Predictive Modeling of Surface Temperature Extremes over North America, with Actuarial Applications in View

Predictive Modeling of Surface Temperature Extremes over North America, with Actuarial Applications in View

AUTHOR   Vytaras Brazauskas, Ph.D., ASA
Sergey Kravtsov, Ph.D.
Paul Roebber, Ph.D.

SPONSOR   Society of Actuaries Climate and Environmental Sustainability Research Committee

CONTENTS

Major Goals of the Project

To estimate potential losses from natural phenomena, actuaries use the so-called catastrophe models (CAT models), which generally consist of three modules: a Science Module, an Engineering Module, and a Financial Module. The Science Module is designed to simulate the natural phenomena themselves, the Engineering Model is used to estimate potential damages from natural factors, and the Financial Module translates the estimated losses into insurance-related quantities. This project emphasizes the development of an appropriate numerically efficient Science Module around the climate variability of surface temperature, which has an immediate socioeconomic effect on areas such as human health and agriculture.

The weather and climate systems are necessarily complex, because they are nonlinear, nonstationary, and composed of multiple, interacting spatial and temporal scales. Additionally, the observational networks do not sample all conditions at all necessary space and time scales to resolve these features. At the same time, state-of-the-art numerical weather prediction models based on first principles are expensive to run and are subject to biases due to imperfect physical parameterizations of unresolved processes. Combining these models with all available observations in an optimal way results in the development of the so-called reanalysis products (e.g., Kalnay et al. 1996), which are well sampled (typically on a uniform grid) in space and time, with relatively high resolution in both dimensions, and they can be used in weather and climate research studies. In particular, the reanalysis data sets can be utilized in validating forecasts of dynamical models and typically serve as the input data for purely statistical emulators of atmospheric and climate dynamics.

The latter emulators constitute an alternative and fairly competitive strategy for weather and climate prediction. These extremely numerically efficient empirical stochastic models are entirely data driven and do not utilize physical principles at all. They have been used in the past and showed success in predicting some of the important weather and climate phenomena, with the forecast skill often comparable with that of dynamical models (e.g., Penland 1989; Penland and Ghil 1993; Winkler et al. 2001; Kravtsov et al. 2005; Kondrashov et al. 2005). Empirical models necessarily concentrate on a limited subset of climatic fields, due to a typically short length or limited spatial coverage (or resolution) of available observational records and are often relatively low-dimensional. Recent work (Kravtsov et al. 2016b) showed, however, that these models may in fact be adequate for capturing detailed high-resolution statistics of select climatic fields of interest on a regional-to-hemispheric scale. In the present project, we apply this technique to obtain ensemble simulations of surface atmospheric temperature over North America; these simulations are used, among other things, to estimate long-term changes in the spatial distribution and magnitude of extreme heat waves and cold spells in the region.

Accomplishments under These Goals

Major activities: We used a surface temperature data set based on National Center for Environmental Prediction North American Regional Reanalysis (NARR) to build our model (see http://www.esrl.noaa.gov/psd/data/gridded/data.narr.html for NARR details). The empirical model is based on a set of coupled ARMA-type models simulating the surface-temperature variability over the entire spatial domain considered and across the range of timescales, from monthly to subdaily. At the outset, we produce surrogate 1979–2015 surface-temperature simulations (over the entire data domain, at three-hour resolution) from the model runs driven by stochastic forcing. The structure of the stochastic forcing depends on the simulated state of the system, which enables the model to capture non-Gaussian processes. The model is also designed to capture seasonal and diurnal effects, including the seasonal cycle of the surface-temperature variance, as well as the effects of the external predictors, which are defined objectively based on the observed variations of the leading regional and hemispheric sea-surface temperature (SST) modes. We have shown that this model is able to capture the complex spatiotemporal structure and magnitude of the observed surface-temperature variability, including the spatial distribution of extreme events. However, the magnitude of the extreme events was underestimated (as reported by Kravtsov et al. 2016a). We therefore developed a post-processing bias-correction procedure to alleviate the latter problem and

computed and analyzed the 1979–2015 time series of the extreme-event probabilities based on 100 surrogate simulations of our empirical surface-temperature model.

