Uncertainty in hottest years ranking: analysis of Tibetan Plateau surface air temperature

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Abstract

Changes in surface air temperature can directly affect hydrology, agriculture, and ecosystems through extreme climate events such as heat waves. For this reason, and to improve climate change adaptation strategies, it is important to investigate the ranking of hottest years. In this study, the Wilcoxon signed-rank test and Monte Carlo simulation are used to estimate the ranking of the hottest years for the Tibetan Plateau (TP) in recent decades, and the uncertainty in the ranking. The Wilcoxon signed-rank test shows that the top 10 hottest years on record over the TP mainly occur after 1998. The top three hottest years are ranked as 2006, 2009, and 2010, but there is almost no significant difference between them. When both sampling and observational errors are considered, only five years have a non-zero probability of being the hottest year, with the three highest probabilities being for the years 2006 (~47.231%), 2009 (~40.390%), and 2010 (~12.376%). Similarly, with respect to a given year that is among the 10 hottest years, our results show that all the years among the ranks of 1–10 resulting from the Wilcoxon signed-rank test have probabilities above 10%, while the years 2001 and 2012 have probabilities of 3% and 4%.

1. Introduction

It is widely accepted that many applications need reliable and well-synthesized information regarding climate extremes and their impacts to form reasonable strategies and make sensible decisions. One way to meet these needs is to use indicators of climate extremes, such as rankings of the hottest years, thus helping to gain a better understanding of the scientific problem. The ranking of hottest years is determined based on data from meteorological observational stations and statistical inference, and as such has been investigated at different temporal scales and in different regions of the world, such as the USA (Shen, Lee, and Lawrimore 2012; Arguez et al. 2013; Shen et al. 2016), Australia (King et al. 2014), China (Zhai et al. 2016), Europe (Luterbacher et al. 2004), and globally (Zhang, Li, and Wan 2016).

The Tibetan Plateau (TP), known as the ‘third pole’, is the highest plateau in the world and home to the headwaters of several important large rivers in East Asia. In recent years, significant warming has been detected over the TP – a trend with the potential to reinforce climate extremes and disasters (Wang et al. 2013). Thus, there is significant demand for information concerning TP climate change resulting from global warming, because such information is important for our understanding of both the causes and the impacts of climate change over the TP on
natural resources and ecosystems in China. Although the hottest years on record over the TP have been ranked in previous studies (eastern part (Li et al. 2015); northeastern part (Pan, Wu, and Liu 2015); southeastern part (Fan et al. 2011); and central part (Yan and Liu 2014)), these studies were mainly based on the arithmetic average of surface air temperature (SAT), without strict statistical inference. Furthermore, such rankings do not consider the various errors in data and related uncertainties of their conclusions. These critical scientific questions remain unanswered, and only by addressing these questions can we build a cumulative understanding of climate and climate change. Accordingly, the present study aims to (1) characterize the annual ranking of TP temperature from 1951 to 2013, and (2) investigate the uncertainty in that ranking.

2. Data and method

The monthly mean maximum and minimum temperature ($T_{\text{max}}$ and $T_{\text{min}}$) records observed at 100 meteorological stations over the TP (above 2000 m), for the period 1951–2013, are employed in this study. The locations and elevations of the stations are given in Figure 1.

The Wilcoxon signed-rank test (Wilcoxon 1945) is used to rank the hottest years. The approach is performed on paired data to test whether a year is significantly hotter than the following year. The $p$-value of the test, returned as a non-negative scalar from 0 to 1, is defined as the probability of observing a test statistic as or more extreme than the observed value under the null hypothesis, to determine whether the samples are significantly different. A Monte Carlo simulation (Guttorp and Kim 2013) is used to explore the uncertainty of the annual rankings for the TP temperature time series. The main idea of Guttorp and Kim (2013) is to assume that the SAT of each year, $\beta(t)$, is treated independently. Then, one can simulate different time series with the annual mean SAT anomaly and standard error, $\epsilon(t)$, by shifting it up or down, i.e.

$$T_i(t) = \beta(t) + \epsilon(t)r(t).$$

Here, $T_i(t)$ is the $i$th simulation annual mean SAT anomaly time series and $r(t)$ is the random normal number. Thus, from a large number of simulated time series, we can calculate the rank of each year in the different simulated time series, as well as count the proportion of a given year that is the hottest year, and among the top 10 hottest years.

3. Results

As the first step of data analysis, the mean temperature ($T_{\text{mean}}$) is calculated as the average of $T_{\text{max}}$ and $T_{\text{min}}$. Table 1 shows the results of the top 10 hottest years ranked by the Wilcoxon signed-rank test. In the 63 years from 1951 to 2013, eight of the top 10 hottest years occur after 2002. Among the other two, one occurs in 1998 and another in 1999. The hottest three years for the TP average annual $T_{\text{mean}}$ are 2006 (1.509 °C), 2009 (1.496 °C), and 2010 (1.432 °C). Table 1 also shows very small differences in SAT anomalies for some years, such as 2006/2009, and these differences may be affected significantly by the selection of spatial averaging or integration methods. This can also be seen in Table 1 in that, although the year 2006 is by far the hottest year, the $p$-value is not really small. Furthermore, the remaining hottest years are not significantly different, statistically, except for the fourth hottest year, 2007, which has a significant $p$-value at a 95% confidence level, making it difficult to definitely say which year is hotter.

