# Relative increase of record high maximum temperatures compared to record low minimum temperatures in the U.S.

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[1] The current observed value of the ratio of daily record high maximum temperatures to record low minimum temperatures averaged across the U.S. is about two to one. This is because records that were declining uniformly earlier in the 20th century following a decay proportional to 1/n (n being the number of years since the beginning of record keeping) have been declining less slowly for record highs than record lows since the late 1970s. Model simulations of U.S. 20th century climate show a greater ratio of about four to one due to more uniform warming across the U.S. than in observations. Following an A1B emission scenario for the 21st century, the U.S. ratio of record high maximum to record low minimum temperatures is projected to continue to increase, with ratios of about 20 to 1 by mid-century, and roughly 50 to 1 by the end of the century. **Citation:** Meehl, G. A., C. Tebaldi, G. Walton, D. Easterling, and L. McDaniel (2009), Relative increase of record high maximum temperatures compared to record low minimum temperatures in the U.S., *Geophys. Res. Lett.*, *36*, L23701, doi:10.1029/2009GL040736.

## 1. Introduction

[2] As of the end of September, 2009, inspection of the National Climatic Data Center web site that archives observed annual record high maximum and record low minimum daily temperatures from weather stations across the U.S. (http://www.ncdc.noaa.gov/oa/climate/research/records/) showed that since January 1, 2000, there had been 291,237 record high maximum daily temperatures set, and 142,420 record low minimum daily temperatures, or a ratio of roughly two to one. Since January 1, 2009 (also compiled to the end of September, 2009), there had been 11,711 record highs and 7,449 record lows, with a ratio of just less than two to one. Though this simple summation does not take into account station record length or any autocorrelation effects, it is not unexpected that there would be more record high maximum temperatures being set than record low minima simply because the annual U.S. average surface temperatures have been increasing since the 1970s [*Karl et al.*, 2006; *Trenberth et al.*, 2007; *Hegerl et al.*, 2007]. A simple shift of the statistical distribution of temperatures at a given station would dictate that there would be more record high temperatures than record lows [*Benestad*, 2003; *Solomon et al.*, 2007, Figure 1, Box TS.5]. However, we would not expect a two to one ratio of record highs to record lows to persist for a long time in a steadily warming climate, and we attempt in this paper to put this particular value of the ratio in context, as we look at observations over the last 50-plus years and, in particular, to model simulations that allow us to study the effects of future warming.

[3] We use a subset of nearly 2000 stations of the over 5000 quality controlled NCDC US COOP network station observations of daily maximum and minimum temperatures, retaining only those stations with less than 10% missing data (in fact the median number of missing records over all stations is 2.6%, the mean number is 1.2%). All station records span the same period, from 1950 to 2006, to avoid any effect that would be introduced by a mix of shorter and longer records. The missing data are filled in by simple averages from neighboring days with reported values when there are no more than two consecutive days missing, or otherwise by interpolating values at the closest surrounding stations. Thus we do not expect extreme values to be introduced by this essentially smoothing procedure. In addition our results are always presented as totals over the entire continental U.S. region or its East and West portions, with hundreds of stations summed up. It is likely that record low minima for some stations are somewhat skewed to a cool bias (e.g., more record lows than should have occurred) due to changes of observing time (see discussion by *Easterling* [2002] and discussion in auxiliary material), though this effect is considered to be minor and should not qualitatively change the results.[5] Additionally, at some stations two types of thermometers were used to record maximum and minimum temperatures. The switch to the Max/Min Temperature System (MMTS) in the 1980s at about half the stations means that thermistor measurements are made for maximum and minimum. This has been documented by *Quayle et al.* [1991], and the effect is also considered to be small. To address this issue, an analysis of records within temperature minima and within temperature maxima shows that the record minimum temperatures are providing most of the signal of the increasing ratio of record highs to record lows (not shown).

[4] The model data are from the NCAR Community Climate System Model version 3 (CCSM3) that was run for simulations of 20th century and 21st century climate [*Meehl et al.*, 2006], where for 20th century, both natural (volcanoes and solar) and anthropogenic (GHGs, ozone and direct effect of sulfate aerosols) forcings are included. In the model, warming over the U.S. at the end of the 20th century is somewhat greater than observed [*Meehl et al.*, 2006], and mostly attributed to human activity [*Meehl et al.*, 2007; *Hegerl et al.*, 2007].

