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Was the 2003 European summer heat wave unusual in a global context?

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[1] We place the European summer heat wave of 2003 in the context of other extreme summer tropospheric temperature events from 22°N to 80°N since 1979, as well as globally using annual averages. The analysis is performed in terms of standard deviations (*SD*) exceeded and correlations between regional extremes and temperatures at larger spatial scales. As has been pointed out previously the heat wave was statistically unusual and was a deep tropospheric phenomenon. In this analysis we also find the following. (1) Extreme warm anomalies equally, or more, unusual than the 2003 heat wave occur regularly. (2) Extreme cold anomalies also occur regularly and occasionally exceed the magnitude of the 2003 warm anomaly in terms of the value of *SD*. (3) There is a correlation between global and hemispheric average temperature and the presence of warm or cold regional anomalies of the same sign (i.e., warmer than average years have more regional heat waves and colder than average years have more cold waves). (4) Natural variability in the form of El Niño and volcanic eruptions appear to be of much greater importance in causing extreme regional temperature anomalies than a simple upward trend in time. Extreme temperature anomalies in the wake of the 1997–98 El Niño were larger than the anomalies seen in summer 2003 both in area affected and *SD* extremes exceeded. (5) Regression analyses do not provide strong support for the idea that regional heat waves are increasing with time. **Citation:** Chase, T. N., K. Wolter, R. A. Pielke Sr., and I. Rasool (2006), Was the 2003 European summer heat wave unusual in a global context?, *Geophys. Res. Lett.*, *33*, L23709, doi:10.1029/2006GL027470.

1. Introduction

[2] The European heat wave of summer 2003 has received considerable attention, both because of a potential link to larger scale warming patterns (e.g., "global warming"), and the large loss of life [see, e.g., *Rozzini et al.*, 2004; http://bmj.bmjjournals.com/cgi/content/full/327/7412/411]. Several studies find that this regional heat wave was quite unique [*Schär et al.*, 2004; *Stott et al.*, 2004; *Trigo et al.*, 2005] and it has been suggested that such an extreme event could be accounted for only by a shift of statistical regime to one with higher variance [*Schär et al.*, 2004]. The uniqueness of the heat wave in a global context, however, needs to be further examined.

[3] In this paper, we utilize the NCEP global reanalysis to assess the heat wave. This reanalysis product, developed by *Kalnay et al.* [1996] has been used to investigate a wide range of atmospheric circulation patterns [e.g., *Castro et al.*, 2001] and global and regional tropospheric temperature trends [e.g., *Chase et al.*, 2000]. As shown by Chase et al., the assessment of large tropospheric temperature trends using the NCEP reanalysis closely mirrors the lower tropospheric temperature trends as reported from the satellite microwave sounding unit (MSU) data [*Spencer and Christy*, 1990]. While errors have been noted in these data (discussed by *Chase et al.* [2000]), they are orders of magnitude smaller than the extreme events we examine here and so are inconsequential to this analysis.

[4] To assess the uniqueness of the heat wave, we use an analysis of regional departures from average expressed as standard deviations (*SD*). *SD* was calculated in the standard manner:

$$SD = \sqrt{\frac{\sum\left(X - \overline{X}\right)^2}{N - 1}}$$

However, because of the relatively small number of samples ($N = 25$) in the time series, we also repeated the analysis

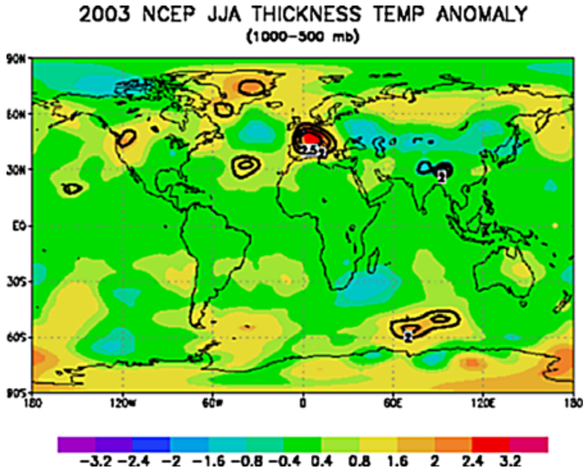

Figure 1. 1000–500 mb thickness temperature anomaly for June, July, and August 2003. Areas exceeding 2.0, 2.5, and 3.0 standard deviations from the 1979–2003 mean are contoured in thick lines for anomalies of both sign.

