# Climate change in China: Communism is cooler

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*Abstract*

With most of the world experiencing more extreme temperatures, one country stands out -- China. Here, we report on a newly compiled data set of historical weather records between 1929-44 at 43 stations in Mainland China. Comparing the historical records with modern weather records between 1951-2010, we document that summer temperatures (as reported) have become less extreme. In July and August, the probabilities of the daily temperature exceeding 35ºC, 37ºC, and 40ºC were lower by 26-36%, 47-51%, and 90% respectively in 1951-2010 as compared with 1929-1944. We explore and rule out various explanations of the apparent "summer cooling" -- the aerosol effect of increased air pollution, movement of weather stations, changes in land use, and changes in meteorological standards. One explanation that we cannot rule out is under-reporting of extreme temperatures to help industry cope with labour laws that regulate hours of work and monetary compensation during periods of hot weather.

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# Introduction

Against the background of global warming (Hansen et al. 2006; Xu and Ramanathan 2012), extreme temperatures have been become more frequent and spread over larger areas (Hansen et al. 2012; Coumou and Rahmstorf 2012). However, one region stands out from the broad pattern of more frequent extreme high temperatures during the summer months -- China. Recent studies using different data-sets and covering different periods find either no increase in the frequency of extreme temperatures in the summer (Hansen et al. 2012: Figure 8) or increased frequency of extreme temperatures only in west-central China (Wen et al. 2013).

This paper investigates the pattern of extreme summer temperatures in China using a radically different approach from previous research. While most previous research considered the weather since 1951 on an annual or monthly basis, our study extends further back in time and analyzes extreme temperatures on a daily basis. From multiple historical sources, we compile the largest known data-set of daily surface air temperature, covering 43 stations, in mainland China between 1929-1944. We match the historical records by station with records for 1951-2010. Rather than spatially extrapolate the data by gridding, we analyze the temperatures at the individual stations and use regression methods to account for global weather trends, seasonal differences, and secular changes specific to the individual stations.

Figure 1(a) compares the frequency distribution of the July and August daily maximum surface air temperatures in the base period, 1929-44, with the frequency distribution in the comparison period, 1951-2010. In the figure, each bar represents the percentage of daily maximum temperatures in the months of July and August in the respective range, i.e., 33.0-33.4ºC, 33.5-33.9ºC, 34.0-34.4ºC, etc.

-- Figure 1. Daily maximum temperature, July and August --

If the underlying distribution of daily temperatures in July and August did not change between 1929-44 and 1951-2010, then the frequency of daily maximum temperatures in each range should be the same in the base and comparison periods. However, the data show differently. Graphically, the blue bars (representing the frequency of the daily maximum temperature in the range during 1929-44) are higher than the red bars (representing the frequency of the daily maximum temperature in the range

during 1951-2010) at all temperature ranges above 34.9ºC. Evidently, the distribution of daily maximum temperatures in July and August shifted to the left -- extreme temperatures above 34.9ºC became less frequent.

Figures 1(b)-(d) carry out a similar analysis, comparing the frequency distribution of the July and August daily maximum temperatures in the base period, 1929-44, with the frequency distributions in three 20-year comparison periods, 1951-70, 1971-90, and 1991-2010. These figures point to the same conclusion as Figure 1(a): the distribution of daily maximum temperatures in July and August shifted to the left, with the effect being most pronounced in the period 1971-90.

However, the difference in the distribution of extreme temperatures may be due to confounding factors such as the base period being generally warmer (Wang et al. 2001; 2004). To abstract from global warming or cooling, we apply the method of multiple regression. The analysis compares the frequency of extremely high temperatures in the base period vis-a-vis the comparison period. The probabilities that the daily maximum surface air temperature exceeded 35ºC, 37ºC, and 40ºC in the months of July and August were lower by 26-36%, 47-51%, and 90% respectively in 1951-2010 as compared with 1929-44. These estimates include statistical controls for each station, each year, and each month, and, so, control for differences in daily maximum temperature by geography and season, as well as overall climate change.

Given the discrepancy in the probabilities of extreme temperatures between the base and later periods, the obvious question is "Why?" We review and rule out three explanations of the apparent "summer cooling". One is reduction in solar radiation due either directly to changes in the relation between the Earth and Sun (Soon et al. 2011) or indirectly to the aerosol effect of increased air pollution (Kaiser and Qian 2002). Less solar radiation would result in lower temperatures. Our historical data-set includes daily records of the duration of sunshine for 28 stations. In one set of multiple regression analyses, we control for the duration of sunshine and still find that temperatures became less extreme in the comparison periods than the base period.

Several other possible explanations of the "summer cooling" are movement of recording stations towards sites with less extreme temperatures, changes in land use such as increases in irrigation that reduce temperatures, and revisions of meteorological standards and procedures. In the most

comprehensive set of multiple regression analyses, we include fixed effects for each station in each year. These control for secular changes in the temperature at each station, and, in particular, movement of stations, changes in land use, and revisions of standards and procedures.

The final explanation, which we cannot rule out, is motivated by extensive media reports that local governments under-report extreme temperatures to help industry cope with Chinese government regulations on work under conditions of hot weather. The regulation stipulates that, when the temperature exceeds specific benchmarks, employers must pay extra cash allowances to workers and limit hours of outdoor work. In the extreme, when the temperature exceeds 40$^{o}$C, all outdoor work must stop. This regulation was progressively introduced across China from 1960 onward.

We find some empirical evidence consistent with the apparent "summer cooling" being related to the regulation on work during hot weather. The "summer cooling" was not random. Rather, extreme temperatures in the comparison period, 1951-2010, were relatively less frequent at stations where the mean maximum temperature was higher in the base period, 1929-44. Most telling, extreme temperatures were more frequent in the comparison period than the base period in Hong Kong and Taiwan, two territories on the immediate periphery of mainland China, for which climate trends should be similar.

## Data

The major challenge in any study of the long-term evolution of the climate of China is to collect information for the years before 1951 (Jones et al. 2008). From 1911 until 1949, China was governed by the Nationalist (Kuomintang) Party. In 1949, the Communist Party overthrew the Nationalist government and founded the People's Republic of China. For the period from 1951 onward, the Chinese Meteorological Administration (CMA) publishes two databases of daily weather records. However, there is no comprehensive resource of pre-1951 weather on a daily basis.

We compiled records of pre-1951 weather -- daily maximum and minimum surface air temperatures and duration of sunshine -- from three groups of sources. The primary source is the Monthly Meteorological Bulletin, published by the National Research Institute of Meteorology, Academia Sinica, in the Nationalist capital city, Nanjing. The Bulletin commenced publication in 1928 as

a quarterly covering only Nanjing. In 1929, it converted to a monthly journal, covering daily weather conditions at 54 stations, expanding to over 80 stations by 1936. The Bulletin ceased publication in January of 1937, the year in which Japan invaded Eastern and Central China. We compiled the data from partial collections of the Bulletin at archives and libraries across China and Taiwan, and supplemented with volumes bought from the used book market.

The second major source of data is the North China Monthly Meteorological Bulletin, published by the North China Meteorological Department of the Japanese Army. The Bulletin reported daily weather conditions at up to 29 stations in North China from 1938 until 1944. We compiled the data from partial collections of the Bulletin at archives and libraries in Japan, Taiwan, and the United States.

The third source of data is monthly meteorological bulletins published by provincial and city-level government agencies including observatories, and agricultural, construction, and water departments. Among these, the sources that yielded the most data were provincial observatories and agencies of Fujian, Hunan, Jiangsu, Manchuria, and Sichuan, city observatories at Dalian and Qingdao, and the Society of Jesus, Kiangnan Mission, Shanghai.

Combining the data from the various sources yielded a unique data-set comprising 363,622 observations of daily maximum and minimum temperature at up to 163 stations and 89,168 observations of daily duration of sunshine at up to 55 stations across mainland China between 1912 and 1949. The coverage of the data is not homogeneous, and is densest in the sixteen-year period, 1929-44, spanning the publication of Monthly Meteorological Bulletin of the Academia Sinica and the North China Monthly Meteorological Bulletin of the Japanese Army.

To our knowledge, this is by far the largest historical data-set of daily weather in mainland China. By contrast, other data-sets provide weather at lower frequency or only average measurements. Specifically, Lin et al. (1995) report average temperatures on a monthly basis, beginning with one station in 1841 and increasing to 133 in 1930, Kaiser et al. (1997) report extreme temperatures from 1841 until 1988, but only on a monthly basis, and Wang et al. (2001) report extreme temperatures from 1880 until 1998, but only on an annual basis. As a result, prior research into extreme temperatures in China has been limited geographically (Yan et al. (2002) is based on just two stations -- Nanjing and Beijing), in frequency (Wang et al. (2001) studies annual extremes), or to the years from 1951 (Wen et

al. 2013).

For the years 1951 and onward, we drew mainly on two sources. The primary source is the Surface Weather Database, version 3.0, published by the CMA, which provides the daily extreme temperatures and duration of sunshine for up to 824 stations. The other is the Global Historical Climatology Network (GHCN), which provides daily extreme temperatures (but not sunshine) for up to 199 stations. The coverage of the CMA Surface Weather Database and GHCN do not completely overlap, and so, we used both sources.

We matched the pre- and post-1951 data by longitude, latitude, and elevation. To ensure a close correspondence, stations were matched only if they were less than five kilometres apart and differed in elevation by less than 100 meters, and if they had at least five years of records in 1929-44. This screening limited the analysis to 43 stations, spread across the north, east, and south China, as depicted in Figure 2. For each station, the record includes the daily maximum and minimum temperatures, and, if available, the hours of sunshine. In aggregate, the matched data-set comprises 1,011,956 observations of daily maximum temperature and 872,506 observations of sunshine duration.

-- Figure 2. Station coverage --

To ensure the quality of the data, we carried out the following checks. First, weather records with more than one source were checked against each other. For instance, we verified records for Changting and Yongan in the Monthly Meteorological Bulletin of the Academia Sinica with the Fukien Monthly Meteorological Bulletin, published by the Fukien Weather Bureau. Second, all observations of daily maximum temperatures exceeding 38°C were manually checked against the original publications to avoid recording errors.

We supplemented the data on mainland China with records of daily maximum temperatures between 1929-2010 at Hong Kong (from the Hong Kong Observatory) and three stations in Taiwan (from the Taiwan Central Weather Bureau), and one station in South Korea (from the GHCN). These data contribute to a comparative analysis of the evolution of extreme temperatures in mainland China vis-a-vis its immediate Eastern periphery.

## Method

By contrast with most prior research, we focus on temperatures at individual stations and do not spatially extrapolate the data by gridding. The focus on individual stations allows the use of regression methods that account for global weather trends, seasonal differences, and secular changes specific to the individual stations. Also, by contrast with prior research, we study the full range of extreme high temperatures on a daily basis, rather than the monthly or annual maximum. As explained below, analysis of weather at a daily (rather than annual or monthly) frequency substantially mitigates the sensitivity of the empirical findings to errors in the data.

Any study of the evolution of extreme temperatures must take account of global trends, whether of warming or cooling. It must also take account of systematic differences in climate between stations at different locations and between seasons. Further, it must take account of systematic changes over time specific to individual stations, particularly, movement of recording stations, changes in land use, and changes in meteorological standards and procedures. Over time, recording stations might have moved towards less densely built up locations (for instance, between 1961-2000, the Beijing station was relocated five times (Ren et al. 2008)). The development of irrigation might have moderated surface air temperatures. In China, recording thermometers were positioned with bulbs at a height of 1.5 metres from 1950-1953, at 2 metres from 1954-1960, and at 1.5 metres from 1961 onward (Kaiser et al. 1997).

We abstract from all of the above confounds by estimation using the method of multiple regression with fixed effects for station and year. Essentially, each fixed effect transforms the dependent variable of the multiple regression into its deviation from the sample average for the domain of the fixed effect. The fixed effects for station and year transform the dependent variable into its deviation from the sample average for each station in each year.

To illustrate the fixed effects for station and year, Figure 3 presents the daily maximum temperatures at Nanjing in the month of July in the years 1934 and 1980. The average annual maximum temperature at Nanjing (depicted in blue) was 20.48ºC in 1934 and 19.26ºC in 1980. Referring to

Figure 3, the daily maximum temperature (depicted in ochre) was mostly higher in July 1934 than July 1980. However, in terms of the deviation from the respective average for the year (depicted in green), the daily maximum temperature in July 1934 was still higher than in July 1980, but the difference was smaller. By specifying the dependent variable as the deviation from the sample average, the analysis abstracts from systematic changes of maximum temperature at that station from year to year, and focuses on the deviation of the daily maximum temperature from the average maximum at that station in that year.

-- Figure 3. Daily maximum temperature, Nanjing, July 1934 and 1980 --

The difference in the average daily maximum temperature between the two years might be due to global warming or cooling, the urban heat island effect, re-location of the station, changes in meteorological standards, recording biases, or changes in land use such as an increase in afforestation and irrigation. For instance, if the thermometer at a station is biased upward by 0.1ºC in a particular year, then, all observations as well as the sample average for the year would be biased upward by the same amount. The *difference* between the daily maximum temperature and the sample average would cancel out the 0.1ºC discrepancy. Hence, any analysis of the difference would not be confounded by the measurement bias.