## 2. Twentieth Century

[5] Probability theory states that, in the case of an independent sequence of random variables identically distributed,

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[5]Auxiliary materials are available in the HTML. doi:10.1029/2009GL040736.

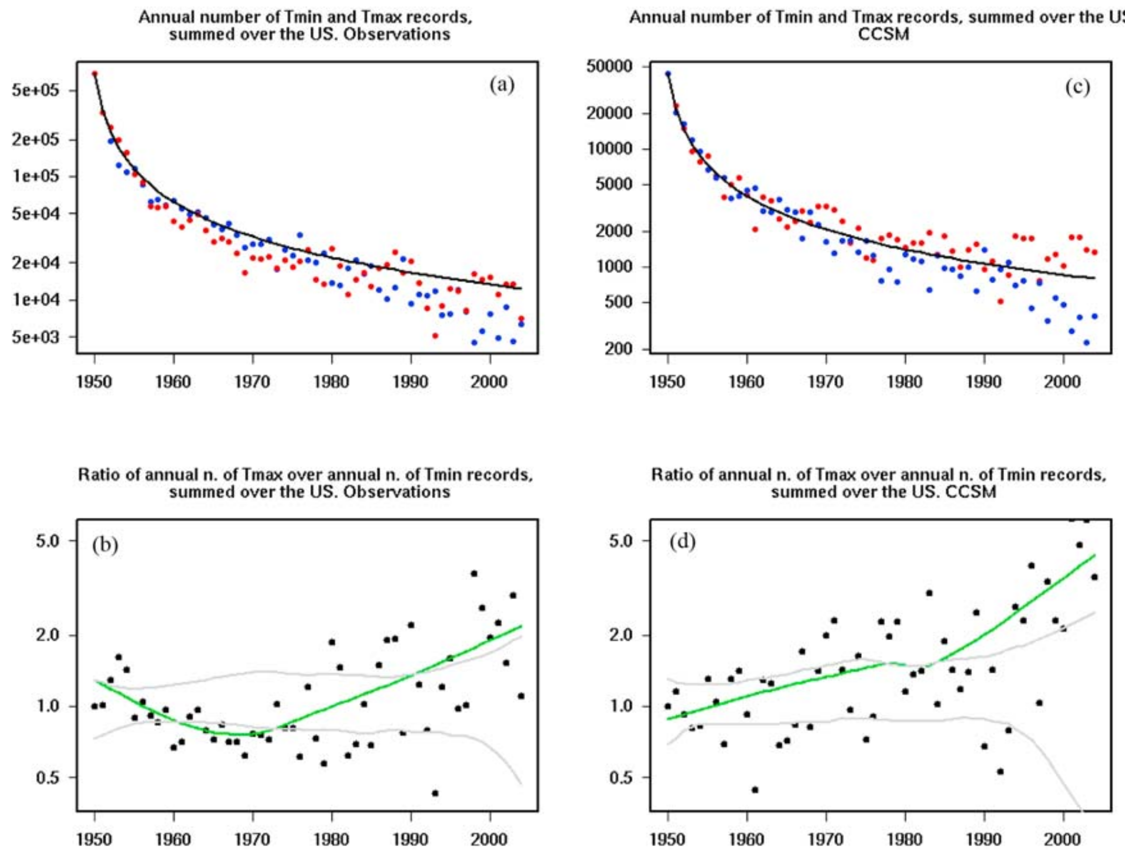


**Figure 1.** Comparison of observed and modeled statistics of records, averaged over the entire U.S. region, (a) annual numbers of record high maximum temperatures (red dots) and record low minimum temperatures (blue dots) compared to the theoretical values (black line) under stationary conditions, following a decay of 1/n where n is the number of years from the start of record counting; (b) observations of the ratio of record highs to record lows each year (dots), solid line is a smoothed curve fit, and the envelope of the 95% CI from the bootstrap is marked by grey lines; (c) same as Figure 1a except from a single simulation of the 20th century from the model; (d) same as Figure 1b except for the model. Note that the heteroscedasticity of the sample values (increased variance over time) is to be expected since the values are obtained as ratios of increasingly smaller numbers (the overall number of annual records decreases with the length of the record). Difference of a few units in large numerators/denominators does not cause the same variability in the ratio as difference of a few units in ratios of small numbers.