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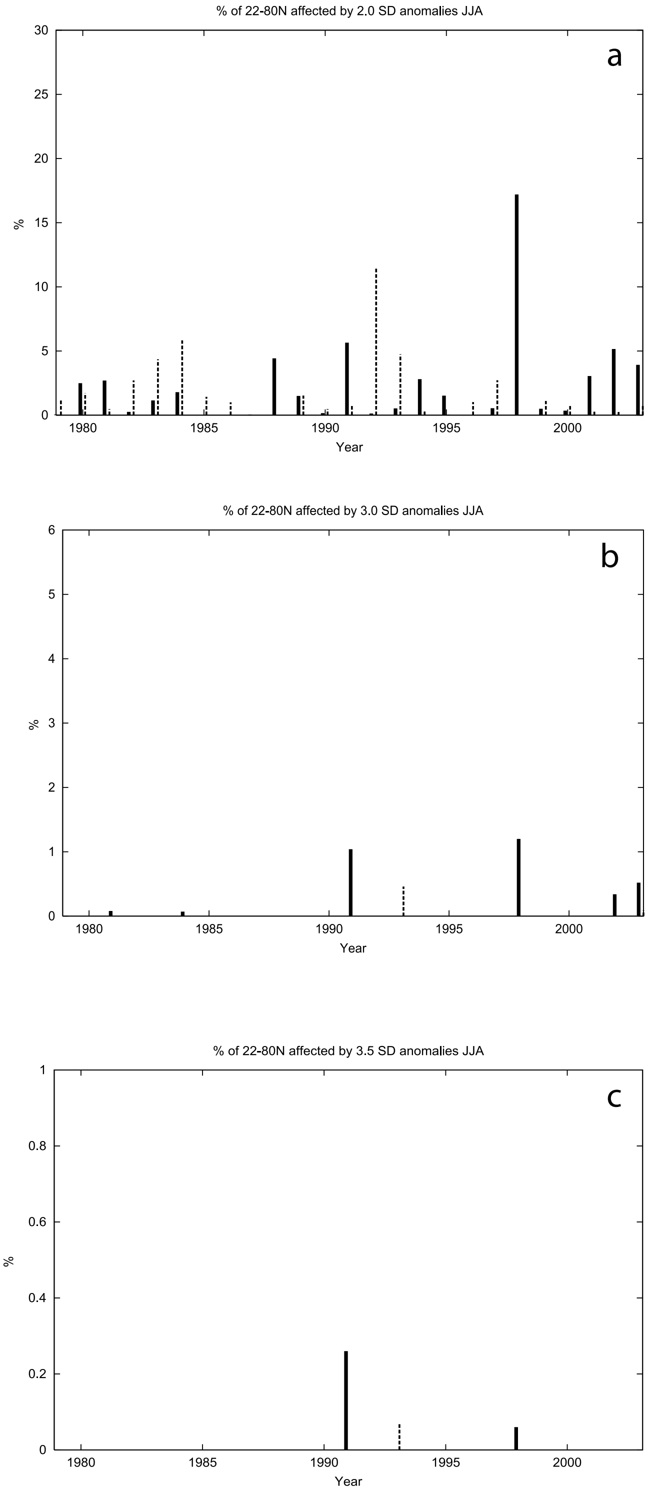

Figure 2. Percentage of the area of 22–80°N covered by thickness temperature anomalies of indicated *SD* level in JJA by year: (a) 2.0 *SD*, (b) 3.0 *SD*, and (c) 3.5 *SD*. Warm anomalies are in thick, solid lines, cold anomalies in thin, dashed lines. Note vertical scale changes between figures.

using a non-parametric estimate of *SD* based on the first and fifth quintiles of data points. As both analyses resulted in the same conclusions, we report our results based on the more familiar definition of *SD*.