Importantly, the fixed effects for station and year also serve to abstract the dependent variable from systematic differences between stations that do not vary over time. In particular, they abstract from differences in the daily maximum temperature between inland and coastal locations and at different elevations. Temperatures would be more extreme at inland than coastal locations and at higher as compared with lower elevations.

Similarly, the fixed effects for station month transform the dependent variable into its deviation from the sample average for each station in each month. To illustrate the fixed effects for station and month, Figure 4 depicts the daily maximum temperatures, average daily maximum temperature for July, and the deviations from the monthly average at Nanjing in July 1934, and the corresponding data for August 1934. The average daily maximum temperature in July, 37.28ºC, is higher than the average in August, 35.63ºC, owing to seasonal differences. Referring to Figure 4, the daily maximum temperature was 39.8ºC on July 31 and 39.4ºC on August 1. However, in terms of the deviation from the

respective monthly average, the July 31 temperature is lower because the July average is higher.

-- Figure 4. Daily maximum temperature, Nanjing, July and August, 1934 --

Below, we apply regression analysis to estimate two models. In the national model, the explanatory variables are fixed effects for station, fixed effects for month, and fixed effects for station and month and comparison time period, and in some specifications, also, fixed effects for year. In the most comprehensive model, the station-specific model, the explanatory variables are fixed effects for station, fixed effects for station and year, fixed effects for station and month, as well as fixed effects for station and month and comparison time period. In the regression, each fixed effect takes the value one if the observation belongs to the domain of the fixed effect, and zero otherwise. For instance, among the 1,011,956 records, the fixed effect for Nanjing and year 1934 takes the value one for the 365 records of Nanjing in the year 1934, and the value zero for all other records.

With inclusion of fixed effects for station and year and fixed effects for station and month, the dependent variable is effectively the difference between: (i) the daily maximum temperature at the station on the date, and (ii) the average of the daily maximum temperature at that station in that year and the average at that station in that month. The variables of key interest in our study are the fixed effects for station and month and comparison time period. The base period is 1929-44, while the comparison time periods are 1951-2010, and sub-periods, 1951-70, 1961-80, and 1981-2010. Generally, the coefficient of each explanatory variable can be interpreted as the effect of a one-unit change in the explanatory variable on the dependent variable.

In one set of regression analyses, we specify the dependent variable as an indicator of whether the daily maximum temperature exceeded the benchmark, 35ºC, 37ºC, or 40ºC. So, for any particular day, month, and year at a station, the dependent variable is one if the daily maximum temperature exceeded the benchmark and zero otherwise. This specification provides a deeper look at the distribution of the daily maximum temperature. In this specification, the coefficient of the fixed effect for station and month and comparison time period represents the *difference* in the probability of the daily maximum temperature exceeding the benchmark in the specific month between the comparison period as compared with the base period, relative to the average probability for the station and year and the

average probability for the station and month.

The present study analyzes maximum temperatures on a daily basis. By contrast, most prior research studied maximum temperatures on an annual or monthly basis. It is important to emphasize that analysis on a daily basis substantially reduces the sensitivity of the findings to errors in the data. For instance, suppose that the daily maximum at Nanjing on July 15, 1934 is wrongly recorded as 50ºC, which exceeds all other daily maxima at Nanjing in 1934. Then the annual maximum would be 50ºC, which would bias 1.39% (one of 72 observations) in an annual study covering 72 years. However, that erroneous observation would bias only 0.004% (one of 25,843 observations) in a daily analysis, which is three orders of magnitude smaller than the error in the annual analysis. Evidently, analysis on a daily basis provides estimates which are much more robust to errors in the data than monthly and annual analyses.

## Estimates: Maximum temperature

We estimated the model of extreme temperatures by ordinary least squares regression using the statistical software, SAS. We estimated two versions of the model, one at the national level, combining all 43 weather stations, and the other at the level of individual stations with separate coefficients for each station.

### □ National model

Table 1 presents the first set of estimates. Column (a) presents estimates of a national model with the dependent variable specified as the monthly maximum temperature, i.e., the highest temperature in any day of the month. The explanatory variables are fixed effects for station, fixed effects for month, and fixed effects for month and comparison period, with the comparison period being 1951-2010. Essentially, this model constrains the fixed effects for station and month to be the same for all stations, and likewise, constrains the fixed effects for station and month and comparison time period to be the same for all stations. This model addresses the question of whether, on average, across all 43 stations, the monthly maximum temperature in the specific month differed between the comparison period and the base period.

-- Table 1. National model of maximum and minimum temperatures --

For technical reasons (to ensure that the regression matrix is non-singular), among the station fixed effects, one must be omitted, and we choose to use Zhangjiakou as the reference station, and omit a fixed effect for that station. Similarly, among the month fixed effects, one must be omitted, and we choose to use December as the reference month, and omit a fixed effect for that month. In specifications that include year fixed effects, one must be omitted, and we choose to use 2010 as the reference year, and omit a fixed effect for that year.

Referring to Table 1, column (a), the coefficients of the months -- January, February, etc. -- represent the daily maximum temperature relative to the reference month of December. Consistent with intuition, the coefficients are positive and significant in the months of February to November, which means that the monthly maximum temperature was significantly higher in the months of February to November than in December.

For the months of March to November, all of the coefficients of the fixed effects for month and comparison time period (March x comparison, April x comparison, etc.) are negative and significant. This means that, on average, across the 43 stations, the monthly maximum temperature in the months of March to November was significantly *lower* in the comparison period, 1951-2010, than the base period, 1929-44. The magnitude of the reduction in maximum temperature ranged from 0.47ºC in April to 1.11ºC in June.

For a more fine-grained analysis, Table 1, column (b), presents estimates of the national model with the dependent variable specified as the daily maximum temperature. The picture from the daily analysis is similar to that of the monthly analysis but the effects are smaller. The coefficients of the fixed effects for month and comparison time period are negative and significant for the months of March, and May to November. These estimates mean that the daily maximum temperature was lower in the comparison period than the base period in those months. The magnitude of the reduction in maximum temperature ranged from 0.12ºC in May to 0.91ºC in June.

Comparing the monthly and daily estimates, we infer that analysis on a monthly basis tends to exaggerate changes in weather patterns. This tendency towards exaggeration should be expected as a

monthly analysis treats a month in which the daily maximum temperature at a station is 40ºC on one day and 30ºC on all other days the same as another month in which the daily maximum temperature at a station is 40ºC on every day of the month. The comparison of the monthly and daily estimates underscores the importance of analyzing weather patterns on a daily basis.

Referring to the estimates in Table 1, column (b), the estimated reduction in the daily maximum temperature in the months of March, and May to November might be due to a general cooling trend, movement of stations, changes in land use, or revision to meteorological standards and procedure. To abstract from such general changes over time, we estimate a version of the national model of the daily maximum temperature, including fixed effects for each year. The year fixed effects abstract from general changes over time that affect the daily maximum temperature at all stations.

Table 1, column (c), reports the estimates of the regression of the national model of daily maximum temperature with year fixed effects. To check the overall reliability of the data and our analysis, Figure 5 presents the year fixed effects. The year fixed effect for a particular year is the average of the daily maximum temperature across all stations in that year. The evolution of the year fixed effects is qualitatively similar to the variation of the annual mean temperature in north, east, and central China as characterized by Wang et al. (2001; 2004). Temperatures were high in the 1930s-40s, then cooled in the 1950s to 1980s, and then rose from the 1990s.

-- Figure 5. Yearly average of daily maximum temperature --

Referring to Table 1, column (c), the coefficients of the fixed effects for month and comparison time period are negative and significant for the months of June to November. These estimates imply that the daily maximum temperature was lower in the comparison period than the base period in the months of June to November. The magnitude of the reduction in maximum temperature ranged from 0.19ºC in November to 0.69ºC in October. The estimated effects range from a quarter to half smaller than those without year fixed effects. These suggest that between a quarter to half of the reduction in maximum temperature might be due to general changes such as cooling trend and movement of stations.

Referring to Table 1, column (c), the coefficients of the fixed effects for month and comparison time period are positive and significant for the months of January, February, and April. For these

months, the daily maximum temperature was *higher* in the comparison period than the base period.

Finally, for completeness, Table 1, column (d), reports estimates of a national model of daily minimum temperature with fixed effects for station, year, and month. Across all months, the daily minimum temperature was higher in the comparison period than the base period, by an amount ranging from 0.13ºC in July to 0.78ºC in April.

## □ Station-specific model

To further investigate the differences in extreme temperatures, we estimate a very general, station-specific model, including fixed effects for station, fixed effects for station and year, fixed effects for station and month, and fixed effects for station and month and comparison time period, 1951-2010. The fixed effects for station and year abstract the regression analysis from changes over time in the daily maximum temperature that are specific to individual stations such as movement of the recording instruments, changes in recording personnel, and changes in land use and irrigation. The fixed effects for station and month abstract the regression analysis from seasonal differences in the daily maximum temperature between station. For instance, the seasonal pattern might differ between stations in the north and south, and between stations in the coast and interior.

The dependent variable is the daily maximum temperature. In the station-specific model, the estimated coefficients of the fixed effects for station, month, and comparison period would vary among stations. Hence, the station-specific model allows the difference in the daily maximum temperature between comparison and base period to vary among stations. (By contrast with the national model, the fixed effects for month and comparison period are constrained to be the same across stations.)

-- Figure 6. Station-specific model: Daily maximum temperature --

Figures 6(a)-(b) illustrate the estimated difference in the daily maximum temperature between comparison and base period for the months of July and August. Stations where the daily maximum temperature was significantly *lower* in 1951-2010 than 1929-44 are marked in blue, stations where the daily maximum temperature was significantly *higher* in 1951-2010 than 1929-44 are marked in red, and other stations where there was no significant difference are marked in grey.

Broadly, the estimates of the station-specific model confirm the findings of the national model,

but reveal particular geographical nuances. For July, temperatures in the comparison period were lower than the base period at 18 stations, broadly distributed along the eastern coast and near interior provinces, while temperatures were higher at 7 stations, concentrated in the north and the southeast province of Fujian, and temperatures were not significantly different in the west. The pattern was similar in the month of August, except that the temperature was higher at fewer stations.

## Estimates: Maximum temperature benchmarks

For another perspective of the evolution of weather, we next study the frequency of the daily maximum temperature exceeding specific benchmarks -- 35ºC, 37ºC, and 40ºC. In the relevant models, the dependent variable is specified as an indicator of whether the daily maximum temperature exceeded the benchmark. So, for any particular day, month, and year at a station, the dependent variable is one if the daily maximum temperature exceeded the benchmark and zero otherwise.

### □ National model

We first estimate a national model with the explanatory variables being fixed effects for station, fixed effects for year, fixed effects for month, and fixed effects for month and comparison period, 1951-2010. When the model is estimated by ordinary least squares, the coefficient of the fixed effect for month and comparison period can be interpreted as the effect of difference between the probability of the daily maximum temperature exceeding the benchmark in the month in the comparison period as compared with the base period.

Referring to Table 2, the coefficients of the fixed effects for month and comparison period are negative and significant for the months of May to September for all three benchmarks. The estimates imply that the probability of the daily maximum temperature exceeding the benchmarks was lower in the comparison period than the base period in the months of May to September. With respect to the 35ºC benchmark, the magnitude of the reduction in probability ranged from 1.5% in May to 7.5% in June.

To assess the proportionate impact of the changes, we compute, for each month and benchmark, the ratio of the difference in probabilities between the base and comparison periods to the probability in the base period. This ratio measures the proportionate change in probability between the

comparison and base periods. As reported in the bottom panel of Table 1, the ratio was uniformly higher for higher benchmark temperatures. This means that the change in the probability of extreme temperatures between comparison and base periods was uniformly larger at higher benchmark temperatures.

For instance, in July and August, the probabilities of the temperature exceeding 35ºC, 37ºC, and 40ºC were lower by 26-36%, 47-51%, and 90% respectively in 1951-2010 as compared with 1929-44. This pattern of results provides formal statistical support to the impression conveyed by Figure 1 that the frequency distribution of temperatures in the comparison period was lower than in (further to the left of) the base period, and shifted relatively more at higher temperature ranges.

To further investigate the evolution of extreme temperatures over time, we estimated an elaborated version of the national model. This allows the difference in the probability of the daily maximum temperature exceeding the benchmark to vary between three successive comparison periods, 1951-70, 1971-90, and 1991-2010. Each comparison period is twenty years long, which is comparable to the sixteen years of the base period, 1929-44.

-- Table 3. National model with multiple comparison periods --

Table 3 reports the estimates. For the months of May, June, July, August, and September, all of the coefficients of the fixed effects for month and comparison time period of 1951-70 are negative and significant at the three benchmarks, 35ºC, 37ºC, and 40ºC. All of the coefficients of the corresponding fixed effects are significant and even more negative for the comparison period, 1971-90. Similarly, all of the coefficients of the corresponding fixed effects are negative and significant for the comparison period, 1991-2010. However, the coefficients for 1991-2010 are smaller than those for 1971-90, suggesting a reversal in the trend towards less extreme temperatures in the later period.