the number of records should decrease as 1/n, where n is the number of realizations of the independent variable accumulating as we observe it. In our case n is time, in particular it is the year for which we observe the value of a calendar day maximum and minimum temperature and we compare it to the standing record highs and lows. As years (and records) accumulate it becomes increasingly difficult for a stationary process to break a record, asymptotically as difficult as an event with probability 1/n. [e.g., *Arnold et al.*, 1998]. Thus, the number of years a station has been operating is an important aspect of accounting for numbers of records. Analysis of observed station data for the U.S. has shown that starting a 1/n calculation by taking all stations available in mid-20th century produces a credible accounting of records with distinct seasonal and geographical features (R. W. Portmann et al., Seasonal and geographic aspects of changes in record temperatures, manuscript in preparation, 2009). They also show that two factors influence changes in the numbers of records that deviate from the theoretical 1/n relationship, involving 1) different natural variability translating into a wider or narrower variance of the climatological distribution of temperature and 2) changes in temperature trends. It has been shown that regional changes of temperatures and precipitation are related to regional changes of extreme temperatures in some areas and seasons [*Portmann et al.*, 2009].

[6] Figure 1a shows the decay of observed annual record high maximum temperatures (red dots) compared to annual record low minimum temperatures (blue dots) averaged over the U.S. since 1950. The smooth line is the theoretical or expected rate of decay corresponding to 1/n times the number of stations over which the records are summed. The expected rate of decay is a good explanation for the time series of annual number of records (both highs and lows) up to about 1980, whereas after 1980 there are clearly more red dots falling above the line and more blue dots below the line, making the theoretical behavior under a stationary process a poorer fit than in the first part of the record. In particular the position of the dots relative to the theoretical line seems to suggest that the number of observed record lows has been declining more rapidly than expected, while record highs stay closer to their expected behavior even in the later part of the period. The ratios of record high maxima to record low minima are shown in Figure 1b, with a non-linear curve fit to the values. The expected ratio in a stationary climate would be 1.0, but it can be seen that in the 1950s this ratio was

somewhat above 1.0, it dropped to a bit below 1.0 in the 1960s and 1970s, and then has been rising ever since such that in the most recent decade the ratio is roughly 2 to 1 as noted earlier. The time evolution of this ratio reflects the rate of change of U.S. average temperatures, with greater rates of warming in the 1950s, almost no warming in the late 1950s and 1960s, and warming since the 1970s [*Karl et al.*, 2006; *Trenberth et al.*, 2007]. From the results in Figure 1a we can also infer that the larger than expected values of the ratio seem to be due to less than expected record lows rather than more than expected record highs. It is also seen that the recent period when the ratio has been 2 to 1 is just the latest value characteristic of a warming climate, while the ratio was less than that in the previous several decades. In order to characterize the significance of these "larger values" of the ratio (i.e., values greater than 1.0), we perform a bootstrap analysis by resampling the sequence of 55 years in the observed records using blocks of three consecutive years to account for the possible presence of time correlation. We produce one hundred new time sequences and we apply them uniformly across the set of stations and for maximum and minimum temperature. We repeat the computation of records for the new artificial sequences of observations, sum the annual numbers of records over space and recompute the 55 values of the ratio for each of the 100 bootstrap samples.

[7] By applying the smooth fit to each, we determine an envelope of possible results where the presence of a trend in the measurement of minimum and maximum temperature would be eliminated by the random resampling of (blocks of) years. This envelope of results is shown as grey lines, against which the observed is plotted as a thick black line (Figure S1). Only one other trajectory of the ratio is higher than the observed after the late-1990s, out of the 100 bootstrapped trajectories, indicating that the large recent values of the ratio as observed are statistically significant. The 95% confidence interval derived by the bootstrap procedure is also shown in Figure 1b.