[5] Figure 1 shows the global thickness temperature anomaly relative to the 1979–2003 average for June, July, and August (JJA) 2003 for the 1000–500 mb layer average. Contours are of standard deviation with 2.0, 2.5, and 3.0 *SD* shown. The 2003 warm anomaly over Europe was a deep atmospheric phenomenon and exceeded 3.0 *SD* above the mean for this period. By definition, exceeding 3.0 *SD* is an

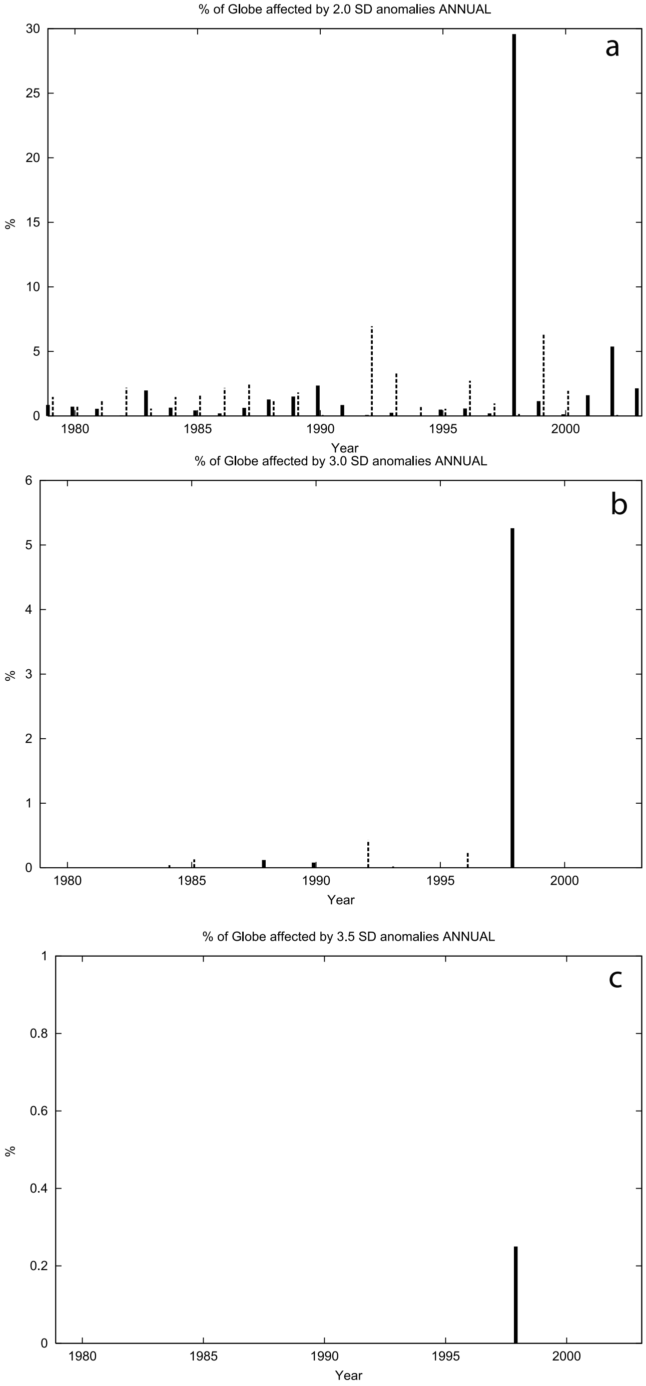

Figure 3. Percentage of the area of the Globe covered by thickness temperature anomalies in annual average by year: (a) 2.0 *SD*, (b) 3.0 *SD*, (c) 3.5 *SD*. Warm anomalies are shown in thick solid lines, Cold anomalies in thin dashed lines. Note vertical axis changes between figures.

Table 1. Correlations Between the Percent Area of Regional WARM Anomalies in JJA from 22–80°N With Average Temperature of 22–80°N

Sigma Level (*SD*)	Pearson Correlation	Spearman Correlation
1.0	0.93	0.96
2.0	0.72	0.79

Table 2. Same as Table 1 but for COLD Anomalies

Sigma Level (*SD*)	Pearson Correlation	Spearman Correlation
1.0	−0.89	−0.92
2.0	−0.67	−0.66

extremely unusual event statistically and would be expected in much less than 1% of observations.

[6] Below we put in context exactly how unusual such a 3.0 *SD* climate phenomenon is in a global context by examining the following: how often these thresholds have been exceeded for both warm and cold anomalies, whether there are any trends in extreme events over time, whether there is a correlation between global average temperatures and the expectation for regional heat or cold waves, and how years with occurrences of natural phenomena such as ENSO or volcanism, known to affect temperature [*Barnston*, 1994; *Robock and Mao*, 1995], compare with the 2003 anomaly.

