The shifting probability distribution of global daytime and night-time temperatures

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[1] Using a global observational dataset of daily gridded maximum and minimum temperatures we investigate changes in the respective probability density functions of both variables using two 30-year periods; 1951–1980 and 1981–2010. The results indicate that the distributions of both daily maximum and minimum temperatures have significantly shifted towards higher values in the latter period compared to the earlier period in almost all regions, whereas changes in variance are spatially heterogeneous and mostly less significant. However asymmetry appears to have decreased but is altered in such a way that it has become skewed towards the hotter part of the distribution. Changes are greater for daily minimum (night-time) temperatures than for daily maximum (daytime) temperatures. As expected, these changes have had the greatest impact on the extremes of the distribution and we conclude that the distribution of global daily temperatures has indeed become "more extreme" since the middle of the 20th century. **Citation:** Donat, M. G., and L. V. Alexander (2012), The shifting probability distribution of global daytime and night-time temperatures, *Geophys. Res. Lett.*, *39*, L14707, doi:10.1029/2012GL052459.

1. Introduction

[2] The most recent assessment on extremes by the Intergovernmental Panel on Climate Change (IPCC), the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), included a frequently asked question "Is the climate becoming more extreme?" (FAQ 3.1, P124). Due to the multitude of extreme events in the climate system and the complexity of defining extremes depending on application, region and/or season this has led to the different characterization of events which has made consistent global analysis difficult. Therefore SREX concluded that suitable metrics had "yet [to be] developed sufficiently to allow us to confidently answer the question posed" [*Seneviratne et al.*, 2012].

[3] One of the reasons for our inability to adequately answer this question is that the data required are generally not available for the globe as a whole or for sufficiently long periods [*Zhang et al.*, 2011]. Therefore studies have mostly focused on regional analysis of changes [e.g., *Barriopedro et al.*, 2011] or where global assessments have been possible they have usually relied on investigating just the extremes rather than the whole distribution [e.g., *Alexander et al.*, 2006; *Brown et al.*, 2008]. Other studies have relied on model output to investigate distribution changes [e.g., *Beniston*, 2004; *Clark et al.*, 2006], or the relationship between mean and extreme changes [*Hegerl et al.*, 2004]. Previous observations-based studies have shown warming trends in both average temperatures [e.g., *Vose et al.*, 2005a, 2005b; *Lawrimore et al.*, 2011] and temperature extremes [*Alexander et al.*, 2006]. However, there is conflicting evidence - mostly based on regional analysis - as to whether the response in extremes is simply a result of a shifting mean [e.g., *Griffiths et al.*, 2005; *Simolo et al.*, 2011] or whether changes in other "higher order moments" of the daily temperature are also occurring [*Della-Marta et al.*, 2007; *Ballester et al.*, 2010]. Assessment of the probability distribution of daily temperatures for the globe would help address this question.

[4] Since the IPCC Third Assessment Report (TAR), it has been postulated how a changing climate would affect the daily temperature distribution and what the associated impact would be on extremes. Schematics were developed indicating how the distribution would shift associated with changes in mean, variance (see Figure 2.32 of TAR [*Folland et al.*, 2001]) and skewness (see SPM. 3 of SREX). However to our knowledge there have been no studies which have actually shown the "real" shifts in the daily global temperature distribution and whether they resemble any of the schematics proposed by IPCC.

[5] To address this we use a global dataset of daily maximum and minimum temperature anomalies to show if and/or how the distribution of temperature has shifted over the past 60 years. In Section 2 we briefly describe the data and methods used in this study, temperature distribution changes are discussed in Section 3, and Section 4 summarizes the main conclusions from this study.

2. Data and Methods

[6] We use HadGHCND [*Caesar et al.*, 2006], a global gridded data set of observed near-surface daily minimum (Tmin) and maximum (Tmax) temperatures from weather stations, available from 1951 and updated to 2010. For this study, we consider daily Tmax and Tmin anomalies calculated with respect to the 1961 to 1990 daily climatological average.

