they reflect an increase in the rate of global warming? What do these new records reveal about the climate response to relatively smooth changes in radiative forcing? These are the primary issues addressed in this article.

2. Background

The data used in this analysis have recently been described in detail elsewhere [*Quayle et al.*, 1999]. They consist of land-based instrumental records and a blend of space-based and in-situ data to derive sea-surface temperatures. The land-based data have been screened and adjusted for numerous discontinuities and biases including urban heat islands [*Peterson et al.*, 1999], station relocations [*Easterling and Peterson*, 1995], and optimal methods of maximizing data availability [*Peterson et al.*, 1998]. The ocean sea surface temperatures (SSTs) have been adjusted for gross changes in observing techniques prior to World War II [*Folland and Parker*, 1995], as also published in the IPCC SAR. Since 1982, the SSTs are a blend of in-situ and space-based data [*Quayle et al.*, 1999].

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3. Analysis of the Global Temperature Record

A casual inspection of the global temperature time series (Fig. 1a) reveals that the increase in global mean temperatures is by no means constant. A linear trend fit to the data reveals several clear-cut episodes of persistent time-dependent residual biases. This is because the increase in temperature in the time series primarily occurs during two sustained periods, one beginning around 1910 and another during the 1970's. This suggests that the time series cannot be well described, nor simulated statistically, without some long-term low frequency behavior. Recent paleoclimatic work [*Mann et al.*, 1995; *Mann et al.*, 1999; *Pollack et al.*, 1998; *Jones et al.*, 1998] has extended the northern hemisphere temperature records back several hundred to one thousand years. These analyses indicate that the Twentieth Century temperatures are clearly warmer than any other century over the past 500, and perhaps even the past thousand years. This implies that if there are any oscillatory characteristics in the global temperature time series they are significantly smaller than the systematic increase in temperature during the early and latter portions of the Twentieth Century. Using this information, we selected an auto-regressive moving average (ARMA) model to represent the global time series with three interventions, or change points to separate the two periods of warming. The identification of the timing for the change points was approached using two different methods. The first method was based on a wavelet analysis and employed the use of passing four Haar wavelets (square waves) through the time series to identify the timing of the three discontinuities. The assumption in this procedure is that the time series discontinuities reflect step changes to a new equilibrium level, rather than change points in the rate of temperature change. As apparent from the sustained periods of temperature increase depicted in the global temperature time series (Fig. 1a), this does not appear to be a good model, but such an approach will provide a measure of the sensitivity of the method used to detect change points. The preferred approach we have selected is to minimize the residual sum of squares of all possible combinations of four line segments representing time intervals of 15 years or more and constrained to have their end points intersect at the year of change point. A comparison of Figs. 2 and 3a indicates that there are only small differences in the timing of

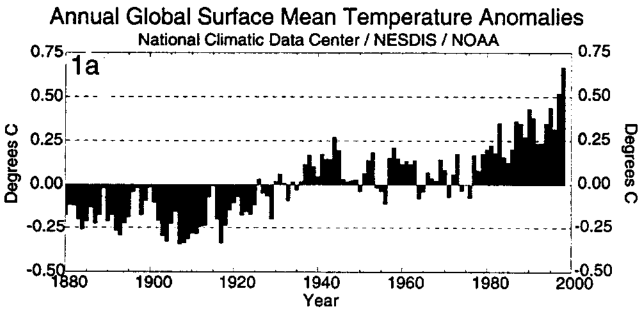

Figure 1a. Annual anomaly (base period 1880-1997) time series of global mean temperatures.

discontinuities derived from the four piecewise trends and the square waves. More importantly, however, there are no apparent long-term oscillations or time dependent biases in the residuals of the intervention model depicted in Fig. 3a.

The residuals from the four piecewise trends (Fig. 3a) were modeled with auto-regressive and moving average components allowed to vary up to order four, e.g., all combinations of ARMA up to (4, 4). Such models are capable of resolving many oscillations in the time series, including El Nino like oscillations. The Bayesian Information Criteria (BIC) and the Akiake Information Criteria (AIC) were used to select the most appropriate model. The BIC tends to be more conservative in the order of the model selected compared to the AIC [*Katz*, 1982]. Although, the preferred model using these information criteria was an ARMA (1, 0) we also used an ARMA (1, 1) and an ARMA (2, 0) to see how sensitive our results were to the order of the model selected. We note that by using an ARMA (2, 0) model, oscillations on the time scale of El Nino events can be readily simulated.