Furthermore, owing to the replacement of instrumentation, the uneven spatial distribution, changing observational practices, the relocation of observation sites, and the effect of urbanization, errors contaminate the observational data and create uncertainties (Jones, Osborn, and Briffa 1997; Brohan et al. 2006; Morice et al. 2013; Hua, Shen, and Wang 2014; Hua et al., forthcoming).

The Wilcoxon signed-rank test can rank the hottest year, but without considering the data error, and therefore the
A question arises as to how the uncertainty might influence the ranking of the hottest years. In statistical climatology, a typical expression of this uncertainty is the standard error. Here, we utilize the standard error from our previous study (Hua et al., forthcoming), which investigated the sampling error (the uncertainty caused by a non-exhaustive survey) and the observational error (the uncertainty caused by station data quality). The sampling error and observational error are calculated based on the correlation-factor method of Shen, Lee, and Lawrimore (2012) and the assumption postulated in Hua et al. (forthcoming). For example, Figure 2 shows the annual mean series with its uncertainties (adapted from Figure 5 in Hua et al. (forthcoming)). From the figure, we can see that the year 2007, with the annual mean anomaly being 1.210 °C, is recorded as the fourth hottest year. However, this year may be ranked as the second hottest year if its anomaly plus error bar at a 95% confidence interval is considered. Similarly, the same year can be ranked as eighth if the anomaly minus error bar is considered. Thus, it is important to understand uncertainty when determining rankings of hottest years.

To explore the uncertainty in ranking, we first simulate the annual mean $T_{\text{mean}}$ time series using Equation (1). We then repeat this a large number of times (10,000 times in this paper) to generate a probability distribution of each year to be the hottest year, with an accuracy of two decimal places in proportions. Figure 3 shows 10 simulated random series. We can then easily obtain the rank of each year in the simulated series. Table 2 shows the probability of a year being the hottest in recent decades.

We can see from Table 2 that there are only five years in recent decades that have non-zero probabilities to be the hottest year on record. In addition, no single year can exceed a 50% probability of being the hottest year. The years 2006, 2009, and 2010 have probabilities above 10%, with values of 47.231%, 40.390%, and 12.376%, respectively. The ranks of 1999 and 2007 are very uncertain, with very small probabilities of 0.001% and 0.002%. Thus, we can say that the year 2006 has the highest probability for reaching the hottest year since 1951. The year 2009 comes second, followed by the year 2010.

But what about the probability that a given year is among the top 10 hottest years? Table 3 shows the results. Among the 63 years from 1951 to 2013, eight have probabilities of more than 70%, and the years 2005 and 2003 have probabilities of more than 35% and 12%. It is worth noting that, although the probabilities are quite small (2%–3%), the years 2001 and 2012 (not ranked in Table 1) come out as being in the top 10 hottest years. Thus, it is not acceptable to neglect the uncertainties in data when performing ranking analyses.
Table 3. The probability (%) that a year is among the top 10 hottest years during 1951–2013. Only years with a probability score >1% are shown.

| Year | Probability (%) | Rank in Table 1 |
|------|----------------|-----------------|
| 1998 | 89.946         | 7               |
| 1999 | 99.872         | 5               |
| 2001 | 2.663          | –               |
| 2003 | 12.152         | 10              |
| 2005 | 35.941         | 9               |
| 2006 | 100.000        | 1               |
| 2007 | 100.000        | 4               |
| 2009 | 100.000        | 2               |
| 2010 | 100.000        | 3               |
| 2011 | 70.425         | 8               |
| 2012 | 3.578          | –               |
| 2013 | 97.214         | 6               |

4. Conclusion

In this paper, the ranking of the hottest years in the TP region and the uncertainty in that ranking are explored using the Wilcoxon signed-rank test and Monte Carlo simulation. The results show that the top 10 hottest years mainly occur after 1998, and the three hottest years over the TP are ranked as 2006, 2009, and 2010, albeit there is almost no significant difference between groups.

To obtain insight into the uncertainty in climate change, both sampling and observational errors are considered to assess the uncertainty in the rankings for the TP SAT time series. Only five years have probabilities above 1% of being the hottest year, with the three highest probabilities being for the years 2006 (~47.231%), 2009 (~40.390%), and 2010 (~12.376%). We also analyze the probability that a given year is included in the top 10 hottest years. All the years ranked in Table 1 have at least more than a 10% probability; moreover, the years 2001 and 2012, although not shown in Table 1, and quite small, certainly have probabilities of being detected in the top 10 hottest years. Although both sampling and observational errors are considered, according to our previous study, the sampling error is greater than the other errors. However, to better understand the uncertainties in climate change, future work could estimate other errors, such as bias error, homogenization adjustment error, normal error, and so on.