[7] Probability Density Functions (PDFs) are calculated using the daily temperature anomalies for two 30-year time periods; 1951–1980 and 1981–2010. Relative frequencies are calculated based on counts of the temperature anomalies between −25°C and +25°C, using a bin width of 0.5°C. We

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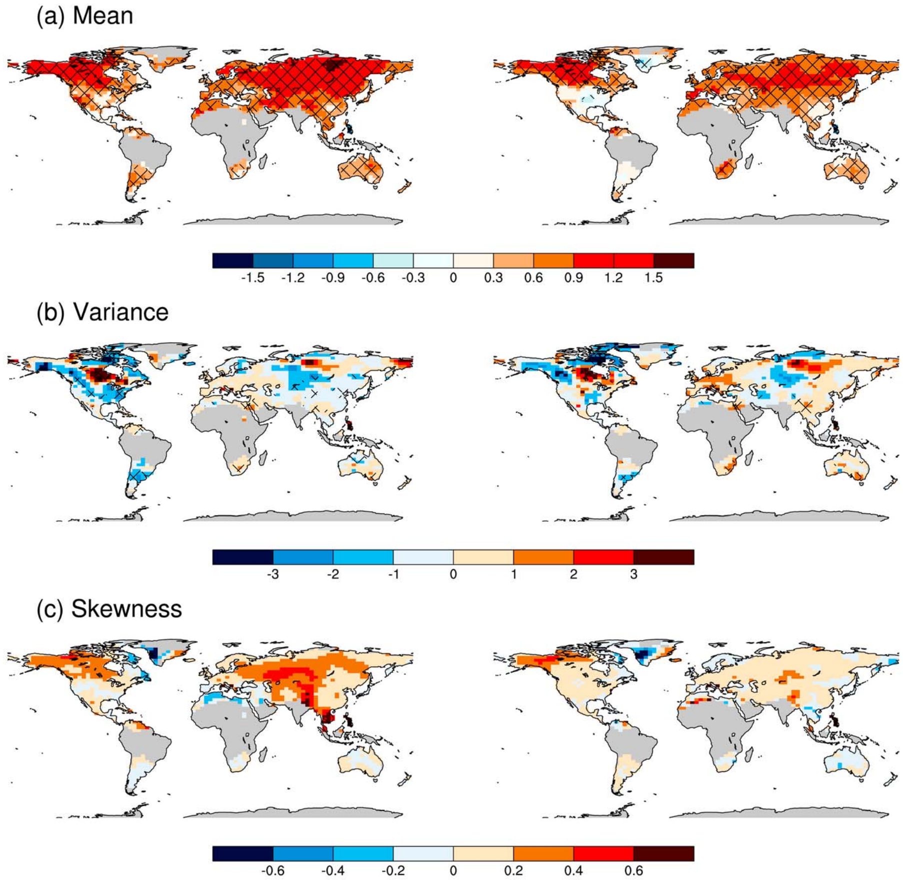

Figure 1. The differences in higher moment statistics of (a) mean, (b) variance, and (c) skewness for each grid box in HadGHCND [*Caesar et al.*, 2006] for (left) daily minimum temperature anomalies and (right) daily maximum temperature anomalies for the two time periods shown. Hatching indicates changes between the two periods that are significant at the 10% level for the mean (using a Student's t-test) and the variance (using an f-test) of the distribution.

use all grid boxes which have at least 50% of daily data available for both of the two 30-year periods. The results are somewhat sensitive to this criterion, particularly regarding changes in variance. For example, when including all grid boxes, the global PDF shows an increase in variance, and in turn applying a stricter criterion (e.g., 80% of data) shows a stronger decrease in the variance of the global PDF than the results presented here (mostly due to the removal of many tropical regions). Thus choosing the 50% criterion reflects a compromise between data coverage and statistical robustness. Considering daily anomalies rather than actual temperatures allows us to aggregate and compare the daily values from different regions.

[8] Figure 1 indicates the spatial coverage of the HadGHCND data set using the chosen data availability criterion. North America, Europe, Australia and large parts of Asia have good spatial coverage although coverage is poor over parts of Africa, South America and India. However this dataset represents the best coverage currently available for daily Tmax and Tmin for this length of record.