[8] To compare to a single realization of 20th century climate from the CCSM, Figure 1d shows that the simulated records diverge from the theoretical 1/n line somewhat earlier in the century for record high maxima and record low minima, and in a more symmetric fashion when comparing lows and highs. Additionally, the ratio for the most recent decade (Figure 1d) has climbed to about 4 to 1. The greater ratio compared to observations suggests a larger base state warming in the model as noted earlier, which also manifests itself in a more even change between the behavior of minimum and maximum temperatures. Similar bootstrap results to those for the observations discussed above confirm the significance of the model simulated large values of the ratio. That is, generating time series of another 100 realizations of simulated 20th century climate indicates that the larger warming (compared to the observations) and corresponding larger ratio is significant (Figures 1d and S2). Notably the results from CCSM do not show decadal modulation of the ratio but rather indicate a steady increase of the ratio over the course of the historical period.

[9] Part of the reason for this greater ratio in the model compared to observations lies in the spatial distribution of annual mean temperature increase, with greater observed warming in the western U.S. compared to the eastern U.S. [*Trenberth et al.*, 2007]. This is reflected in the eastern vs. western U.S. record temperatures in Figure 2, with less of a divergence from the expected 1/n decay for record highs versus record lows in the east (all stations east of 100W, Figure 2) compared to the west (Figures 2a and 2b), with a ratio for the eastern U.S. that is somewhat less than 2 to 1 where warming has been less, compared to the west where the ratio is over 3 to 1 associated with greater base state warming. By applying the spatial disaggregation to the bootstrapped results described above, we can test the significance of the large values of these two ratios as well (Figure S3). The values in the Eastern part of the United States are significantly different from what should be expected in the absence of a trend only at a 10% or greater level, while in the West the significance of the results is such that none of the bootstrapped sequence of ratio values lies above the observed.

[10] The model shows some indications of greater average warming in the western U.S. compared to the east [e.g., *Meehl et al.*, 2006] as evidenced by a simulation of greater decreases of frost days (nighttime minimum temperatures below freezing [*Meehl et al.*, 2004]) and greater heat wave intensity [*Meehl and Tebaldi*, 2004; *Tebaldi et al.*, 2006] in the west compared to the east. In terms of records, though not as pronounced as in the observations, the model shows a divergence from the expected 1/n relationships between record highs and record lows for the two parts of the country (Figures 2c and 2d), with a ratio of less than 4 to 1 for the east compared to a ratio of over 5 to 1 for the west. Therefore, the model is capturing some elements of the greater ratio of record highs to record lows in the west compared to the east as seen in the observations, but with ratios that are higher than observed, and a more symmetric change in the numbers of record lows and record highs as they deviate from the expected rate. Bootstrap-based tests have confirmed the significance of these large values of the ratios similar to what was found for observations (Figure S4).

## 3. Twenty-First Century

[11] Earlier we posed the question of whether the recently observed 2 to 1 ratio of record high maximum temperatures to record low minimum temperatures is somehow a unique characteristic of a warming climate. To address that question we plot this ratio from the model for the 20th century and 21st centuries (the latter following the mid-range A1B scenario [*Meehl et al.*, 2006]) in Figure 3. It can be seen that as the climate continues to warm during the 21st century, the number of record highs fall in larger and larger measure above the theoretical expectation line as compared to the number of record lows falling below the same line (Figure 3a). This is reflected in the ongoing increase in the ratio (Figure 3b) such that by mid-century the ratio is about 20 to 1, and by late century it is around 50 to 1. Presumably at some point after 2100 there would come a time when there would be no more record low minima being set, and only record high maxima would be recorded, though the model indicates that this has not yet occurred in the A1B scenario over the U.S. by 2100. We conducted a similar analysis on simulations from CCSM under SRES B1 (lower forcing than A1B) and A1FI (higher forcing than A1B). For the low scenario B1 the values of the ratio are about 8 to 1 by mid-century, but are in the range of hundreds to one for scenario A1FI by mid-century, when computed on the same set of grid