Specific objectives:

- To construct a multiscale empirical stochastic model of surface-temperature variability over North America
- To produce a large ensemble of climate simulations with this model "forced" by the observed history of the external SST predictors
- To apply a nonlinear mapping procedure (quantile mapping; Cannon et al. 2015) to "fix" the local probability density distributions of the model-simulated temperature. Quantile mapping of *each* surrogate simulation onto the observed temperature was done at each geographical location and within each season [December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), September-October-November (SON)]. By construction, the probability density functions (PDFs) of the observed and simulated data based on all of the data (1979–2015) were made identical, but spatiotemporal information, such as spatial correlation and trend patterns, is still all "live" and predicted by the model.
- To compute and visualize, based on 100 (bias-corrected) surrogate model simulations, time-dependent surface-temperature probability distributions and conduct preliminary analysis of their variability.

Significant results: The major deliverable of this project is a collection of statistically independent surrogate simulations of the spatially extended three-hour surface-temperature time series mimicking the NARR time series and saved on the original NARR high-resolution spatial grid over North America. These simulations can be used to estimate various probabilistic characteristics of the nonstationary surface-temperature distributions over the 1979–2015 period. For example, Figure 1 shows the time series of select characteristics of the PDF for the surface temperature at a grid point closest to Chicago O'Hare International Airport. The two panels of this figure display the results for the DJF daily minimum temperatures (top) and JJA daily maximum temperatures (bottom), which both exhibit quite a range of values throughout the time series (on the order of 40°C for DJF minimum temperatures and of 25°C for JJA maximum temperatures). Interannual (year-to-year) variability and long-term trends in the surface-temperature distributions (for example, changes in the annual median or 99th percentile) are also present but are naturally very slight compared to the overall range of variability, which indicates the slowness of climate change compared with the day-to-day temperature variability. Yet statistically significant long-term trends in these quantities are real and noticeable; they reflect the effect of the external SST predictors on the surface-temperature variability in the context of the present empirical model. A notable feature of the JJA surface-temperature behavior includes an apparent jump (of around 1°C) to warmer conditions after 1997, following a major El Niño episode in 1997–1998. Indications suggest that this regional climate shift may be related to a larger-scale climate shift (Mukhin et al. 2015) associated with a nonlinear variability in the so-called Pacific Decadal Oscillation (Mantua et al. 1997).

No matter how slight the latter long-term changes may seem, they are reflected in the noticeable changes in the probability of extreme events. For example, the probability of the JJA maximum daily surface temperatures to exceed the 99th percentile of this quantity (computed over the entire 1979–2015 period) increases by a factor of two after the 1997–1998 transition to warmer conditions (Fig. 2, top); likewise, a clear, albeit more continuous, 1979–2015 downward trend is seen in the probability of the DJF daily minimum surface temperature to fall below its overall 1st percentile (Fig. 2, bottom). Note that the highest temperature of about 40°C at O'Hare Airport was recorded only once in the real observational record (on July 13, 1995). Yet the empirical model simulations predict a nonzero likelihood of such events over most of the 1979–2015 period, with 1995 being, on average, less likely to produce such extreme warmth than the later periods, as shown in Fig. 2. The point here is that the types of probabilistic information that our model simulations supply cannot really be obtained based on direct statistical analysis of the observational record, which demonstrates the essential utility of our proposed methodology.

Similar time series can be obtained for all locations over North America in our simulation domain. Figures 3 and 4 show the climatological (1979–2015 average) characteristics of the simulated surface temperature distributions, including their overall mean, average interquartile range (IQR), and 1st (99th) percentiles of the daily minimum (maximum) temperature, for DJF and JJA seasons, respectively. All these characteristics

exhibit a pronounced interannual variability (Fig. 5) and statistically significant long-term trends (Figs. 6 and 7). The decadal trends in the minimum daily surface temperature (Fig. 6) are most pronounced over Canada, around Hudson Bay. Note the long-term statistically significant shifts in both the surface-temperature mean (Figs. 6a,b) and IQR (Figs. 6c,d), which may both contribute to the long-term change in the distribution of extreme events (Figs. 6e,f). These results indicate that the dynamics of this polar amplification of long-term warming might centrally involve the ice-albedo feedback. By contrast, the daily maximum JJA temperature changes are more widespread and occur over all of North America, but in this case the IQR essentially remains the same (Figs. 7c,d), while the changes in the mean (Figs. 7a,b) and extremes (Figs. 7e,f) have a very similar pattern, thus indicating a uniform shift in the whole distribution to warmer temperatures.