[9] Statistical characteristics of the PDFs, such as the higher moments (mean, variance, skewness and kurtosis), are calculated both for each grid box and spatial aggregations (global, tropics, northern and southern hemisphere extra-tropics). This is done to account for potential biases that could exist because of the smaller variation in tropical temperature anomalies compared to extratropical temperatures.

[10] To estimate if the PDFs for the two time periods are significantly different from each other, we use a Student's t-test (to test if the sample means are different) and an f-test (to test whether the sample variances are drawn from different populations). This allows us to estimate if the changes in the PDFs are due to significant changes in location, in variability, or both. As the daily temperature grids are highly auto-correlated both in space and time, the effective number of degrees of freedom is considerably lower than the sample size. We follow *Zwiers and von Storch* [1995] to calculate the equivalent sample sizes, which are then used for calculating both the t-test and f-test statistics. Our conclusions also remain valid when using non-parametric tests based on the quantiles of the distributions [*Ferro et al.*, 2005].

3. Results and Discussion

[11] Figure 1 indicates changes in three of the higher moment statistics (mean, variance, skewness). Significant increases in the Tmax and Tmin mean have been observed almost everywhere and this agrees with studies such as *Vose et al.* [2005a]. However, there are some regions where the mean is decreasing, mostly only for maximum temperatures and the obvious east-west differential in daily maximum