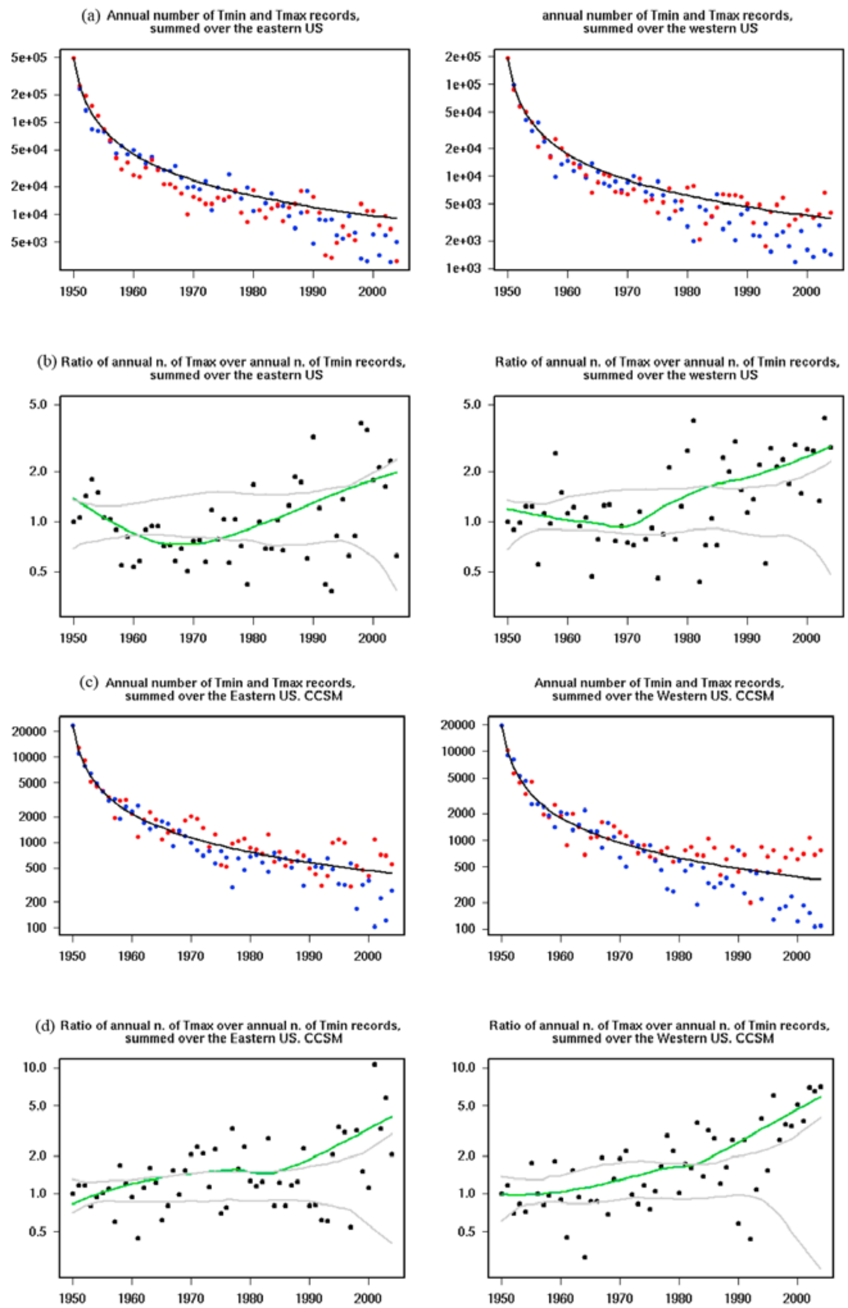


**Figure 2.** As Figure 1, but for observations and model, and splitting the stations between Western (right column) and Eastern regions (left column) of the U.S., along the 100W meridian. (a) Annual numbers of record highs (red dots) and lows (blue dots) and expected behavior (black line) for observations. (b) Annual values of the ratio of number of record highs to lows and a smooth curve fit, plus the 95% CI computed by bootstrap for observations. (c) Same as Figure 2a but for the model and (d) as Figure 2b but for the model.

points covering the continental U.S. (on the order of 80 gridpoints). These specific values for the ratios over the 21st century are very likely model-dependent, and thus are only indicative of how these ratios could evolve. Rather they are suggestive of the order of magnitude of the changes of the ratios in a future warming climate.