The rates of temperature change for the two periods of warming, 1912-1941 and 1976-1998, are highly significant ($p<.0001$) using a standard t-test, even after reducing the number of degrees to account for serial correlation [Davis, 1976]. The ARMA models [ARMA (1, 1), ARMA (2, 0), and ARMA (1, 0)] were also used to test the statistical significance of the piecewise trends by simulating 50,000 time series and searching for slopes of comparable magnitude and duration within the time series. The rate of temperature increase during the two periods of warming

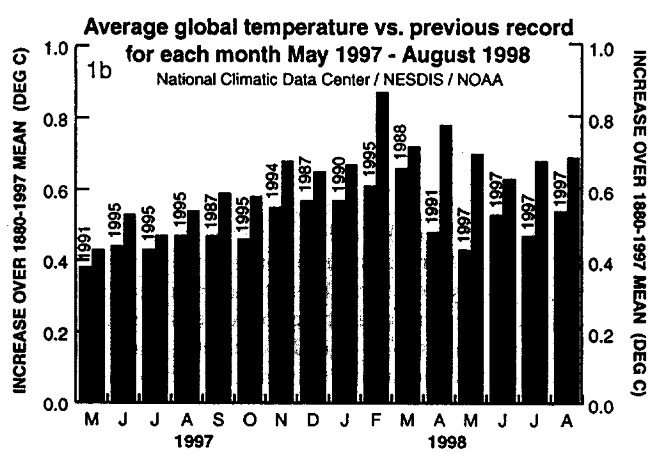

Figure 1b. Anomalies (base period 1880-1997) associated with the 16-month string of consecutive record breaking temperatures.

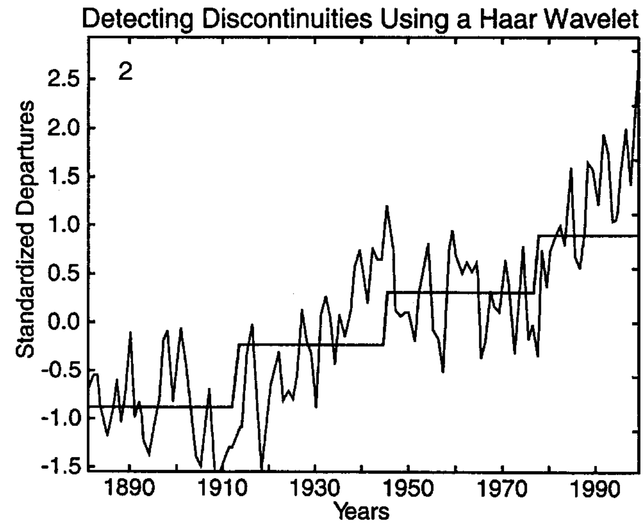

Figure 2. Annual global temperatures (base period 1880-1997) with three discontinuities identified using four Haar Wavelets.

were again found to be highly significant ($p<.0001$). The three ARMA models applied to the four piecewise trends were then used to calculate the probability of 16 consecutive months of record-breaking mean monthly temperature anomalies occurring during the most recent warming period. In a stationary time series the probability of breaking records decreases as the length of the time series increases, but since this time series is clearly non-stationary, our interest is to understand if the large number of records set near the end of the time series is consistent with the rate of warming represented by the trends, or whether the recent records reflect yet another emerging change point in the time series.

Each of the three ARMA models were used to simulate 50,000 time series to provide an estimate of the probability of observing 16 consecutive monthly record-breaking global mean monthly temperatures. In addition, various rates of warming were also simulated during the most recent period of global warming. These rates of change ranged from no warming since 1976 up to a rate of 5°C/Century (Fig. 3b). The results (Table 1) indicate that, depending on the model selected, the probability of observing sixteen consecutive monthly record high temperatures varies from about 0.009 to 0.041 using the rate of temperature increase (2°/Century) closest to that derived from the change point trend analysis. The rate of warming during the most recent period, that is most consistent (probability of 0.50) with the record warmth, however, was between 2.5 and 3.0°C/Century for the ARMA (1, 1) and ARMA (2, 0) models and between 3.0 and 3.5°C/Century for the ARMA (1, 0).