## □ Station-level model

To further investigate the differences in extreme temperatures, we estimate a station-specific model, including fixed effects for station, fixed effects for station and year, fixed effects for station and month, and fixed effects for station and month and comparison time period, with the comparison period being 1951-2010. By contrast with the national model, in the station-level model, the difference in the

probability of the daily maximum temperature exceeding the various benchmarks in the month between base period and comparison period may vary among stations. Figure 7 illustrates the results for the benchmark of 37ºC.

-- Figure 7. Probability of daily maximum temperature exceeding benchmark in 1929-44 vis-a-vis 1951-2010 --

In Figure 7, stations where the probability of the daily maximum temperature exceeding the benchmark was significantly lower in 1951-2010 than 1929-44 are marked in blue, stations where the probability of the daily maximum temperature exceeding the benchmark was significantly higher in 1951-2010 than 1929-44 are marked in red, and other stations where there was no significant difference are marked in grey. The pattern of the estimates is similar to the estimates of the station-specific model of the daily maximum temperature, depicted in Figures 6(a)-(b).

## □ Robustness checks

To check the sensitivity of our results to the sample and method of estimation, we carry out two robustness checks of the models of the daily maximum temperature exceeding the benchmarks. For brevity, we limit ourselves here to a broad discussion and leave the details to an appendix.

The first robustness check addressed sensitivity to sample selection. The analysis so far used the sample of stations with at least five years of records in the base period, 1929-44. Using the more stringent criterion of stations with at least seven years of records in the base period, the sample reduces to 35 stations. Estimating the national model on the more stringent sample yields almost identical results. The probabilities of the daily maximum temperature exceeding the benchmark (35ºC, 37ºC, and 40ºC) are lower in the comparison period, 1951-2010, than in the base period, 1929-44, in the months of May, June, July, August, and September, and the diminution is larger at higher levels of the benchmark.

The second robustness check addressed sensitivity to method of estimation. The regression analyses above were carried out with the linear probability model, i.e., ordinary least squares. The linear probability model has the advantages of being easy to estimate and producing coefficients that are easy to interpret as the effect of a unit change in the explanatory variable on the probability of the dependent

variable exceeding the benchmark. However, if the explanatory variables take values far from their sample means, the linear probability model could imply estimated probabilities less than zero and greater than one, which do not make sense. By contrast, the probit discrete choice regression method is specifically designed to estimate binary dependent variables and always generates estimated probabilities between zero and one.

Accordingly, to validate our findings, we repeat the estimation of the national model using probit regression. The results are qualitatively similar to those with the linear probability model. The probabilities of the daily maximum temperature exceeding the benchmark (35ºC, 37ºC, and 40ºC) are lower in the comparison period, 1951-2010, than in the base period, 1929-44, in the months of May, June, July, August, and September, and the diminution is larger at higher levels of the benchmark.

## Explanations

Given the evidence that extreme temperatures are significantly less frequent in the comparison period relative to the base period, the obvious question is the reason for the change. What explains the apparent cooling of summer extremes?

### □ Aerosol effect

The first and most obvious explanation of the "summer cooling" is reduction in solar radiation. The reduction in radiation could be the direct outcome of changes in the relation between Earth and the Sun (Soon et al. 2011). Or the reduction could be due to an aerosol effect of increased air pollution resulting in less sunshine and lower temperatures. Kaiser and Qian (2002) observe a systematic decrease in the duration of sunshine of between 2% and 3% per decade over eastern China. They associate this decrease in sunshine with increased atmospheric anthropogenic aerosol loading.

To address this alternative explanation, we collected historical data on the duration of sunshine by day. Although historical records of sunshine are relatively sparse, we managed to compile data for 32 stations in the period 1929-44. For the years after 1951, we obtain the duration of sunshine by day from the CMA Surface Weather Database, version 3.0. (By contrast, Soon et al. (2011) correlated surface air temperatures in China with the *monthly* duration of sunshine in Japan. This provides a less

precise control to the extent that sunshine over Chinese stations differs from that over Japan and to the extent that the duration of sunshine varies within months.)

Then, in the national model, we include the duration of sunshine as an additional explanatory variable. The coefficient of the daily hours of sunshine would represent the effect of sunshine on the dependent variable. More importantly, the coefficient of the fixed effect for month and comparison time period, 1951-2010, would represent the difference in the dependent variable between the comparison period and base period, holding constant the daily hours of sunshine. The fixed effects for years would account for a change in the method of recording sunshine hours from Jordan's Photographic Sunshine Recorder to the Campbell-Stokes Sunshine Recorder in 1954 (Kaiser et al. 1997).

-- Table 4. National model including duration of sunshine --

Table 4, column (a), reports the estimate of the national model of the daily maximum temperature, including the duration of sunshine as an additional explanatory variable. The estimated coefficients of the fixed effect for month and comparison time period are negative and significant for the months of June to November. Moreover, the estimates are larger in magnitude than those in Table 1, column (c), that do not control for sunshine. Apparently, with accounting for differences in sunshine, the reduction in the daily maximum temperature between comparison and base periods is even larger.

Table 4, columns (b)-(d), report the estimates of the national model of the indicator of the daily maximum temperature exceeding benchmarks, including the duration of sunshine. For the months of June, July, and August, the coefficients of the fixed effects for month and comparison time period are negative and significant at all three benchmarks, 35ºC, 37ºC, and 40ºC. The probabilities of the temperature exceeding 35ºC, 37ºC, and 40ºC in July and August were lower by 26-35%, 24-59%, and 69-89% respectively in 1951-2010 as compared with 1929-44. However, these effects are somewhat smaller than those from the national model without controlling for sunshine, reported in Table 2.

Overall, the results reported in Table 4 are consistent with our conclusion that the daily maximum temperature was lower in the comparison than base period. One possible explanation for these differences is the changes in solar radiation, possibly due to the aerosol effect. Another possible

reason is purely statistical. The 32 stations and days for which we were able to collect records of sunshine might differ from the entire sample. To check, we ran the national model on the stations and days for which we had sunshine records but without controlling for sunshine. The results (for brevity, not reported) are quite similar to those in Table 4, suggesting that the difference in the estimates with and without sunshine is due to differences in the sample rather than sunshine.

The estimates of the national model with multiple comparison periods, reported in Table 3, also provide some evidence on the aerosol effect. In China, particulate emissions have grown in tandem with the economy, and so, the aerosol effect should have strengthened over time. However, as reported in Table 3, the trend towards less extreme temperature reversed in the 1991-2010 period, which is inconsistent with the aerosol effect on surface air temperatures.

## □ Movement of recording stations and changes in land use and meteorological standards

Another possible explanation of the "summer cooling" is movement of recording stations towards locations with less extreme temperatures, changes in land use such as increases in irrigation, and changes in meteorological standards and procedures and recording personnel. We accounted for these confounding factors in the station-specific model through fixed effects for station and year. Essentially, these fixed effects transform the dependent variable to be the deviation from the average for the station and year. Accordingly, they abstract the dependent variable from the effects of movement of recording stations, changes in land use, and changes in meteorological standards and procedures. As depicted in Figures 6 and 7, the estimates of the station-specific model are consistent with our overall conclusion that temperatures were less extreme in the comparison period than base period.

## □ Urban heat island effect

Urbanization is associated with changes in land surfaces towards materials that store short-wave radiation, which, typically, is released at night, and so, slowing the night-time cooling. In China, urbanization has been observed to result in an increase in minimum temperatures and a smaller increase in maximum temperatures (Ren et al. 2007). Hence, if anything, the urban heat island effect should result in more, not less, extreme temperatures, which is contrary to our findings.

The station-specific model included fixed effects for each station and year, which would control for changes over time in the average maximum daily temperature at each station in each year. Hence, our analysis focuses on variation in the daily maximum temperature relative to secular increases in the average maximum at the station, and so, abstracts from the urban heat island effect.

## □ Regulation of hot weather work

The Chinese news media have provided one explanation of the apparent "summer cooling". Local (provincial and city) meteorological departments face official pressure to tone down forecasts of extremely hot weather. In July 1960, the Ministries of Health and Labour and China Federation of Trade Unions jointly published interim national regulation, No. 207 of 1960, to govern work during hot weather. The interim regulation suggested various measures including improving ventilation and provision of liquids and nourishing foods.

In July 2012, the government published a much more stringent final regulation, No. 89 of 2012. The regulation stipulates a cash allowance for all workers when the daily maximum temperature exceeds 35ºC unless the workplace is cooled to below 33ºC. Further, the regulation limits outdoor work. Specifically, when the daily maximum temperature is between 35ºC and 37ºC, overtime work is not permitted outdoors, when the daily maximum temperature is between 37ºC and 40ºC, outdoor work is limited to a total of six hours and no more than three hours continuously, and when the daily maximum temperature exceeds 40ºC, all outdoor work is prohibited.

It is important to note that the Nationalist government did not regulate work during hot weather. Further, in the 52 years between the publication of the interim and final regulations by the Communist government, various aspects of the final regulation, and in particular, those stipulating cash allowances and limiting outdoor work, had been progressively introduced across the country. This is consistent with a general Chinese government practice of experimenting with policies in specific regions and progressively introducing the policies across the country before finally promulgating the law or regulation (Heilmann 2011; Liebman 2011). For instance, in 1963, the city of Guangzhou promulgated regulations on work under hot weather conditions (No. 150 of 1963), expliciting stipulating monetary compensation for work outdoors and in temperatures above 35ºC.

Chinese government officials at local levels are very aligned with the interests of industry. Prior to the economic reforms that began in 1978, all economic enterprises belonged to the government and were required to meet targets set by the central planning bureau. Officials would face sanctions for failing to meet production targets. Following the economic reforms that liberalized the economy, the Communist Party assessed local officials by the economic performance of their territories, and so, local officials have been very minded to cater to the needs of industry and boost economic growth (Li and Zhou 2005).

Each specialized function of the Chinese government, including meteorological services, is decentralized to the provincial level. (Strictly, China comprises 22 provinces, 5 autonomous regions, and 4 municipalities, but, for simplicity, we describe all of these second-level administrative units as "provinces".) Accordingly, every province administers its own meteorological service.

High temperatures that trigger limitations on outdoor work would interfere with business activity in all industries, and particularly, mining, construction, and transportation. High temperatures that trigger provision of cash allowances would add to labor costs and increase the overall cost of production, and so, reduce enterprise profits. Hence, to the extent that local government officials need to meet production targets or are concerned about the economic performance of their territories, they would have incentive to under-report hot weather. Such under-reporting would be consistent with their tendency to under-state reports of emissions to comply with regulations on air pollution (Chen et al. 2012; Ghanem and Zhang 2013).

Among the Chinese people, there is widespread belief that local governments under-report hot weather to help employers avoid work stoppage and deprive workers of their hot weather allowances (see, for instance, Nanfangdaily (2010)). The government has repeatedly denied that meteorological services under-report high temperatures (CMA 2012). Nevertheless, the public continues to be sceptical (People's Daily 2013).

-- Figure 8. Change in daily maximum temperature and mean daily maximum temperature in base period --

To address hypothesis of official under-reporting, Figures 8(a)-(b) use the estimates of the station-specific model to correlate the change in daily maximum temperature with the mean daily

maximum temperature in the base period. In each figure, the vertical axis represents the coefficient of the fixed effect for station and month and comparison time period, i.e., the difference in the daily maximum temperature between the comparison period, 1951-2010 and the base period, 1929-44. Apparently, there is no clear pattern for July. However, for August, it seems that changes in temperatures were related to temperatures in the base period. The higher was the mean daily maximum temperature in the base period, then, the smaller was the increase in daily maximum temperature in the comparison period.

-- Figure 9. Change in probability of daily maximum temperature exceeding 37ºC and mean daily maximum temperature in base period --

To address hypothesis of official under-reporting from another perspective, Figures 9(a)-(b) use the estimates of the station-specific models to correlate the change in the probability of the daily maximum temperature exceeding the 37ºC benchmark with the mean daily maximum temperature in the base period. In each figure, the vertical axis represents the coefficient of the fixed effect for station and month and comparison time period, i.e., the difference in the probability that the daily maximum temperature exceeds 37ºC between the comparison and base period. Apparently, the changes in extreme temperatures were not random, but rather, systematically related to temperatures in the base period. The higher was the mean daily maximum temperature in the base period, then, the lower was the probability of an extreme temperature in the comparison period. The patterns depicted in Figures 8(a)-(b) are consistent with official under-reporting of extreme temperatures in hot cities.

Another way to investigate the hypothesis of official under-reporting is to study the evolution of extreme temperatures on the periphery of mainland China. Hong Kong and Taiwan are located on the immediate eastern periphery of mainland China. Their weather should evolve in a way very similar to that of the mainland. Accordingly, to investigate, we apply the national model to the daily maximum temperatures in Hong Kong and three Taiwan stations (Taipei, Taichu, and Penghu).