## 4. Conclusions

[12] Analysis of observed annual U.S. record high maximum compared to record low minimum daily temperatures shows that the recent values of the ratio of about 2 to 1 are just the transient values of a ratio that has been increasing with mean annual mean temperature over the U.S. since the late 1970s. B. C. Trewin and H. Vermont (Changes in the frequency of record temperatures in Australia, 1957–2007, submitted to *Australian Meteorological and Oceanographic Journal*, 2009) have also documented a similar recent ratio of about 2 to 1 over Australia for monthly temperature records. As noted in other studies (Portmann et al., manuscript in preparation, 2009), there are geographic and seasonal characteristics to these records, and it is shown that the greater values of the ratio

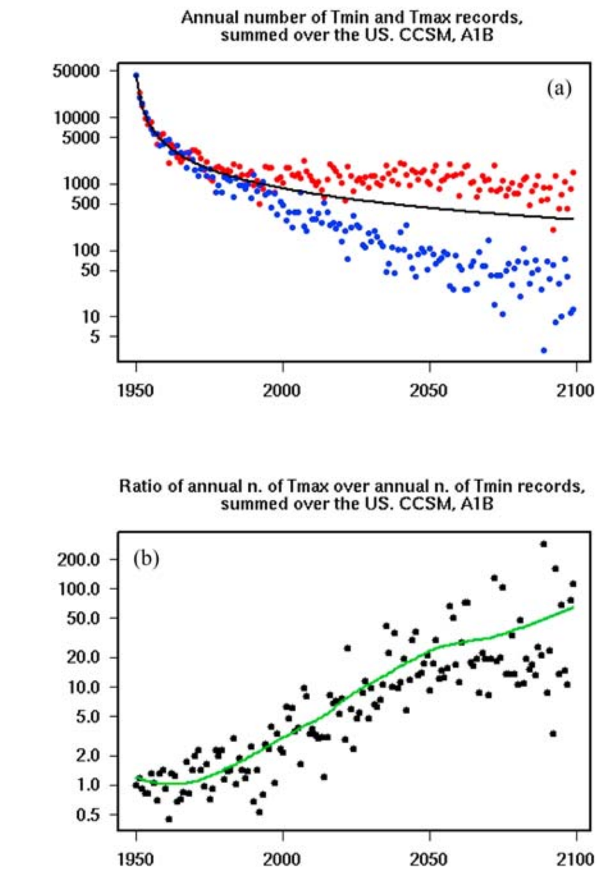


**Figure 3.** (a) Annual numbers of record highs and lows and (b) their ratio computed from the model, using 20th century and SRES A1B 21st century experiments. Plots are similar to Figures 1c and 1d but extend the time horizon to the end of the 21st Century.

for the western U.S. (where mean warming has been greater) compared to eastern U.S. are simulated with reduced contrast in the model, with greater values of the ratio simulated in the model, likely indicative of the greater mean warming in the model over the U.S. compared to observations (about 30%) by the early 21st century. Additionally, while observations seem to indicate that record lows have been declining in larger measure than record highs have been increasing, the model simulates a more symmetric behavior between minimum and maximum record temperatures. For later in the 21st century, the model indicates that as warming continues (following the A1B scenario), the ratio of record highs to record lows will continue to increase, with values of about 20 to 1 by mid-century, and roughly 50 to 1 by late century.

[13] Two factors contribute to this increase as noted by Portman et al. (manuscript in preparation, 2009): 1) increases in temperature variance in a future warmer climate (as noted in the model by *Meehl and Tebaldi* [2004]), and 2) a future increasing trend of temperatures over the U.S. (model projections given by *Meehl et al.* [2006]). Since the A1B mid-range scenario is used, a lower forcing scenario (e.g., B1) produces reduced values of the ratio in the 21st century, and a higher forcing scenario (e.g., A2) produces greater values. The model cannot represent all aspects of unforced variability that may have influenced the observed changes of record temperatures to date, and the model over-estimates warming over the U.S. in the 20th century. The future projections may also reflect this tendency and somewhat over-estimate the future increase in the ratio. Under any future scenario that involves increases of anthropogenic greenhouse gases and corresponding increases in temperature, the ratio of record high maximum to record low minimum temperatures will continue to increase above the current value.

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