Disclosure statement

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References

Arguez, A., T. R. Karl, M. F. Squires, and S. V. Russell. 2013. “Uncertainty in Annual Rankings from NOAA’s Global Temperature Time Series.” Geophysical Research Letters 40: 5965–5969.

Brohan, P., J. J. Kennedy, I. Harris, S. F. B. Tett, and P. D. Jones. 2006. “Uncertainty Estimates in Regional and Global Observed Temperature Changes: A New Data Set from 1850.” Journal of Geophysical Research Atmospheres 111: D12106. doi:10.1029/2005JD006548.

Fan, Z., B. Achim, T. Axel, J. Li, and K. Cao. 2011. “Spatial and Temporal Temperature Trends on the Yunnan Plateau (Southwest China) during 1961–2004.” International Journal of Climatology 31: 2078–2090.

Guttorp, P., and T. Y. Kim. 2013. “Uncertainty in Ranking the Hottest Years of U.S. Surface Temperatures.” Journal of Climate 26: 6323–6328.

Hua, W., G. Z. Fan, Y. W. Zhang, L. H. Zhu, Y. L. Zhang, B. Y. Yang, M. J. Zhang, Y. Hu, and Q. Y. Wu. Forthcoming. “Trends and Uncertainties in Surface Air Temperature over the Tibetan Plateau, 1951–2013.” Journal of Meteorological Research 31: 1–12. doi:10.1007/s13351-017-6013-x.

Hua, W., S. S. P. Shen, and H. J. Wang. 2014. “Analysis of Sampling Error Uncertainties and Trends in Maximum and Minimum Temperatures in China.” Advances in Atmospheric Sciences 31: 263–272.

Jones, P. D., T. J. Osborn, and K. R. Briffa. 1997. “Estimating Sampling Errors in Large-scale Temperature Averages.” Journal of Climate 10: 2548–2568.

King, A. D., D. J. Karoly, M. G. Donat, and L. V. Alexander. 2014. “Climate Change Turns Australia’s 2013 Big Dry into a Year of Record-breaking Heat.” Bulletin of the American Meteorological Society 95: S41–S45.

Li, Z. S., G. H. Liu, L. Gong, M. Wang, and X. C. Wang. 2015. “Tree Ring-based Temperature Reconstruction over the past 186 Years for the Miyaluo Natural Reserve, Western Sichuan Province of China.” Theoretical and Applied Climatology 120: 495–506.

Luterbacher, J., D. Dietrich, E. Xoplaki, and M. Grosjean. 2004. “European Seasonal and Annual Temperature Variability, Trends, and Extremes since 1500.” Science 303: 1499–1503.

Morice, C. P., J. J. Kennedy, N. A. Rayner, and P. D. Jones. 2013. “Quantifying Uncertainties in Global and Regional Temperature Change Using an Ensemble of Observational Estimates: The HadCRUT4 Data Set.” Journal of Geophysical Research Atmospheres 117: D08101. doi:10.1029/2011JD017187.

Pan, T., S. Wu, and Y. Liu. 2015. “Relative Contributions of Land Use and Climate Change to Water Supply Variations over Yellow River Source Area in Tibetan Plateau during the past Three Decades.” PLoS One 10: e0123793.

Shen, S. S. P., C. K. Lee, and J. Lawrimore. 2012. “Uncertainties, Trends, and Hottest and Coldest Years of U.S. Surface Air Temperature since 1895: An Update Based on the USHCN V2 TOB Data.” Journal of Climate 25: 4185–4203.

Shen, S. S. P., O. Wied, A. Weithmann, T. Regele, B. A. Bailey, and J. H. Lawrimore. 2016. “Six Temperature and Precipitation Regimes of the Contiguous United States between 1895 and 2010: A Statistical Inference Study.” Theoretical and Applied Climatology 125: 197–211.

Wang, S. J., M. J. Zhang, B. L. Wang, M. P. Sun, and X. F. Li. 2013. “Recent Changes in Daily Extremes of Temperature and
Precipitation over the Western Tibetan Plateau, 1973–2011.” *Quaternary International* 313: 110–117.

Wilcoxon, F. 1945. “Individual Comparisons by Ranking Methods.” *Biometrics* 1: 80–83.

Yan, L., and X. Liu. 2014. “Has Climatic Warming over the Tibetan Plateau Paused or Continued in Recent Years?” *Journal of Earth, Ocean and Atmospheric Sciences* 1: 13–28.

Zhai, P., R. Yu, Y. J. Guo, Q. X. Li, X. J. Ren, Y. Q. Wang, W. H. Xu, Y. J. Liu, and Y. H. Ding. 2016. “The Strong El Niño of 2015/16 and Its Dominant Impacts on Global and China’s Climate.” *Journal of Meteorological Research* 30: 283–297.

Zhang, C., S. L. Li, and J. H. Wan. 2016. “The Warmest Year 2015 in the Instrumental Record and Its Comparison with Year 1998.” *Atmospheric and Oceanic Science Letters* 9: 487–494.