-- Table 4. Periphery of mainland China --

As reported in Table 4, column (a), at Hong Kong and the three Taiwan stations, the daily maximum temperature was higher by 0.56ºC in July and 0.32ºC in August in the comparison period, 1951-2010, than the base period, 1929-44. As reported in Table 4, column (b), the probability of the

daily maximum temperature exceeding 35ºC in July and August was significantly higher in the comparison than base period. These results contrast with our findings for Mainland China and are consistent with official under-reporting of extreme temperatures by Chinese local government officials. (It was not possible to investigate the temperatures in Hong Kong and Taiwan relative to the other benchmarks because they almost never exceed 37ºC.)

## Discussion

Comparing historical records of weather between 1929-44 with modern weather records between 1951-2010, we document that summer temperatures (as reported) have become less extreme. We explore and rule out various explanations of the apparent "summer cooling" -- the aerosol effect of increased air pollution, movement of weather stations, changes in land use, and changes in meteorological standards.

We cannot rule out the summer cooling being explained by official under-reporting of hot weather. Indeed, we find some evidence consistent with official under-reporting. Extreme temperatures in the comparison period, 1951-2010, were relatively less frequent at stations where the mean maximum temperature was higher in the base period, 1929-44. Extreme temperatures were more frequent in the comparison period than base period in Hong Kong and Taiwan, where trends in climate should be similar to mainland China.

To the extent of such under-reporting, our empirical results have obvious and serious implications for health and welfare and the study of climate change. The regulations on hot weather work were promulgated to safeguard Chinese workers. If the regulations are subverted by under-reporting of hot weather, the health and welfare of Chinese workers would be eroded in a surreptitious way. Further, the under-reporting would also affect the general population by increasing their (unwitting) exposure to extreme temperatures.

Reliable weather information is essential to understanding changes in climate and developing policies to mitigate climate change. Thus far, concern about inaccuracy of weather data has focused on historical times (Tollefson 2012). The reliability of data on weather in the modern era has not been

questioned.

China provides station-level weather records to international organizations and other countries. These station-level records are the input into computations of gridded temperatures, which are the main measures of climate change. To the extent that the Chinese summer temperatures are managed downward, the worldwide measures of summer temperatures will be biased downward, and the extent of warming under-stated.

Indeed, in the related context of carbon dioxide emissions, the statistics published by the Chinese central government differ substantially from those published by provincial governments. The discrepancy is as large as the emissions of Japan, the world's fourth largest emitter (Guan et al. 2012). Moreover, discrepancies in provincial reporting of emissions are not random and are likely the result of systematic under-reporting (Chen et al. 2012; Ghanem and Zhang 2013).

Against the backdrop of global warming and the nascent controversy over the accuracy of Chinese government statistics, our results suggest that reported Chinese weather statistics be treated with caution. In addition, two important directions for further research are the implications of under-reporting of extreme temperatures for the health and welfare of the Chinese people and the effect of independent mass media and social networks on under-reporting of extreme temperatures.

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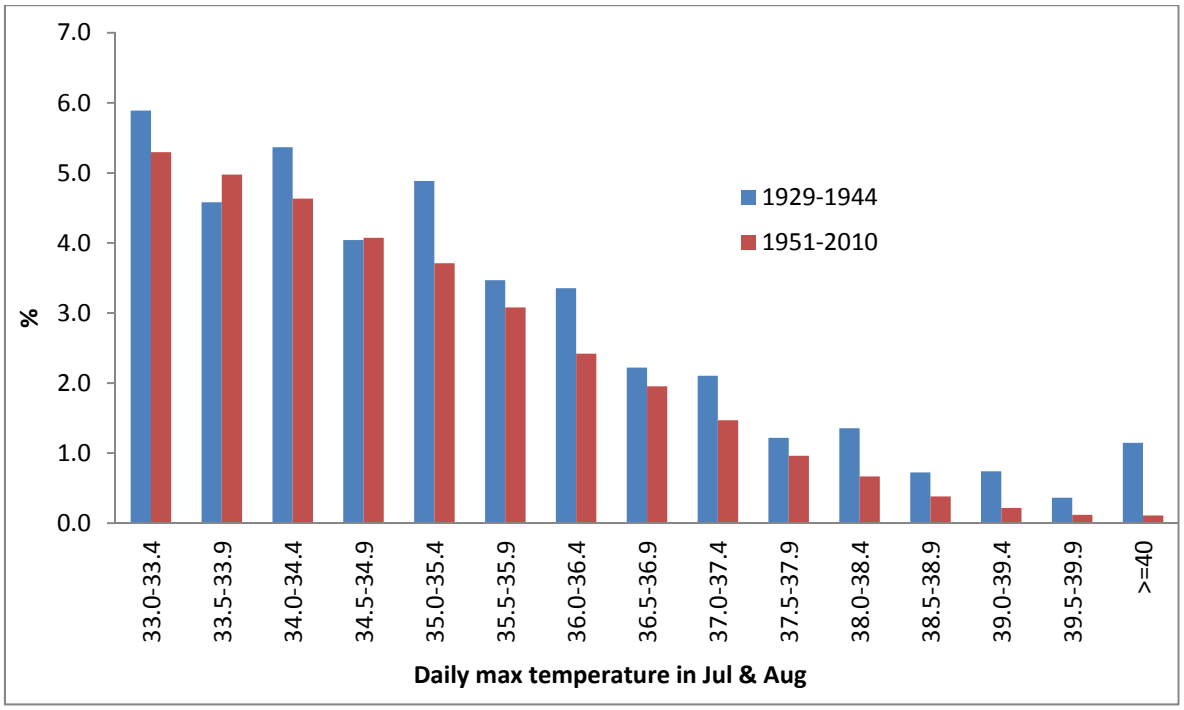
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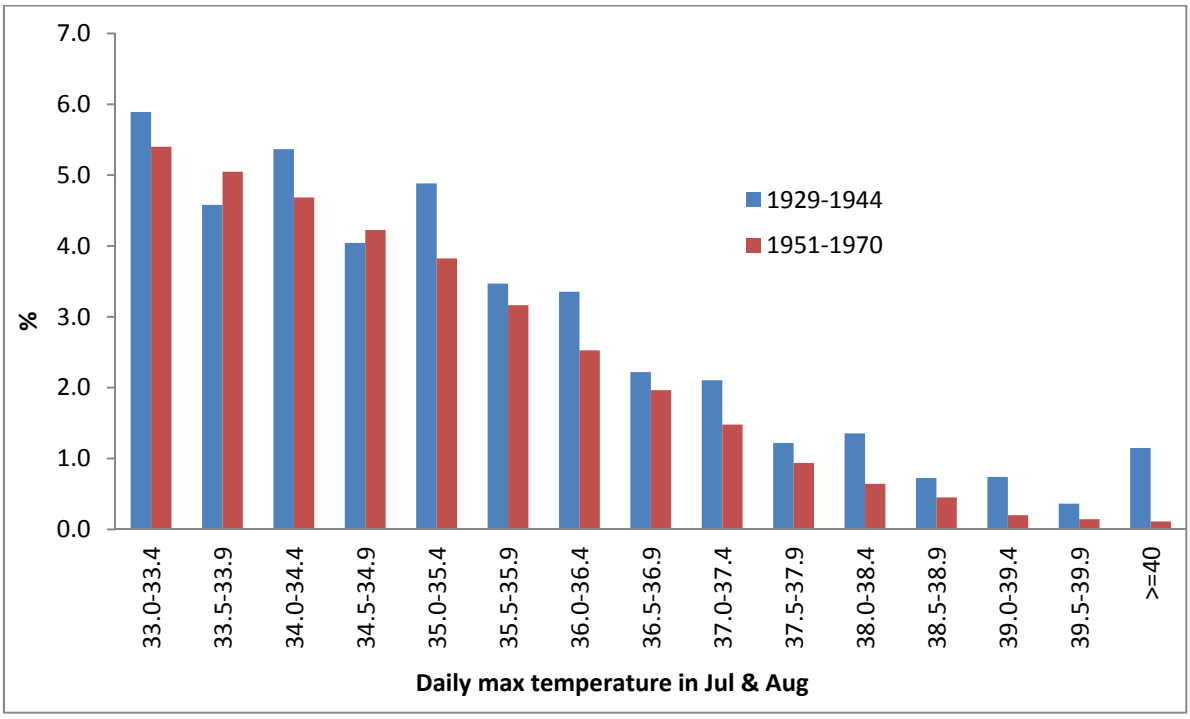
**Climate change in China: Communism is cooler**
Figures and tables