4. Discussion

We interpret the results to indicate that the rate of warming since 1976 is clearly greater than the mean rate of warming averaged over the late 19th and 20th Centuries. It is less certain whether the rate of temperature change has been constant since 1976 or whether the recent string of record breaking temperatures represents yet another in-crease in the rate of temperature change. Based on intervention analysis of piecewise linear trends the recent string of records is unlikely (less than 5% probability) for an average rate of temperature change of nearly 2°C/Century

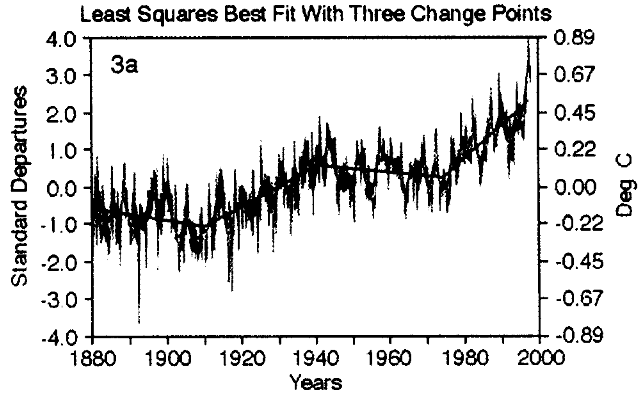

Figure 3a. Monthly anomaly (base period 1880-1997) time series of global mean temperatures (red) smoothed with an 11-point binomial filter (blue) and a least squares fit of four linear trends with three dynamic change points.

since 1976, but unusual events can occur and the probabilities of observing the consecutive string of record breaking temperatures are not uncharacteristically low. On the other hand, the probability of observing the record temperatures is more likely with higher average rates of warming, around 3 °C/Century. This is higher than the 2°C/Century least squares estimate suggesting that a change point with higher rates of warming may have occurred in 1997. At this point, however, it may be premature to abandon the hypothesis of a constant rate of temperature increase since 1976.

It is noteworthy that several climate model simulations are capable of reproducing discontinuities in the rate of global temperature increase with similar timing and magnitude similar to that found in the historical data [*Kattenberg et al.*, 1996; *Wigley et al.*,1997; *Knutson et al.*, 1999], but projections of temperature change into the next Century, using IPCC business as usual scenarios of anthropogenic forcing (CO_2 and sulfates), have relatively constant rates of global temperature increase. By comparison the data suggest that the rate of global warming since

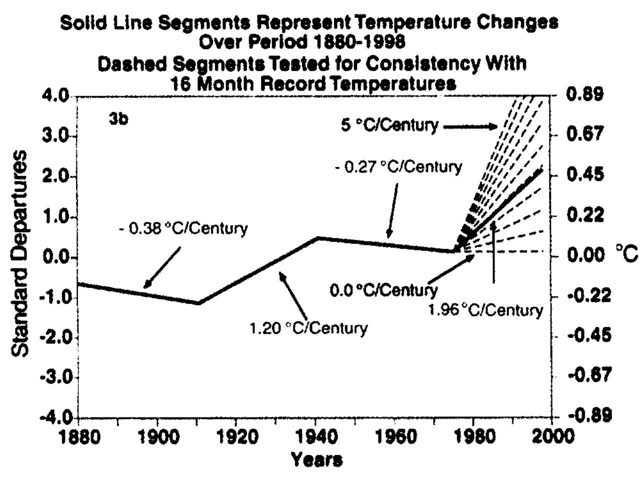

Figure 3b. Depiction of the trends and change points identified by the constrained change point model used in this analysis, and a depiction of the rates of temperature change tested in the three ARMA models [ARMA(1, 0), ARMA(2, 0), and ARMA (1, 1)] used to estimate the probability of having sixteen consecutive record high monthly global temperature anomalies.

Table 1. Probabilities of Observing at Least 16 Consecutive Months of Record Breaking Monthly Anomalies During the Period 1976-1998 With Various Rates of Temperature Change Given the Trends and Change Points Depicted in Figure 3b.

	Rates of Temperature Change (°C/Century) 1976-1998					
Model	1.5	2.0	2.5	3.0	3.5	4.0
ARMA (1, 0)	0.001	0.009	0.086	0.390	0.819	0.985
ARMA (2, 0)	0.007	0.030	0.162	0.516	0.876	0.991
ARMA (1, 1)	0.010	0.041	0.197	0.547	0.883	0.991

1976 is comparable to the rate of warming projected by the IPCC [*Kattenberg et al.*, 1996] for the Twentieth-First Century in their business as usual scenario. This means that over the past two and one-half decades we have already experienced the rate of warming projected to continue throughout the next Century. This implies that the impacts of and adjustments to changes in climate over the past two decades may already be particularly insightful as related to future effects of climate change. Moreover, these results imply that if the climate continues to warm at present rates of change, more events like the 1997 and 1998 record warmth can be expected.

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