Key Outcomes

- We constructed an extremely numerically efficient empirical model for simulating the (nonstationary) statistical characteristics of surface air temperature over North America, across a range of time scales and for all seasons.
- We used this model to produce a large ensemble of surrogate simulations of the surface temperature over the 1979–2015 period, which is the major deliverable of this project. The associated data set is made publicly available and is hosted by nature.com. The data set's user guide (Kravtsov et al. 2017) and the link to the actual data are available from http://www.nature.com/articles/sdata2017155.
- The database of these surrogate simulations can be used to estimate variable statistics of the surface-temperature variability over the simulation period. We performed some analyses of this type and established the ability of the model to simulate climate shifts (for example, the 1997–1998 shift) and other forced signals (such as the SST forced drought conditions; see Kravtsov et al. 2016a).
- The model identifies polar-intensified wintertime warming (mostly around Hudson Bay), which is also characterized by the enhanced surface-temperature variance in the same region. By contrast, summertime warming trends are dominated by the (possibly jumplike, around 1997–1998) shift in the mean temperature, but essentially the same day-to-day temperature variability throughout the entire record.
- The results from this project were presented at two atmospheric-science meetings: the 2016 American Geophysical Union Meeting in San Francisco on December 12–16, 2016,[1] and the joint Japan Geophysical Union–American Geophysical Union meeting in Chiba, Japan, on May 20–25, 2017,[2] as well as at two actuarial and statistical meetings: the 52nd Actuarial Research Conference in Atlanta on July 26–29, 2017, and the American Statistical Association Mid-Michigan Chapter Annual Meeting in Mt. Pleasant on October 19, 2017. This research is being further publicized via a submission to the CAS 2018 Climate Change call for papers (Roebber et al. 2017).

Future Plans

- As an illustration of the utility of the surrogate surface temperature database, provide examples of estimating contributions of internal atmospheric dynamics and external forcings in the observed surface-temperature variability, for example, by estimating time-dependent probability of the prolonged drought events over the U.S. Central Plains
- Estimate predictability of extreme temperature events
- Extrapolate the extreme-event trends into future decades, both statistically and with the use of SST projections from global climate models
- Develop an empirical model that also includes surface dew-point temperature and hence be able to simulate discomfort indices and better isolate environmental conditions hazardous for health.

---

[1] https://people.uwm.edu/kravtsov/files/2016/04/Kravtsov_AGU2016_poster1-10kcdw1.pdf

[2] https://people.uwm.edu/kravtsov/files/2016/04/JpGU_AGU2017_poster-11qr1ib.pdf

References

Cannon, A. J., S. R. Sobie, and T. Q. Murdock. 2015. Bias Correction of GCM Precipitation by Quantile Mapping: How Well Do Methods Preserve Changes in Quantiles and Extremes? *Journal of Climate* 28:6938–6959

Kalnay and Coauthors. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, 77: 437-471.

Kondrashov, D., S. Kravtsov, A. W. Robertson, and M. Ghil. 2005. A Hierarchy of Data-Based ENSO Models. *Journal of Climate* 18:4425–4444.

Kravtsov, S., V. Brazauskas, and P. Roebber. 2016a. Predictive Modeling of Risk Associated with Temperature Extremes over North America. Presentation at the 2016 American Geophysical Union Fall Meeting, San Francisco. Available from https://people.uwm.edu/kravtsov/presentations/.

Kravtsov, S., D. Kondrashov, and M. Ghil. 2005. Multi-level Regression Modeling of Nonlinear Processes: Derivation and Applications to Climatic Variability. *Journal of Climate* 18:4404–4424.

Kravtsov, S., P. Roebber, and V. Brazauskas. 2017. A Virtual Climate Library of Surface Temperature over North America for 1979–2015. *Scientific Data* 4, article number 170155, doi:10.1038/sdata.2017.155.

Kravtsov, S., N. Tilinina, Y. Zyulyaeva, and S. Gulev. 2016b. Empirical Modeling and Stochastic Simulation of Sea-Level Pressure Variability. *Journal of Applied Meteorology and Climatology* 55:1197–1219.

Mantua, N. J., Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. *Bulletin of the American Meteorological Society* 78:1069–1079.

Mukhin, D., A. Gavrilov, A. Feigin, E. Loskutov, and J. Kurths. 2015. Principal Nonlinear Dynamical Modes of Climate Variability. *Nature Scientific Reports* 5, article 15510, doi:10.1038/srep15510.