-- Figure 1. Daily maximum temperature, July and August (histogram) –

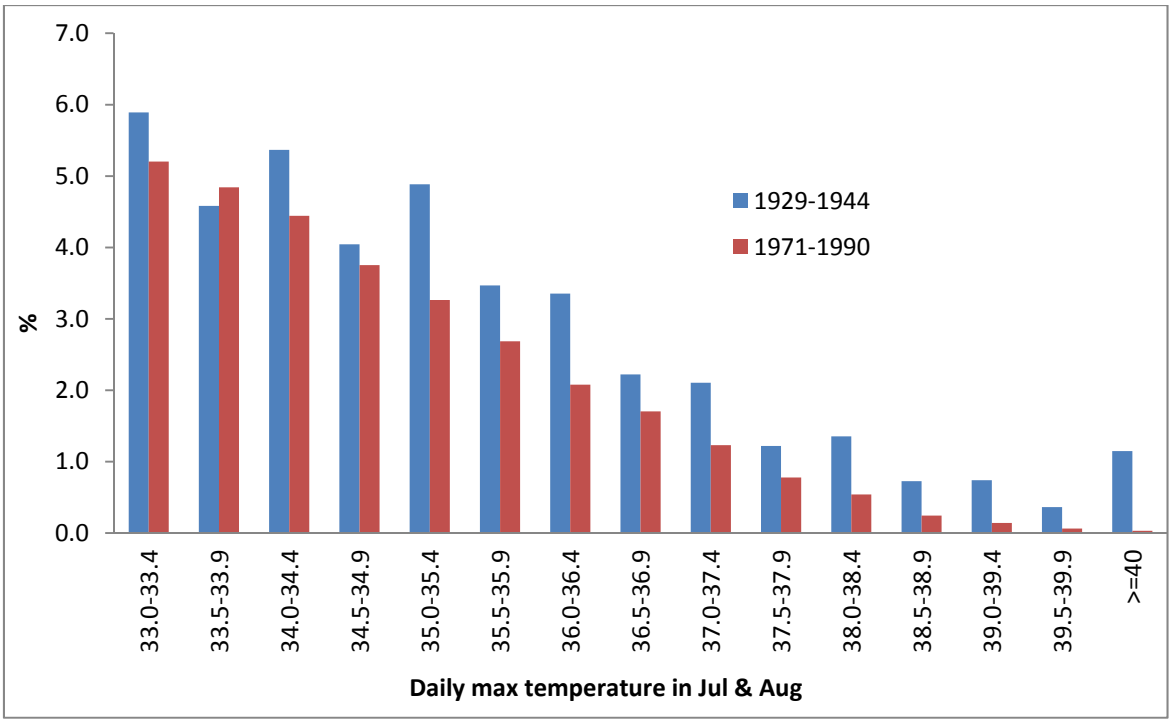
(a) 1929-44 vis-à-vis 1951-2010



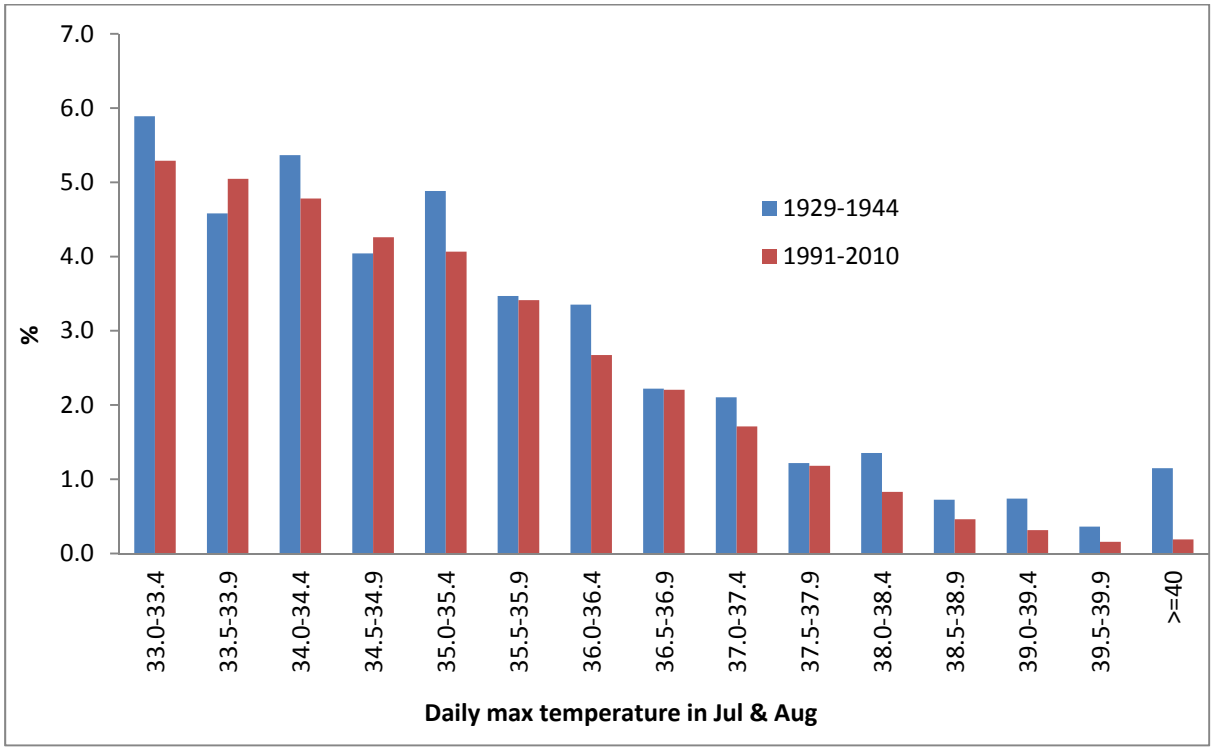

(b) 1929-44 vis-à-vis 1951-1970



(c) 1929-44 vis-à-vis 1971-90



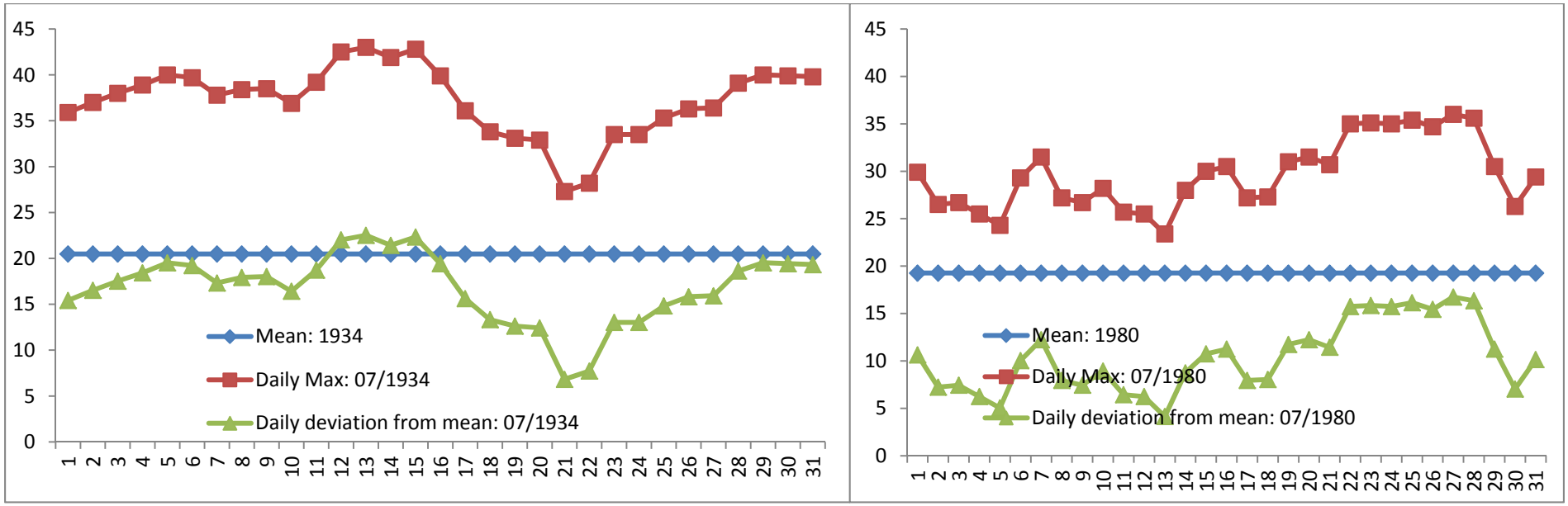

(d) 1929-44 vis-à-vis 1991-2010



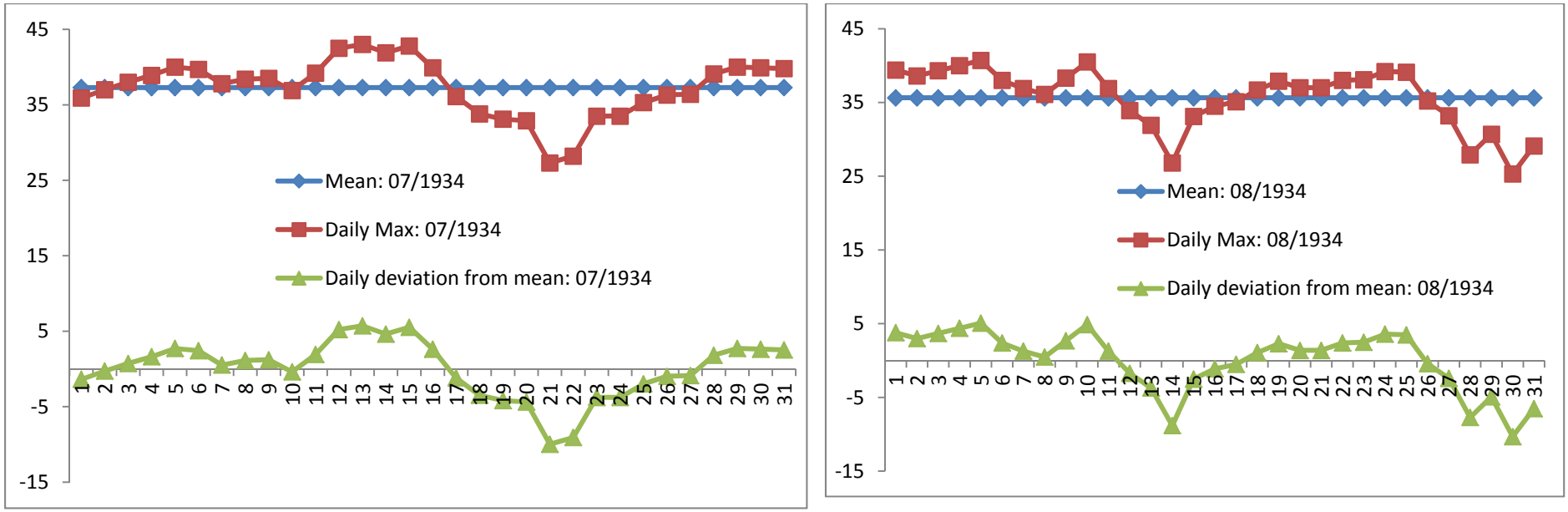
-- Figure 2. Station coverage –



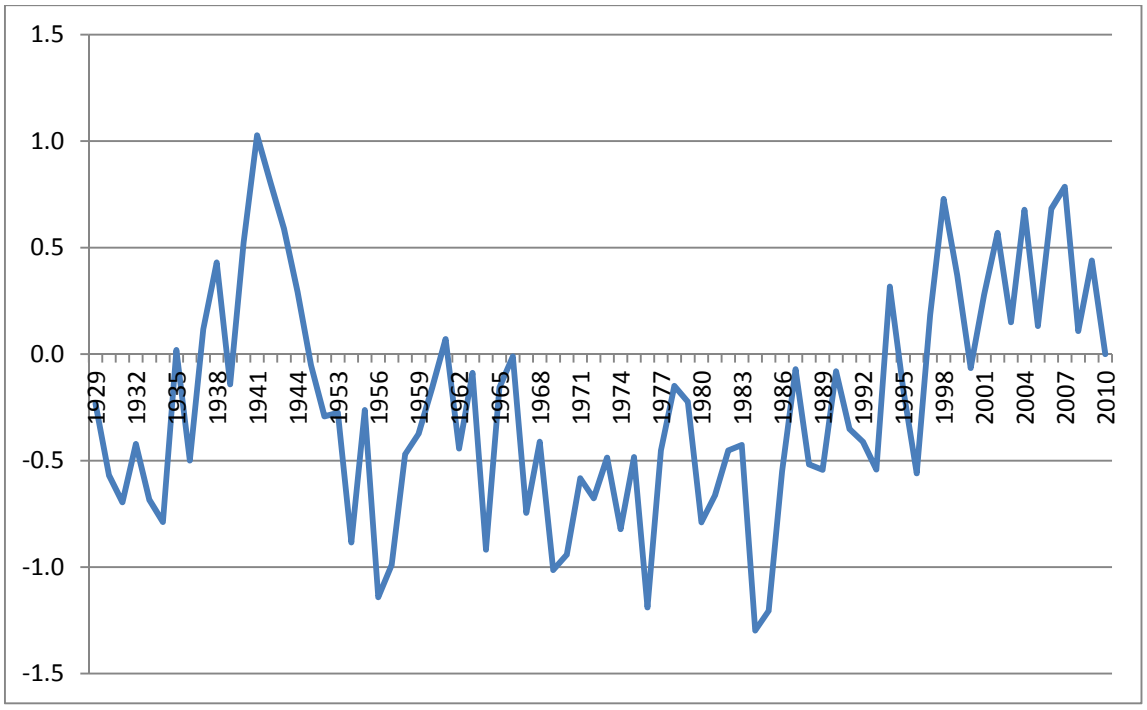
-- Figure 3. Daily maximum temperature, Nanjing, July 1934 and 1980 --