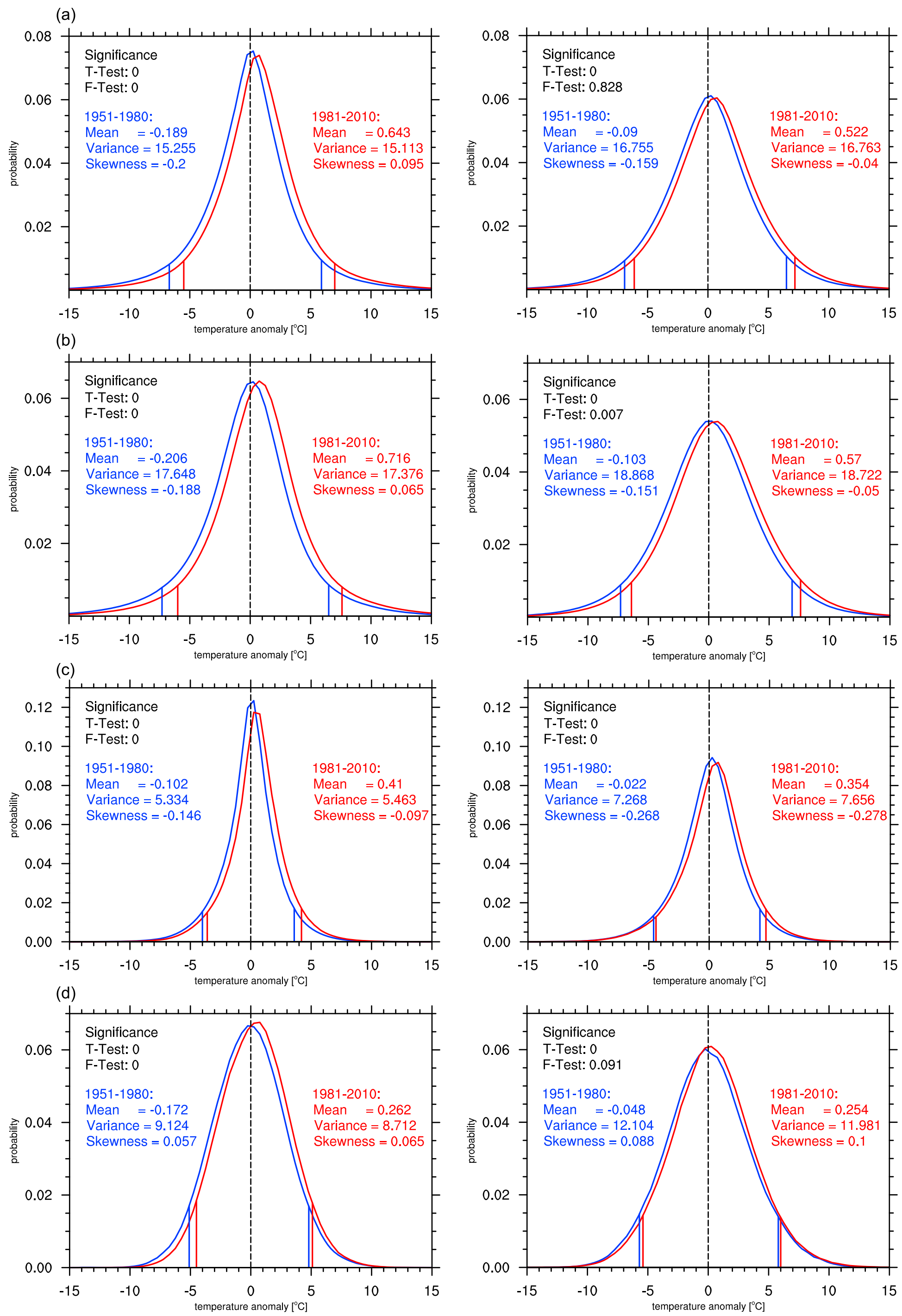

Figure 2. Probability density functions for two periods 1951–1980 (blue) and 1981–2010 (red) of anomalies of (left) daily minimum temperature and (right) daily maximum temperature. Statistics related to the shape, scale and location parameters are also shown. The distribution functions are presented for (a) the globe, (b) northern hemisphere extra-tropics (30°N–60°N), (c) tropics (30°S–30°N), and (d) southern hemisphere extra-tropics (30°S–90°S). The vertical lines represent the 5th and 95th percentiles of the respective distribution.

temperature anomalies in the USA is apparent (the so-called "warming hole" [*Portmann et al.*, 2009]).

[12] Changes in variance are spatially much more heterogeneous and generally less significant, although the patterns of change for Tmin and Tmax are somewhat similar, i.e., if there is a decrease (increase) in variance in a region in daily minimum temperature then on the whole there is an associated decrease (increase) in variance in daily maximum temperatures. In most regions, both Tmax and Tmin have become more positively skewed in more recent decades which indicates a change in shape towards the hotter part of the distribution. Some exceptions are parts of Australia, South America, Greenland and North Africa, where locally, and more so for Tmin, changes towards a slightly more

negative skewness are found. In the case of Greenland, for example, this may be a data artifact since there are few observations in this region in HadGHCND. Kurtosis changes (not shown) were also found to be spatially heterogeneous.

[13] Figure 2 shows the probability distribution functions from pooling all grid boxes for the periods 1951–1980 and 1981–2010. In all cases the distributions between the two periods are shown to be statistically significantly different from each other at the 1% level (see Data and Methods section), generally related with a significant shift in the location parameter (mean) of the PDFs.

[14] For the globe, the mean daily minimum temperature anomaly increased by 0.8°C between the earlier and latter period (Figure 2a). While the asymmetry appears to have decreased between the two periods, results indicate that the distribution in more recent years has become skewed towards the hotter part of the distribution (this is similar as to what is suggested by SREX figure SPM.3). The changing location, scale and shape of the distribution have had a greater impact on the minimum temperature extremes than on the mean. The 5th and the 95th percentile of daily minimum temperatures have increased by 1.2°C and 1.1°C respectively. This increases extreme temperatures in such a way that the 95th percentile of the first period is the 92.7th percentile of the second period (i.e., there is a 40% increase in more recent decades in the number of extreme temperatures defined by the warmest 5% of the 1951–1980 distribution). The 5th percentile of the earlier period changes to the 3.2nd percentile in the last 30 years.