2. Climate Extremes 1979–2003

2.1. June-July-August (JJA) Extra-Tropics (Northern Hemisphere)

[7] For a more direct comparison with the European heat wave we first examine the Northern hemisphere extratropics (22–80°N) during JJA for extreme events. Reanalysis data is most reliable when the very high latitudes are excluded as there are relatively few observations to constrain the reanalysis. Excluding the deep tropics, where little yearly variability is observed relative to high latitudes allows us to concentrate on extreme events which are also of relatively large absolute magnitude. We examine all the available data globally in the next section. Figures 2a, 2b, and 2c show the percentage of the area covered by these latitudes to have experienced a 2.0, 3.0 and 3.5 *SD* climate anomaly in a given year respectively. Solid lines are the percent area of all warm anomalies, while dashed lines represent the percent area of cold anomalies

[8] We note that warm anomalies similar in size to that seen in 2003 are regular occurrences and are strongly dominated by the post-El Niño year of 1998 both in area affected and *SD* thresholds exceeded (1998 was one of two years, the other being 1991, to experience up to 4.0 *SD* extremes albeit in very small regions). Warm anomalies are not obviously more common than cold anomalies during this period and cold anomalies can be of equal or greater size to the 2003 warm anomaly.

[9] In order to explain the occurrence of extreme temperature anomalies during the Northern Hemisphere summer season, two mechanistic explanations can be invoked. On the one hand, warm anomalies appear to spread away from the Equator in the wake of an El Niño event [*Angell*, 2000; *Trenberth et al.*, 2002], typically taking two seasons to show their peak influence in the extratropics [*Angell*, 2000]. This behavior is reliable enough to be of potential use in the prediction of summer temperature anomalies over North America [*Barnston*, 1994]. If we use a threshold of at least three consecutive months with Niño 3.4 anomalies in excess of +1°C (data at http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices), the post-El Niño summers of 1983, 1987, 1988, 1992, 1995, 1998, and 2003 would be candidates for this mechanism. On the other hand, large volcanic eruptions, such as experienced with El Chichón (1982) in Mexico, and Pinatubo (1991) in Indonesia appear to maximize their cooling influence during Northern Hemisphere summer seasons one to two years after eruption [*Robock and Mao*, 1995]. This would favor cold anomalies in the summers of 1983/84 and 1992/93, in particular. In Figure 2, the El Niño events of 1982–3 and 1991–2 appear to have been overshadowed in their summer temperature effects by El Chichón's and Pinatubo's eruptions, respectively. The remaining two years with big warm temperature extremes (1991 and 2002) are harder to understand without a more detailed analysis.

[10] A trend analysis using a lag 4 autoregressive model indicated no highly significant ($p<0.1$) trends in the percent area experiencing either warm or cold anomalies at any *SD* level during this period in this latitude band (22°N–80°N). Note that because of limited sample sizes at higher *SD* levels, trends were performed only for 1.0 and 2.0 *SD* levels.

2.2. Annual, Global Averages

[11] To expand to larger time and spatial scales and to examine whether the previous analysis in the NH extratropics was unusual in a global context, Figures 3a, 3b, and 3c are similar to Figure 2 except that annual and global averages are shown.

[12] Again, the dominance of El Niño in producing extreme warm anomalies in 1998 is evident, and has been noted before [*Angell*, 2000; *Trenberth et al.*, 2002]. Cold anomalies are also a regular feature during this period, particularly in 1992, which shows a strong cold anomaly in excess of the 2003 warm anomaly, presumably as a result of Pinatubo.

Table 3. Correlation Coefficients Over Time Between the Area of WARM Anomalies and COLD Anomalies of the Same Sigma Level for 22–80°N, JJA

Sigma Level (*SD*)	Pearson Correlation	Spearman Correlation
1.0	−0.70	−0.82
2.0	−0.27	−0.38

Table 4. Correlations Between the Percent Area of Regional WARM Anomalies in Annual Average Over the Globe and Average Global Temperature

Sigma Level (*SD*)	Pearson Correlation	Spearman Correlation
1.0	0.90	0.92
2.0	0.61	0.79

[13] Using the same regression analysis as described in the previous section, no significant trends in either warm or cold anomalies were found in the global, annual average.