-- Figure 4. Daily maximum temperature, Nanjing, July and August 1934 --

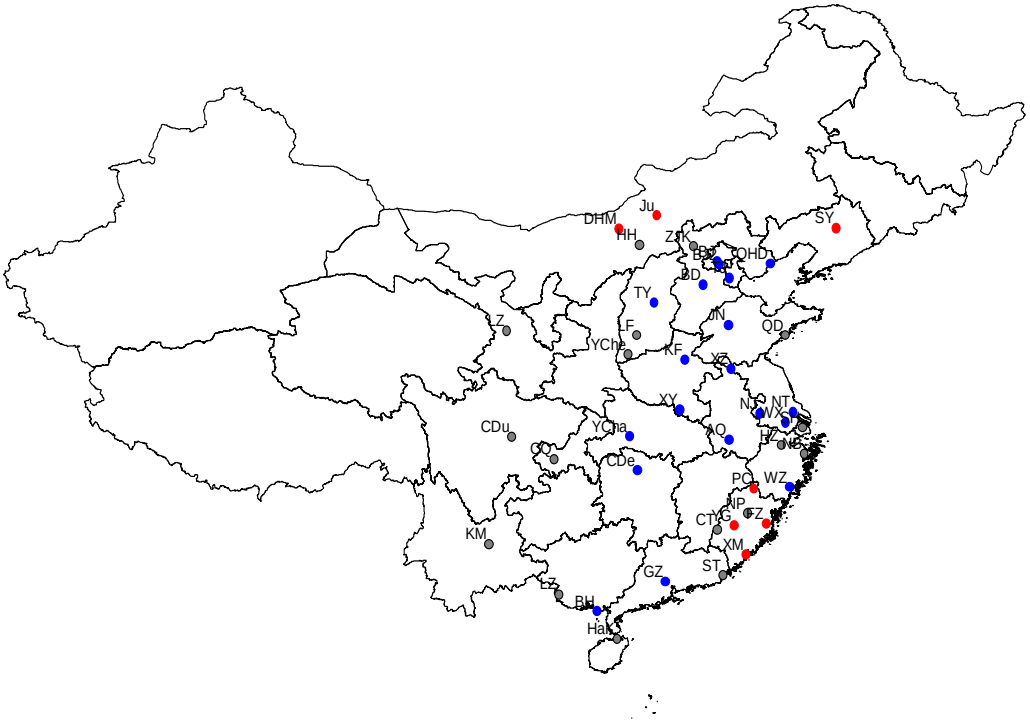


-- Figure 5. Yearly average of daily maximum temperature --

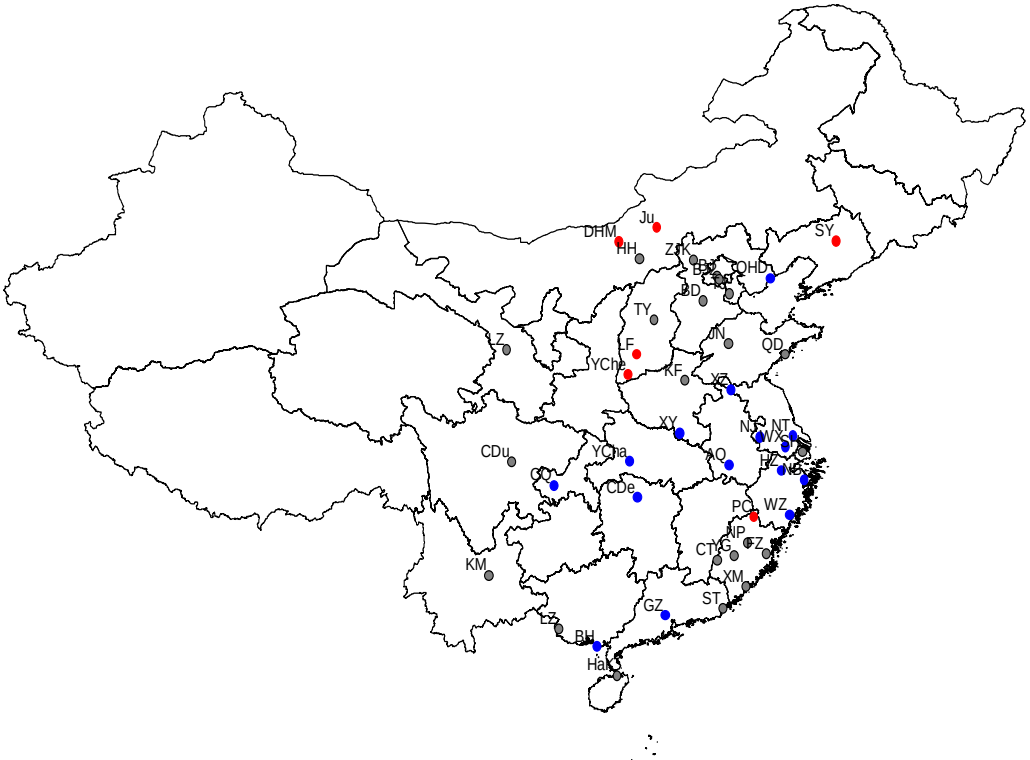


-- Figure 6. Station-specific model: Daily maximum temperature –

(a) July

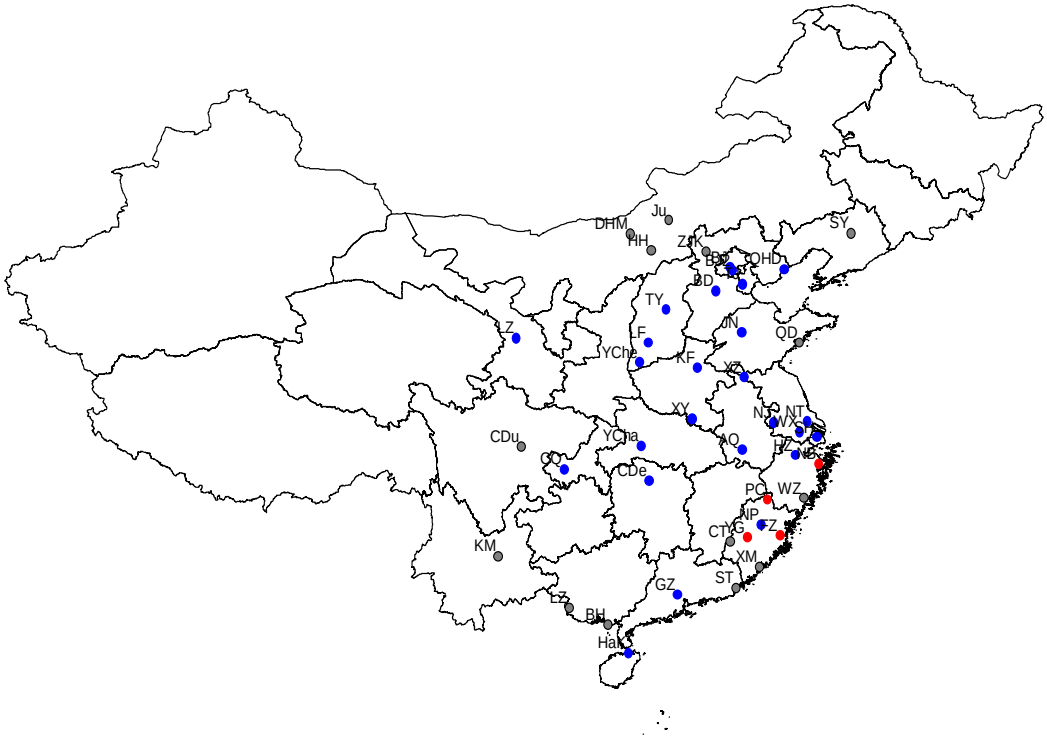



(b) August

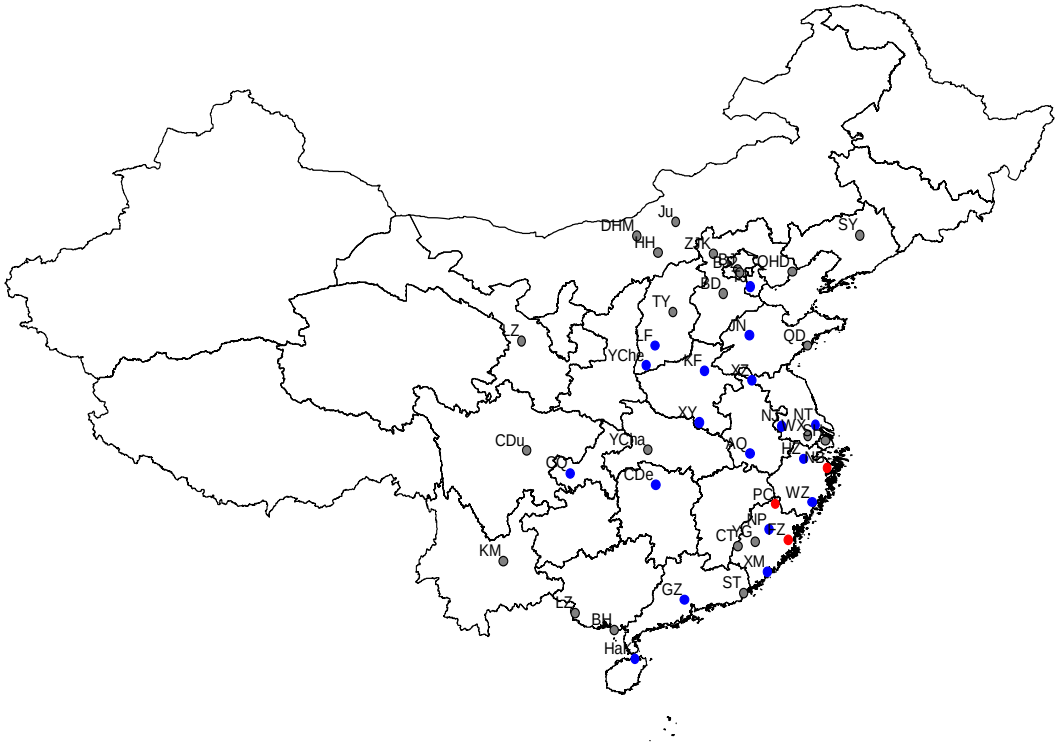


-- Figure 7. Station-specific model: Daily maximum temperature exceeding 37ºC –

(a) July

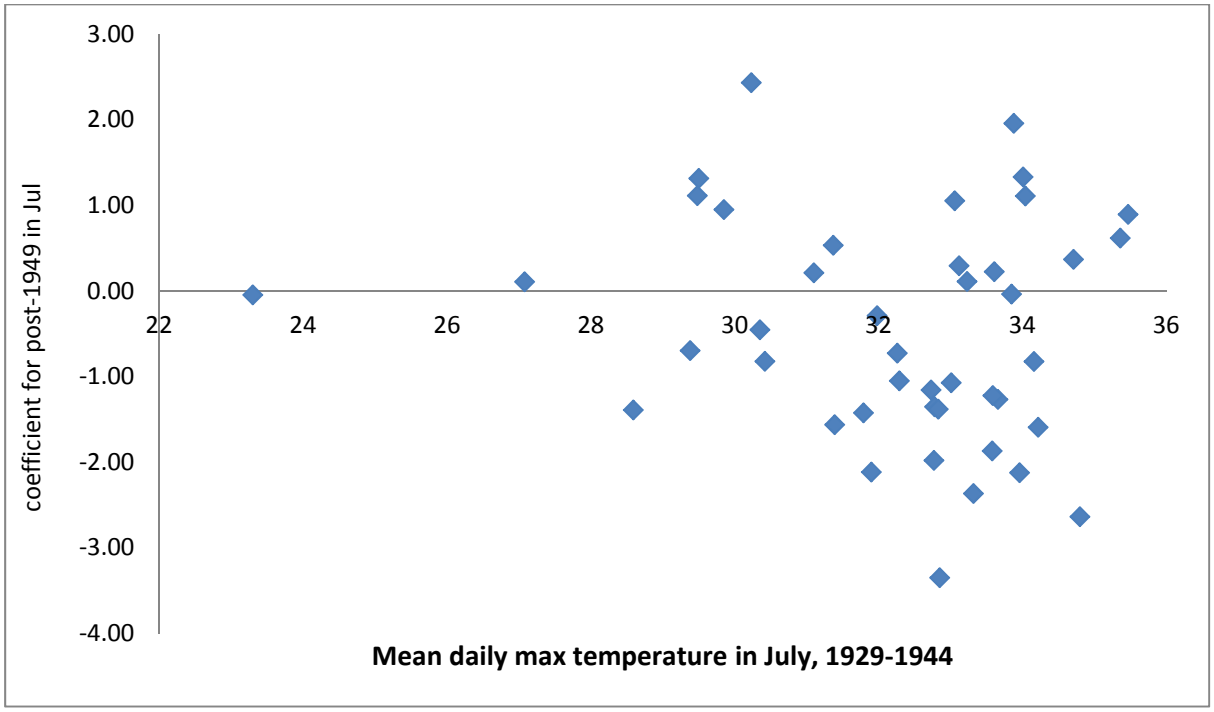



(b) August

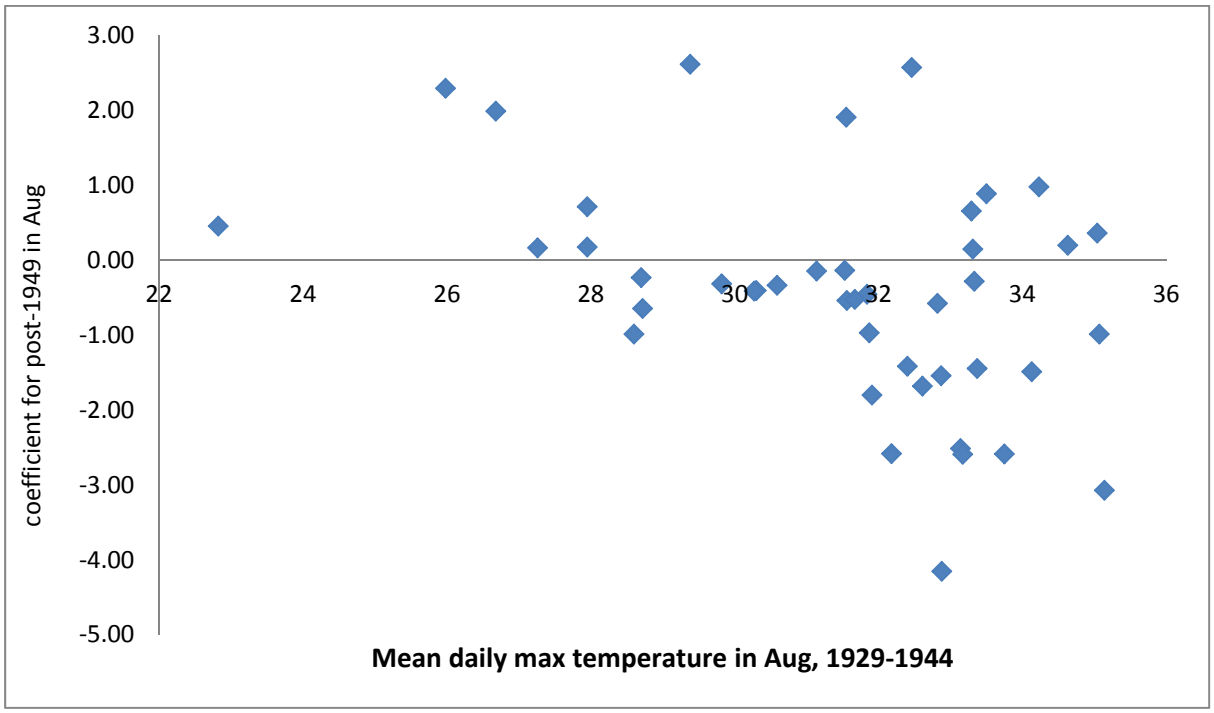


-- Figure 8. Change in daily maximum temperature in the comparison period and mean daily maximum temperature in base period --