Penland, C. 1989. Random Forcing and Forecasting Using Principal Oscillation Pattern Analysis. *Monthly Weather Review* 117:2165–2185.

Penland, C., and M. Ghil. 1993. Forecasting Northern Hemisphere 700-mb Geopotential Height Anomalies Using Empirical Normal Modes. *Monthly Weather Review* 121:2355–2372.

Roebber, P., V. Brazauskas, and S. Kravtsov. 2018. The Actuarial Utility of Weather and Climate Predictions. *Submitted for publication.*

Winkler, C. R., M. Newman, and P. D. Sardeshmukh. 2001. A Linear Model of Wintertime Low-Frequency Variability. Part I: Formulation and Forecast Skill. *Journal of Climate* 14:4474–4494.
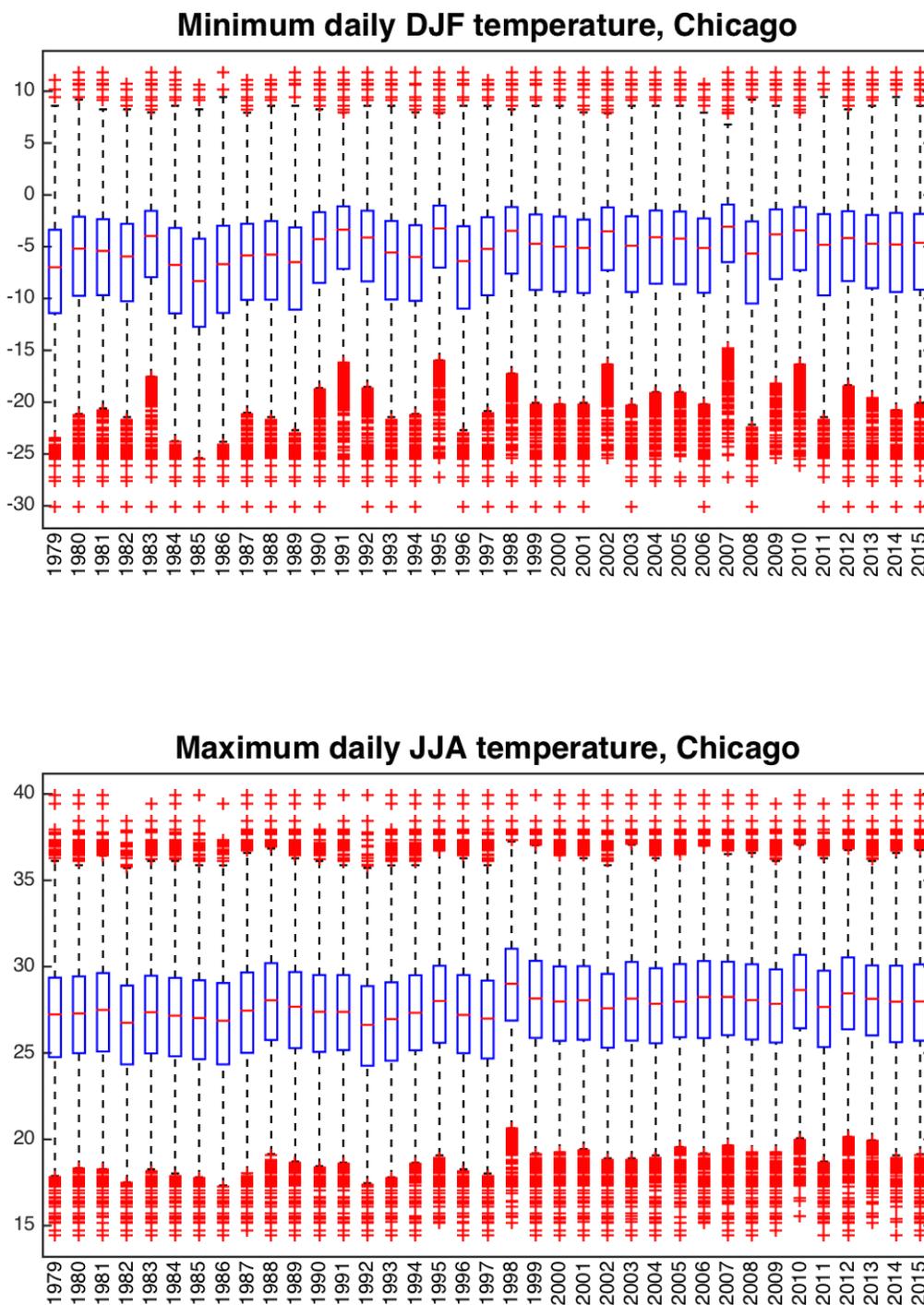
Figure 1: Boxplots of DJF daily minimum (top) and JJA daily maximum (bottom) surface temperature at O'Hare Airport, based on one hundred 1979–2015 empirical model simulations. For each year (approximately 9,000 input data points), the central mark represents the median, and the edges of the box are the 25th and 75th percentiles. The whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually with plus signs.