3. Correlations With Hemispheric and Global Temperature

[14] We also performed a correlation analysis to determine if there was any relationship between the occurrence of warm and cold anomalies at various *SD* levels in simultaneous years or with hemispheric and global 1000–500 hPa layer averaged temperatures. Because of limited samples at high *SD* we performed this analysis only at 1.0 and 2.0 *SD* levels.

3.1. 22–80N JJA Correlations

[15] Tables 1 and 2 give the Pearson and Spearman correlation coefficients between the percentage of area covered by warm and cold anomalies by *SD* level and with the average temperature anomaly for JJA, 22–80°N. There is clearly a strong correlation between the area of regional anomalies and the average temperature from 22–80°N, particularly at lower *SD* levels.

[16] It is of interest as to whether warm and cold anomalies occur simultaneously in a given year or are relatively separated in time as Tables 1 and 2 might indicate.

[17] Table 3 therefore gives the correlations between the areas of warm and cold anomalies at each *SD* level. There is a strong anti-correlation at the lowest sigma levels between warm and cold anomalies indicating some separation.

3.2. Global, Annual Correlations

[18] The correlation analysis in the global annual average data between the area of regional anomalies and the globally averaged temperature is given in Tables 4 and 5 and are similar in result to the previous section. Again, there is a tendency for warm and cold anomalies to correlate with global average temperature that decreases with higher *SD* levels.

[19] Table 6 again shows that regional anomalies at low sigma levels are strongly anti-correlated in a given year though this relationship again weakens at the higher level.

4. Discussion and Conclusions

[20] We compared extreme tropospheric temperature events from 22°N to 80°N in JJA and globally using annual averages to the European summer heat wave of 2003 in terms of standard deviations exceeded and correlations between regional extremes and temperatures at larger spatial scales. As pointed out previously by *Schär et al.* [2004] and *Beniston* [2004] the European warm anomaly during the summer of 2003 at 3.0 standard deviations was statistically unusual and was a deep tropospheric phenomenon. In this analysis we also find the following.

Table 5. Same as Table 4 but for COLD Anomalies

Sigma Level (*SD*)	Pearson Correlation	Spearman Correlation
1.0	−0.89	−0.95
2.0	−0.55	−0.71

Table 6. Correlation Coefficients Over Time Between the Area of Warm Anomalies and Cold Anomalies of the Same Sigma Level for Global, Annual Average Data

Sigma Level (*SD*)	Pearson Correlation	Spearman Correlation
1.0	−0.67	−0.79
2.0	−0.24	−0.56

[21] 1. Extreme warm anomalies equally, or more, unusual than the 2003 heat wave occur regularly.

[22] 2. Extreme cold anomalies also occur regularly and can exceed the magnitude of the 2003 warm anomaly in terms of the value of *SD*. Cold anomalies are somewhat less extreme, on average, than warm anomalies during this period.

[23] 3. There is a correlation between global and hemispheric average temperature and the presence of warm or cold regional anomalies of the same sign (i.e., warmer than average years have more regional heat waves and colder than average years have more cold waves). This correlation is stronger for warm anomalies than for cold anomalies and diminishes with more extreme anomalies. This relationship between warm years globally and regional heat waves is also reflected in the tendency for regional warm and cold anomalies to be anti-correlated with each other in a single year (i.e., years with strong regional warm anomalies do not generally also have strong cold anomalies and vice versa).

[24] 4. Natural variability in the form of El Niño and volcanism appears of much greater importance than any general warming trend in causing extreme regional temperature anomalies as regional extremes during 1998 in particular were larger than the anomalies seen in summer 2003 both in area affected and *SD* extremes exceeded. Other natural modes of variability such as the summer annular mode [*Ogi et al.*, 2005] or SST variability [*Sutton et al.*, 2005] implicated in the 2003 heat wave appear to have a smaller effect than ENSO.

[25] 5. Regression analyses do not provide strong support for the idea that regional heat or cold waves are significantly increasing or decreasing with time during the period considered here (1979–2003).

[26] As with all analyses based on short time series, the above conclusions should be viewed with caution. However, our analysis does not support the contention that similar anomalies as seen in summer 2003 are unlikely to recur without invoking a non-stationary statistical regime [*Schär et al.*, 2004; *Beniston*, 2004] with a higher average temperature and increased variability. Similarly, the finding of *Baldi et al.* [2006] that regional heat waves in the Mediterranean have been increasing in recent years does not appear to reflect hemispheric or global trends terms of the areas affected.

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