(a) July

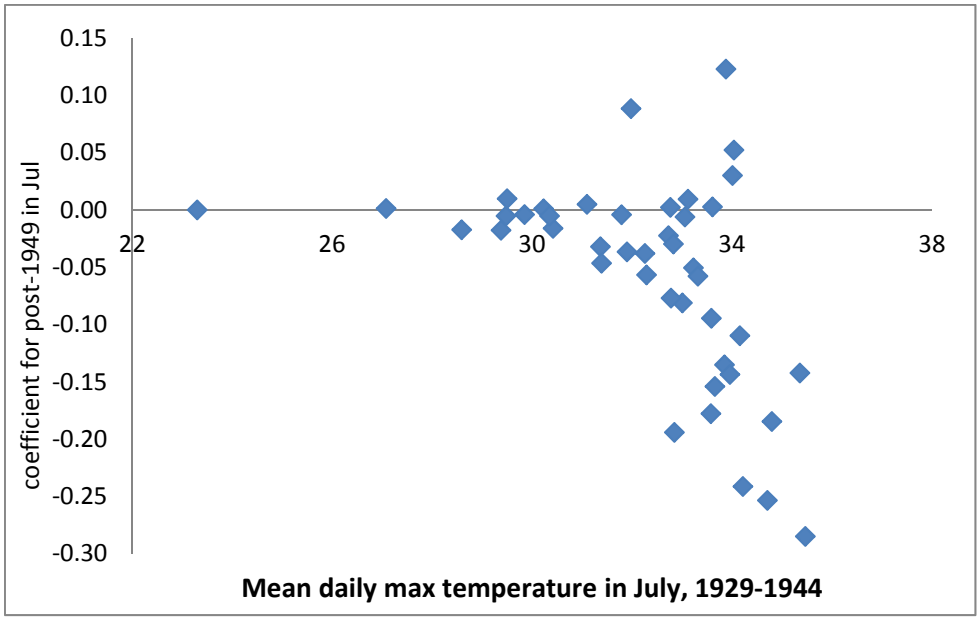



(b) August

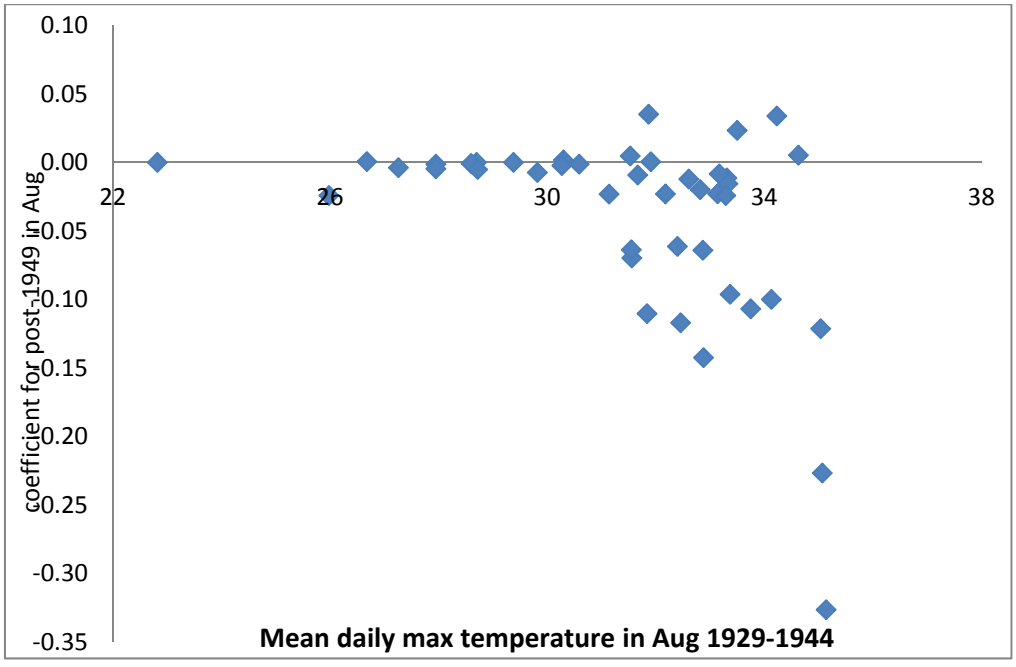


-- Figure 9. Change in probability of daily maximum temperature exceeding 37ºC and mean daily maximum temperature in base period --

(a) July




(b) August



-- Table 1. National model of maximum and minimum temperatures --

| | (a) Monthly maximum | | (b) Daily maximum | | (c) Daily maximum | | (d) Daily minimum | |
|---|---|---|---|---|---|---|---|---|
| | Coeff. | s.e. | Coeff. | s.e. | Coeff. | s.e. | Coeff. | s.e. |
| Jan | -1.6471 | 0.2062 | -2.1493 | 0.0526 | -2.3433 | 0.0718 | -2.3338 | 0.0612 |
| Feb | 1.4854 | 0.2033 | -0.2497 | 0.0541 | -0.4375 | 0.0729 | -0.4799 | 0.0621 |
| Mar | 8.2875 | 0.2031 | 5.3396 | 0.0517 | 5.1455 | 0.0714 | 4.1077 | 0.0608 |
| Apr | 13.0434 | 0.2077 | 11.3029 | 0.0537 | 11.1292 | 0.0726 | 9.7801 | 0.0618 |
| May | 16.4327 | 0.2080 | 16.5845 | 0.0530 | 16.4059 | 0.0720 | 15.1412 | 0.0613 |
| Jun | 19.0358 | 0.2042 | 20.2916 | 0.0528 | 20.0893 | 0.0718 | 19.3742 | 0.0612 |
| Jul | 20.0462 | 0.2042 | 22.3098 | 0.0521 | 22.1221 | 0.0713 | 22.1674 | 0.0607 |
| Aug | 19.2660 | 0.2042 | 21.5883 | 0.0520 | 21.4040 | 0.0712 | 21.4620 | 0.0607 |
| Sep | 16.2019 | 0.2039 | 18.0415 | 0.0528 | 17.8529 | 0.0718 | 17.2116 | 0.0611 |
| Oct | 12.3972 | 0.2009 | 13.2800 | 0.0512 | 13.0908 | 0.0707 | 11.3929 | 0.0602 |
| Nov | 6.7688 | 0.2033 | 6.2372 | 0.0526 | 6.0473 | 0.0717 | 5.2900 | 0.0610 |
| Jan x comparison | 0.0231 | 0.2076 | 0.0047 | 0.0529 | 0.2297 | 0.0761 | 0.2996 | 0.0648 |
| Feb x comparison | 0.2440 | 0.2046 | 0.3593 | 0.0547 | 0.5799 | 0.0772 | 0.6055 | 0.0658 |
| Mar x comparison | -1.0704 | 0.2044 | -0.2159 | 0.0521 | 0.0093 | 0.0756 | 0.6582 | 0.0644 |
| Apr x comparison | -0.4704 | 0.2090 | 0.2573 | 0.0541 | 0.4621 | 0.0768 | 0.7839 | 0.0654 |
| May x comparison | -0.5241 | 0.2093 | -0.1187 | 0.0533 | 0.0910 | 0.0763 | 0.4498 | 0.0649 |
| Jun x comparison | -1.1110 | 0.2055 | -0.5577 | 0.0533 | -0.3243 | 0.0761 | 0.2049 | 0.0649 |
| Jul x comparison | -1.0404 | 0.2055 | -0.4161 | 0.0524 | -0.1970 | 0.0755 | 0.1282 | 0.0643 |
| Aug x comparison | -1.0603 | 0.2055 | -0.4314 | 0.0524 | -0.2158 | 0.0755 | 0.1675 | 0.0644 |
| Sep x comparison | -0.5982 | 0.2052 | -0.5395 | 0.0532 | -0.3197 | 0.0761 | 0.2905 | 0.0648 |
| Oct x comparison | -1.0212 | 0.2022 | -0.9143 | 0.0515 | -0.6937 | 0.0750 | 0.4937 | 0.0639 |
| Nov x comparison | -0.7524 | 0.2046 | -0.4124 | 0.0530 | -0.1909 | 0.0760 | 0.3472 | 0.0647 |
| FE for stations | Yes | | Yes | | Yes | | Yes | |
| FE for months | Yes | | Yes | | Yes | | Yes | |
| FE for years | | | | | Yes | | Yes | |
| N | 33270 | | 1011956 | | 1011956 | | 1009938 | |
| $R^2$ | 0.8407 | | 0.7827 | | 0.7851 | | 0.8583 | |

-- Table 2. National model of daily maximum temperature exceeding benchmark --

| | (a) Daily max ≥ 35ºC | | (b) Daily max ≥ 37ºC | | (c) Daily max ≥ 40ºC | |
|---|---|---|---|---|---|---|
| | coeff | s.e. | coeff | s.e. | coeff | s.e. |
| Jan | -0.0029 | 0.0026 | -0.0013 | 0.0014 | -0.0003 | 0.0004 |
| Feb | -0.0003 | 0.0027 | 0.0000 | 0.0015 | -0.0001 | 0.0004 |
| Mar | 0.0007 | 0.0026 | -0.0004 | 0.0014 | -0.0001 | 0.0004 |
| Apr | 0.0088 | 0.0027 | 0.0021 | 0.0015 | 0.0000 | 0.0004 |
| May | 0.0342 | 0.0026 | 0.0102 | 0.0014 | 0.0011 | 0.0004 |
| Jun | 0.1499 | 0.0026 | 0.0576 | 0.0014 | 0.0090 | 0.0004 |
| Jul | 0.2469 | 0.0026 | 0.0927 | 0.0014 | 0.0121 | 0.0004 |
| Aug | 0.1847 | 0.0026 | 0.0599 | 0.0014 | 0.0107 | 0.0004 |
| Sep | 0.0431 | 0.0026 | 0.0128 | 0.0014 | 0.0011 | 0.0004 |
| Oct | 0.0047 | 0.0026 | 0.0007 | 0.0014 | 0.0000 | 0.0003 |
| Nov | -0.0005 | 0.0026 | -0.0002 | 0.0014 | 0.0000 | 0.0004 |
| Jan x comparison | 0.0029 | 0.0028 | 0.0013 | 0.0015 | 0.0003 | 0.0004 |
| Feb x comparison | 0.0006 | 0.0028 | 0.0000 | 0.0015 | 0.0001 | 0.0004 |
| Mar x comparison | 0.0005 | 0.0028 | 0.0004 | 0.0015 | 0.0001 | 0.0004 |
| Apr x comparison | -0.0042 | 0.0028 | -0.0010 | 0.0015 | 0.0000 | 0.0004 |
| May x comparison | -0.0154 | 0.0028 | -0.0069 | 0.0015 | -0.0010 | 0.0004 |
| Jun x comparison | -0.0747 | 0.0028 | -0.0399 | 0.0015 | -0.0081 | 0.0004 |
| Jul x comparison | -0.0632 | 0.0028 | -0.0435 | 0.0015 | -0.0109 | 0.0004 |
| Aug x comparison | -0.0661 | 0.0028 | -0.0304 | 0.0015 | -0.0097 | 0.0004 |
| Sep x comparison | -0.0196 | 0.0028 | -0.0090 | 0.0015 | -0.0010 | 0.0004 |
| Oct x comparison | -0.0040 | 0.0027 | -0.0007 | 0.0015 | 0.0000 | 0.0004 |
| Nov x comparison | 0.0005 | 0.0028 | 0.0002 | 0.0015 | 0.0000 | 0.0004 |
| FE for stations | Yes | | Yes | | Yes | |
| FE for months | Yes | | Yes | | Yes | |
| FE for years | Yes | | Yes | | Yes | |
| N | 1011956 | | 1011956 | | 1011956 | |
| $R^2$ | 0.1333 | | 0.0463 | | 0.0094 | |
| Ratio | | | | | | |
| May | -0.4496 | | -0.6794 | | -0.9272 | |
| June | -0.4980 | | -0.6939 | | -0.9008 | |
| July | -0.2560 | | -0.4695 | | -0.9043 | |
| Aug | -0.3580 | | -0.5078 | | -0.9029 | |
| Sept | -0.4555 | | -0.7036 | | -0.8802 | |