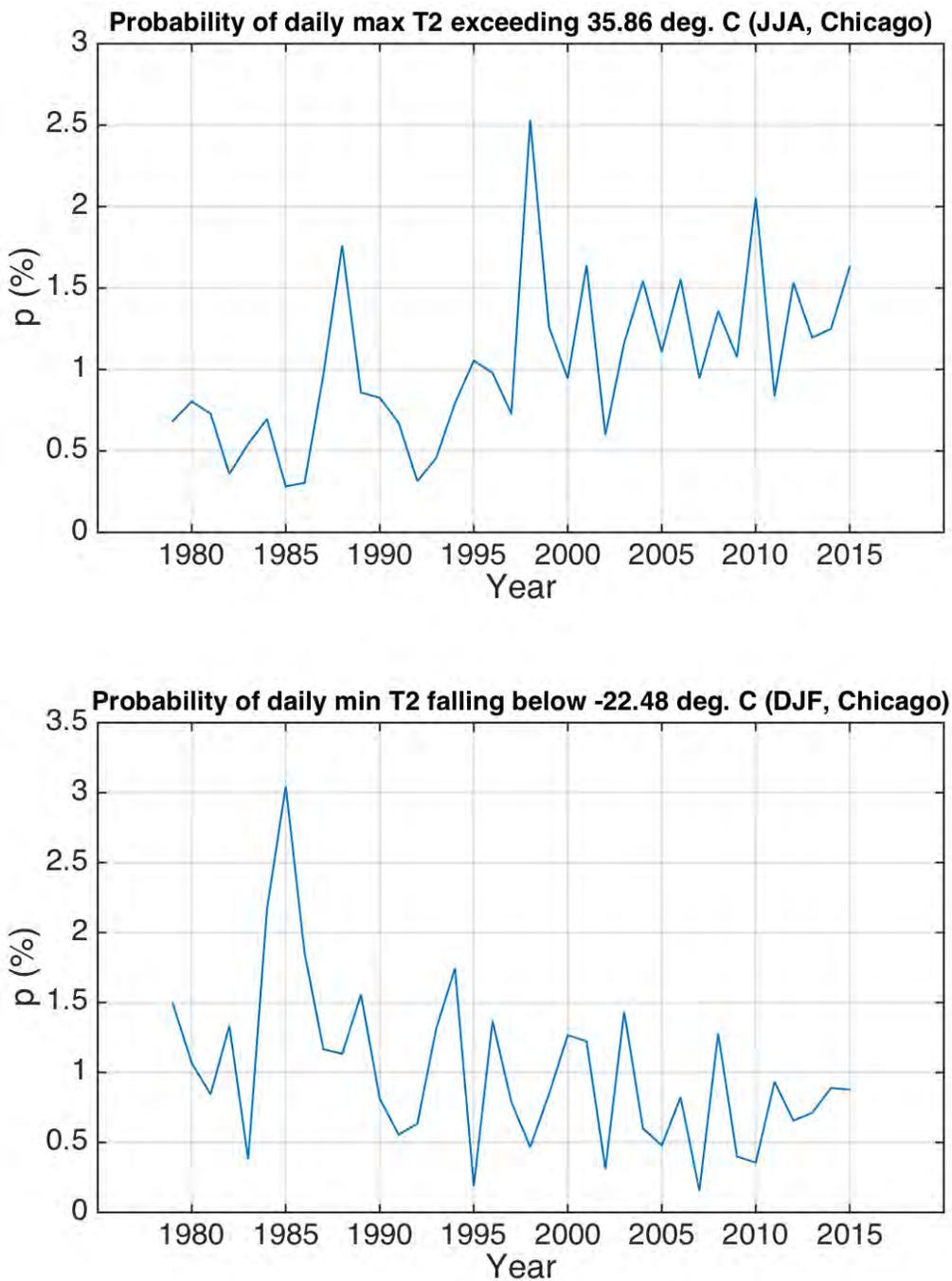
Figure 2: Probability of extreme temperature events at O'Hare Airport. Top: Probability of daily maximum JJA temperature to exceed the 99th percentile threshold based on the entirety of 1979–2015 simulations. Bottom: Probability of daily minimum DJF temperature to fall below the 1st percentile threshold based on all 1979–2015 simulations. The threshold values are given in the panel titles.
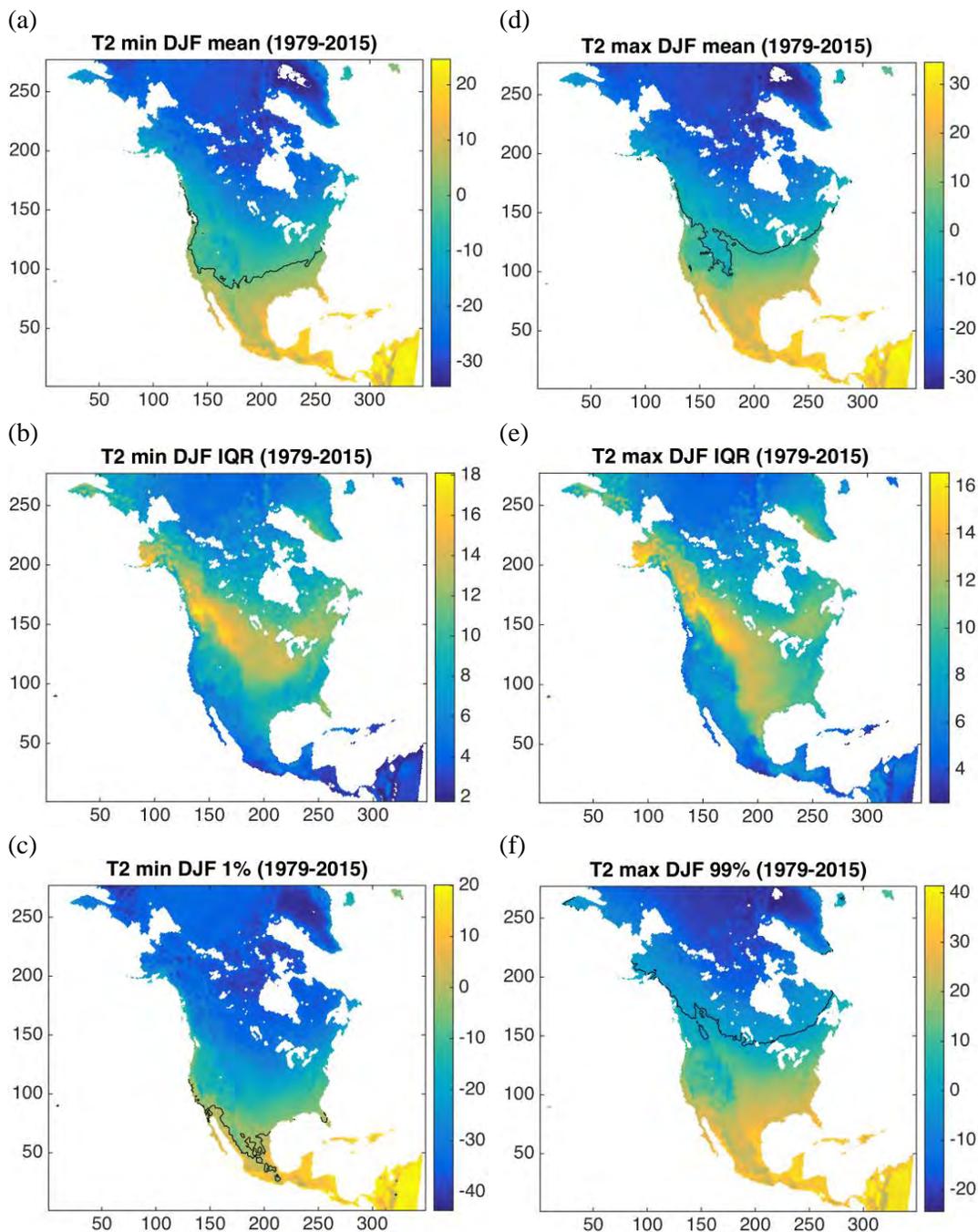