[15] For daily maximum temperatures over the globe, the mean anomaly has increased by 0.6°C, so slightly less than the daily minimum temperature anomalies (Figure 2b). The distribution is negatively skewed in both periods but less so for the latter period indicating a tendency towards warmer temperatures. The changing distribution parameters have increased the upper 5th percentile threshold by a similar amount as the mean (0.7°C) and the lower 5th percentile threshold has increased by 0.8°C. Similar to Tmin, the value of the 95th percentile in the first 30 years equates to the 93rd percentile in the latter period, and only 3.7% of the values from the latter period lie below the 5th percentile of the first 30 years.

[16] As the mean daily temperature anomalies are unevenly distributed over the globe (generally larger in the extra-tropics than in the tropics), the tails in Figure 2a could thus likely be dominated by the extra-tropics. Therefore we addressed this by calculating PDFs for different latitudinal regions: northern hemisphere extra-tropics (30°N–90°N, Figure 2b), tropics (30°S–30°N, Figure 2c), and southern hemisphere extra-tropics (90°S–30°S, Figure 2d). As already suggested by Figure 1a, there is a positive shift in the location of the PDF for all of these regions. The PDF has become wider in the tropics for both Tmin and Tmax in the latter period, indicated by a higher variance, whereas for the (aggregation of) extra-tropical grid boxes the variance seems to become somewhat lower. Note, however, that variance changes were heterogeneous on regional scales (Figure 1b), showing also in the extra-tropics regions of (largely non-significant) increased and reduced variance – which mostly compensate when aggregating over the entire extra-tropics. A tendency towards more positive (or less negative) skewness is found in all of the sub-regions apart from Tmax in the tropics, suggesting a systematic deformation of the PDFs towards warmer temperatures, additional to the shift in location.

[17] The results imply that for both minimum and maximum daily temperatures, it is a combination of changes in mean, variance and skewness which are associated with the changes that have been observed in extreme daytime and night-time temperatures over the latter part of the 20th century [e.g., *Alexander et al.*, 2006]. Note that changes in the statistical parameters calculated are mostly greater for daily minimum than maximum temperatures implying a greater effect on global night-time temperatures. Our results agree with some climate modeling studies which suggest that changes in temperature extremes under anthropogenic forcing cannot be explained solely through changes in the mean [e.g., *Clark et al.*, 2006; *Hegerl et al.*, 2004], although other studies [e.g., *Barnett et al.*, 2006] argue that changes in extreme temperatures are primarily the response of a simple shift in the distribution.

[18] A caveat to this study is that the data set lacks coverage over parts of South America, Africa and India. Also we have found some sensitivity in the global PDFs to different data completeness criteria (mainly affecting variance), as this includes or excludes grid boxes mainly in the tropics (Africa, northern South America) where locally significant increases in variance are found. Furthermore, HadGHCND does not specifically address artificial changes in individual station time series, although assuming these are randomly distributed, this should have a minor effect when spatially averaging a large number of stations [*Caesar et al.*, 2006]. However, HadGHCND is currently the most comprehensive data set of daily temperature fields. The use of climate model data or new observational data sets with improved coverage may help to enhance the confidence particularly for data sparse regions.

4. Conclusions

[19] In this study we present how the global daily temperature distribution of both maximum and minimum temperatures has experienced change since the middle of the 20th century. Using daily anomalies has allowed us to make a consistent comparison across the globe. This relatively simple study adds to the state of knowledge, helping to understand the patterns of the observed recent warming and the influence this has had on changes in extremes. We show that the PDFs of both Tmin and Tmax have shifted towards warmer temperatures almost everywhere. Changes in variance appear spatially heterogeneous; however in the tropics we find generally wider distributions. In most regions we find changes in skewness towards the hotter part of the distribution.

[20] Thus, we show that based on observational data the changes in the temperature distributions reflect aspects of all the changes that are suggested by the schematic figure SPM.3 presented in SREX, i.e., an increase in mean and skewness, with spatially more heterogeneous changes in variance.

[21] Using the data from this study we conclude that daily temperatures (both daytime and night-time) have indeed become “more extreme” and that these changes are related to shifts in multiple aspects of the daily temperature distribution other than just changes in the mean. However evidence

is less conclusive as to whether it has become "more variable".

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