-- Table 3. National model with multiple comparison periods --

| | (a) Daily maximum | | (b) Daily max ≥ 35ºC | | (c) Daily max ≥ 37ºC | | (d) Daily max ≥ 40ºC | |
|---|---|---|---|---|---|---|---|---|
| | coeff | se | coeff | s.e. | coeff | se | coeff | se |
| Jan | -2.3433 | 0.0718 | -0.0029 | 0.0026 | -0.0013 | 0.0014 | -0.0003 | 0.0004 |
| Feb | -0.4375 | 0.0728 | -0.0003 | 0.0027 | 0.0000 | 0.0015 | -0.0001 | 0.0004 |
| Mar | 5.1455 | 0.0713 | 0.0007 | 0.0026 | -0.0004 | 0.0014 | -0.0001 | 0.0004 |
| Apr | 11.1292 | 0.0725 | 0.0088 | 0.0027 | 0.0021 | 0.0015 | 0.0000 | 0.0004 |
| May | 16.4059 | 0.0720 | 0.0342 | 0.0026 | 0.0102 | 0.0014 | 0.0011 | 0.0004 |
| Jun | 20.0893 | 0.0718 | 0.1499 | 0.0026 | 0.0576 | 0.0014 | 0.0090 | 0.0004 |
| Jul | 22.1221 | 0.0712 | 0.2469 | 0.0026 | 0.0927 | 0.0014 | 0.0121 | 0.0004 |
| Aug | 21.4040 | 0.0712 | 0.1847 | 0.0026 | 0.0599 | 0.0014 | 0.0107 | 0.0004 |
| Sep | 17.8529 | 0.0717 | 0.0431 | 0.0026 | 0.0128 | 0.0014 | 0.0011 | 0.0004 |
| Oct | 13.0908 | 0.0706 | 0.0047 | 0.0026 | 0.0007 | 0.0014 | 0.0000 | 0.0003 |
| Nov | 6.0473 | 0.0716 | -0.0005 | 0.0026 | -0.0002 | 0.0014 | 0.0000 | 0.0004 |
| Jan x 1951-70 | 0.1859 | 0.0843 | 0.0029 | 0.0031 | 0.0013 | 0.0017 | 0.0003 | 0.0004 |
| Feb x 1951-70 | 0.2561 | 0.0857 | 0.0004 | 0.0031 | 0.0000 | 0.0017 | 0.0001 | 0.0004 |
| Mar x 1951-70 | -0.0595 | 0.0839 | 0.0003 | 0.0031 | 0.0004 | 0.0017 | 0.0001 | 0.0004 |
| Apr x 1951-70 | 0.2845 | 0.0851 | -0.0046 | 0.0031 | -0.0013 | 0.0017 | 0.0000 | 0.0004 |
| May x 1951-70 | 0.1637 | 0.0844 | -0.0115 | 0.0031 | -0.0062 | 0.0017 | -0.0010 | 0.0004 |
| Jun x 1951-70 | -0.2196 | 0.0844 | -0.0724 | 0.0031 | -0.0357 | 0.0017 | -0.0075 | 0.0004 |
| Jul x 1951-70 | 0.0156 | 0.0837 | -0.0645 | 0.0031 | -0.0474 | 0.0017 | -0.0109 | 0.0004 |
| Aug x 1951-70 | 0.0331 | 0.0837 | -0.0573 | 0.0031 | -0.0258 | 0.0017 | -0.0096 | 0.0004 |
| Sep x 1951-70 | -0.1608 | 0.0843 | -0.0195 | 0.0031 | -0.0097 | 0.0017 | -0.0011 | 0.0004 |
| Oct x 1951-70 | -0.6410 | 0.0832 | -0.0038 | 0.0030 | -0.0007 | 0.0017 | 0.0000 | 0.0004 |
| Nov x 1951-70 | -0.1138 | 0.0842 | 0.0005 | 0.0031 | 0.0002 | 0.0017 | 0.0000 | 0.0004 |
| Jan x 1971-90 | 0.2386 | 0.0834 | 0.0029 | 0.0031 | 0.0013 | 0.0017 | 0.0003 | 0.0004 |
| Feb x 1971-90 | 0.0046 | 0.0848 | 0.0005 | 0.0031 | 0.0000 | 0.0017 | 0.0001 | 0.0004 |
| Mar x 1971-90 | -0.2728 | 0.0830 | 0.0006 | 0.0030 | 0.0005 | 0.0017 | 0.0001 | 0.0004 |
| Apr x 1971-90 | 0.3424 | 0.0842 | -0.0057 | 0.0031 | -0.0014 | 0.0017 | 0.0000 | 0.0004 |
| May x 1971-90 | -0.0977 | 0.0836 | -0.0194 | 0.0031 | -0.0078 | 0.0017 | -0.0010 | 0.0004 |
| Jun x 1971-90 | -0.4342 | 0.0836 | -0.0892 | 0.0031 | -0.0449 | 0.0017 | -0.0086 | 0.0004 |
| Jul x 1971-90 | -0.3678 | 0.0829 | -0.0920 | 0.0030 | -0.0533 | 0.0017 | -0.0118 | 0.0004 |
| Aug x 1971-90 | -0.2830 | 0.0829 | -0.0844 | 0.0030 | -0.0388 | 0.0017 | -0.0104 | 0.0004 |
| Sep x 1971-90 | -0.6016 | 0.0835 | -0.0297 | 0.0031 | -0.0109 | 0.0017 | -0.0010 | 0.0004 |
| Oct x 1971-90 | -0.7529 | 0.0824 | -0.0041 | 0.0030 | -0.0007 | 0.0017 | 0.0000 | 0.0004 |
| Nov x 1971-90 | -0.3292 | 0.0834 | 0.0005 | 0.0031 | 0.0002 | 0.0017 | 0.0000 | 0.0004 |
| Jan x 1991-2010 | 0.2620 | 0.0839 | 0.0029 | 0.0031 | 0.0013 | 0.0017 | 0.0003 | 0.0004 |
| Feb x 1991-2010 | 1.4907 | 0.0853 | 0.0008 | 0.0031 | 0.0000 | 0.0017 | 0.0001 | 0.0004 |
| Mar x 1991-2010 | 0.3694 | 0.0835 | 0.0006 | 0.0031 | 0.0004 | 0.0017 | 0.0001 | 0.0004 |
| Apr x 1991-2010 | 0.7577 | 0.0847 | -0.0023 | 0.0031 | -0.0003 | 0.0017 | 0.0000 | 0.0004 |
| May x 1991-2010 | 0.2173 | 0.0841 | -0.0149 | 0.0031 | -0.0067 | 0.0017 | -0.0010 | 0.0004 |
| Jun x 1991-2010 | -0.3110 | 0.0840 | -0.0617 | 0.0031 | -0.0389 | 0.0017 | -0.0083 | 0.0004 |
| Jul x 1991-2010 | -0.2249 | 0.0834 | -0.0319 | 0.0031 | -0.0296 | 0.0017 | -0.0101 | 0.0004 |
| Aug x 1991-2010 | -0.3868 | 0.0834 | -0.0556 | 0.0031 | -0.0261 | 0.0017 | -0.0089 | 0.0004 |
| Sep x 1991-2010 | -0.1800 | 0.0840 | -0.0092 | 0.0031 | -0.0063 | 0.0017 | -0.0008 | 0.0004 |
| Oct x 1991-2010 | -0.6831 | 0.0829 | -0.0041 | 0.0030 | -0.0007 | 0.0017 | 0.0000 | 0.0004 |
| Nov x 1991-2010 | -0.1217 | 0.0839 | 0.0005 | 0.0031 | 0.0002 | 0.0017 | 0.0000 | 0.0004 |
| FE for stations | Yes | | Yes | | Yes | | Yes | |
| FE for months | Yes | | Yes | | Yes | | Yes | |
| FE for years | Yes | | Yes | | Yes | | Yes | |
| N | 1011956 | | 1011956 | | 1011956 | | 1011956 | |
| $R^2$ | 0.7854 | | 0.1347 | | 0.0472 | | 0.0095 | |

-- Table 4. National model including duration of sunshine --

| | (a) Daily maximum | | (b) Daily max ≥ 35ºC | | (c) Daily max ≥ 37ºC | | (d) Daily max ≥ 40ºC | |
|---|---|---|---|---|---|---|---|---|
| | coeff | s.e. | coeff | s.e. | coeff | s.e. | coeff | s.e. |
| Jan | -2.877 | 0.104 | -0.009 | 0.003 | -0.003 | 0.002 | -0.001 | 0.000 |
| Feb | -0.796 | 0.105 | -0.008 | 0.003 | -0.003 | 0.002 | -0.001 | 0.000 |
| Mar | 5.490 | 0.104 | -0.015 | 0.003 | -0.005 | 0.002 | -0.001 | 0.000 |
| Apr | 12.184 | 0.105 | -0.013 | 0.003 | -0.005 | 0.002 | -0.001 | 0.000 |
| May | 18.272 | 0.104 | -0.001 | 0.003 | -0.002 | 0.002 | -0.001 | 0.000 |
| Jun | 22.383 | 0.104 | 0.069 | 0.003 | 0.027 | 0.002 | 0.002 | 0.000 |
| Jul | 24.579 | 0.103 | 0.159 | 0.003 | 0.054 | 0.002 | 0.006 | 0.000 |
| Aug | 23.864 | 0.102 | 0.086 | 0.003 | 0.020 | 0.002 | 0.002 | 0.000 |
| Sep | 20.009 | 0.106 | 0.008 | 0.003 | 0.000 | 0.002 | -0.001 | 0.000 |
| Oct | 14.496 | 0.105 | -0.017 | 0.003 | -0.006 | 0.002 | -0.001 | 0.000 |
| Nov | 6.716 | 0.103 | -0.009 | 0.003 | -0.003 | 0.002 | 0.000 | 0.000 |
| Jan x comparison | 0.474 | 0.108 | 0.009 | 0.003 | 0.003 | 0.002 | 0.001 | 0.000 |
| Feb x comparison | 1.019 | 0.110 | 0.006 | 0.003 | 0.002 | 0.002 | 0.000 | 0.000 |
| Mar x comparison | 0.245 | 0.108 | 0.010 | 0.003 | 0.003 | 0.002 | 0.001 | 0.000 |
| Apr x comparison | 0.664 | 0.109 | 0.005 | 0.003 | 0.002 | 0.002 | 0.001 | 0.000 |
| May x comparison | -0.048 | 0.108 | -0.003 | 0.003 | 0.000 | 0.002 | 0.001 | 0.000 |
| Jun x comparison | -0.564 | 0.108 | -0.030 | 0.003 | -0.018 | 0.002 | -0.001 | 0.000 |
| Jul x comparison | -0.716 | 0.107 | -0.056 | 0.003 | -0.032 | 0.002 | -0.005 | 0.000 |
| Aug x comparison | -0.606 | 0.107 | -0.023 | 0.003 | -0.005 | 0.002 | -0.002 | 0.000 |
| Sep x comparison | -0.510 | 0.111 | -0.002 | 0.003 | 0.000 | 0.002 | 0.001 | 0.000 |
| Oct x comparison | -0.632 | 0.109 | 0.011 | 0.003 | 0.004 | 0.002 | 0.001 | 0.000 |
| Nov x comparison | -0.275 | 0.107 | 0.007 | 0.003 | 0.003 | 0.002 | 0.000 | 0.000 |
| Sunshine hours | Yes | | Yes | | Yes | | Yes | |
| FE for stations | Yes | | Yes | | Yes | | Yes | |
| FE for months | Yes | | Yes | | Yes | | Yes | |
| FE for years | Yes | | Yes | | Yes | | Yes | |
| N | 654827 | | 654827 | | 654827 | | 654827 | |
| $R^2$ | 0.8318 | | 0.1204 | | 0.0370 | | 0.0045 | |
| Ratio | | | | | | | | |
| June | | | -0.4299 | | -0.6773 | | -0.6160 | |
| July | | | -0.3527 | | -0.5884 | | -0.8860 | |
| Aug | | | -0.2638 | | -0.2472 | | -0.6944 | |

-- Table 5. Periphery of mainland China –

| | (a) Daily maximum | | (b) Daily max ≥ 35ºC | |
|---|---|---|---|---|
| | coeff | s.e. | coeff | s.e. |
| Jan | -2.1298 | 0.1001 | 0.0000 | 0.0043 |
| Feb | -1.7668 | 0.1026 | 0.0000 | 0.0044 |
| Mar | 0.4049 | 0.1001 | 0.0000 | 0.0043 |
| Apr | 4.2114 | 0.1010 | 0.0000 | 0.0043 |
| May | 7.7309 | 0.1001 | 0.0011 | 0.0043 |
| Jun | 9.6238 | 0.1010 | 0.0254 | 0.0043 |
| Jul | 10.5159 | 0.1001 | 0.0492 | 0.0043 |
| Aug | 10.4126 | 0.1001 | 0.0580 | 0.0043 |
| Sep | 9.6437 | 0.1010 | 0.0266 | 0.0043 |
| Oct | 6.9236 | 0.1001 | 0.0033 | 0.0043 |
| Nov | 3.7318 | 0.1010 | 0.0000 | 0.0043 |
| Jan x comparison | 0.2249 | 0.1118 | 0.0000 | 0.0048 |
| Feb x comparison | 0.2863 | 0.1145 | 0.0000 | 0.0049 |
| Mar x comparison | 0.6436 | 0.1118 | 0.0001 | 0.0048 |
| Apr x comparison | 0.4076 | 0.1127 | 0.0006 | 0.0048 |
| May x comparison | -0.0361 | 0.1118 | 0.0063 | 0.0048 |
| Jun x comparison | -0.0477 | 0.1127 | 0.0076 | 0.0048 |
| Jul x comparison | 0.5643 | 0.1118 | 0.0544 | 0.0048 |
| Aug x comparison | 0.3237 | 0.1118 | 0.0173 | 0.0048 |
| Sep x comparison | -0.0933 | 0.1127 | -0.0073 | 0.0048 |
| Oct x comparison | -0.0583 | 0.1118 | -0.0025 | 0.0048 |
| Nov x comparison | -0.2076 | 0.1127 | 0.0000 | 0.0048 |
| FE for stations | Yes | | Yes | |
| FE for months | Yes | | Yes | |
| FE for years | Yes | | Yes | |
| N | 109,207 | | 109,207 | |
| $R^2$ | 0.0954 | | 0.7087 | |