Figure 3: Climatology of the daily minimum (a–c) and daily maximum (d–f) surface temperature for the DJF season, as derived from one hundred 1979–2015 simulations of the empirical model: (a, d) Mean temperature; (b, e) interquartile range (IQR, between 25th and 75th percentiles of temperature); (c, f) 1st or 99th percentile of the corresponding temperature. All quantities were computed as the averages over the 37 estimates for individual years. Black contour corresponds to 0°C.
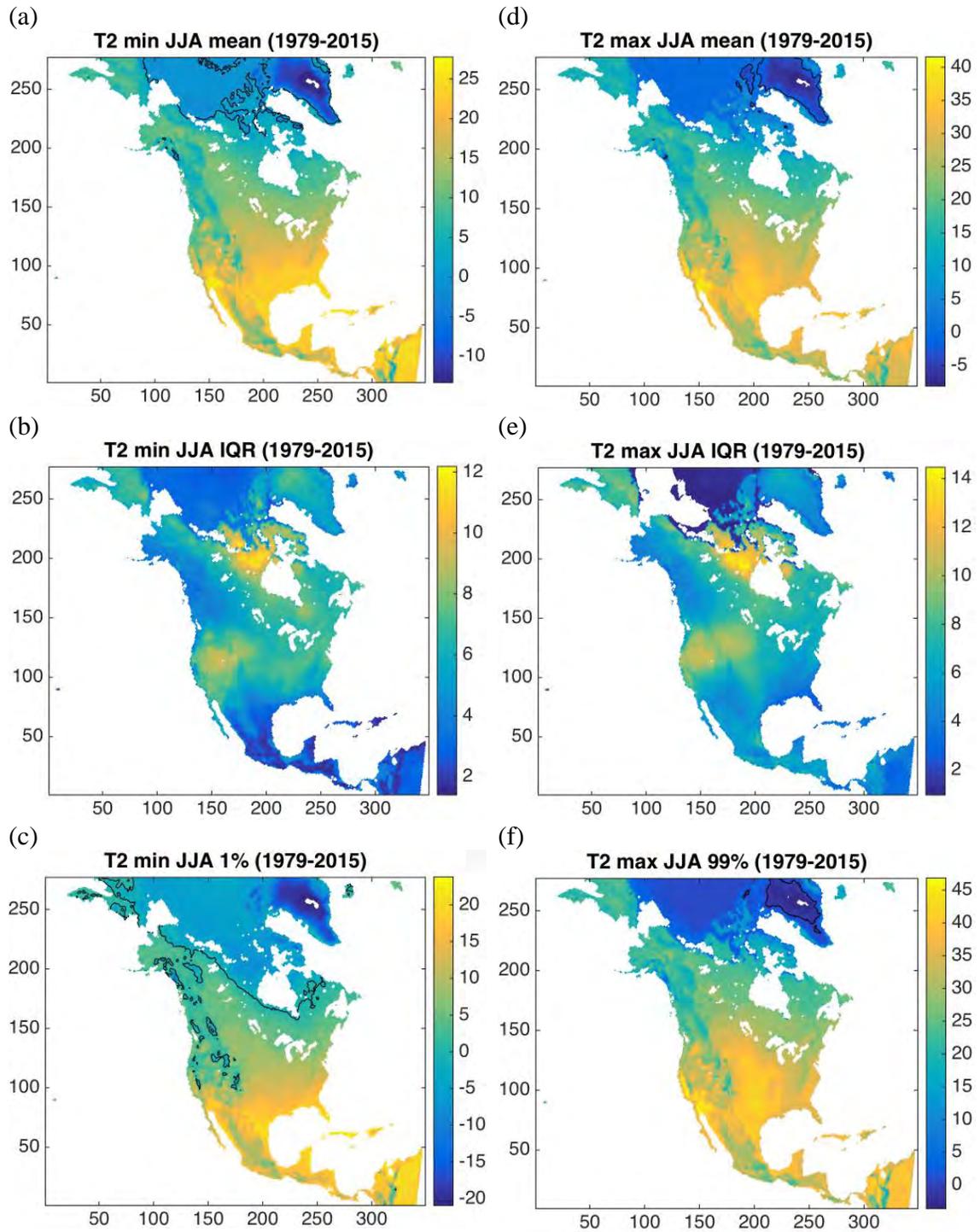
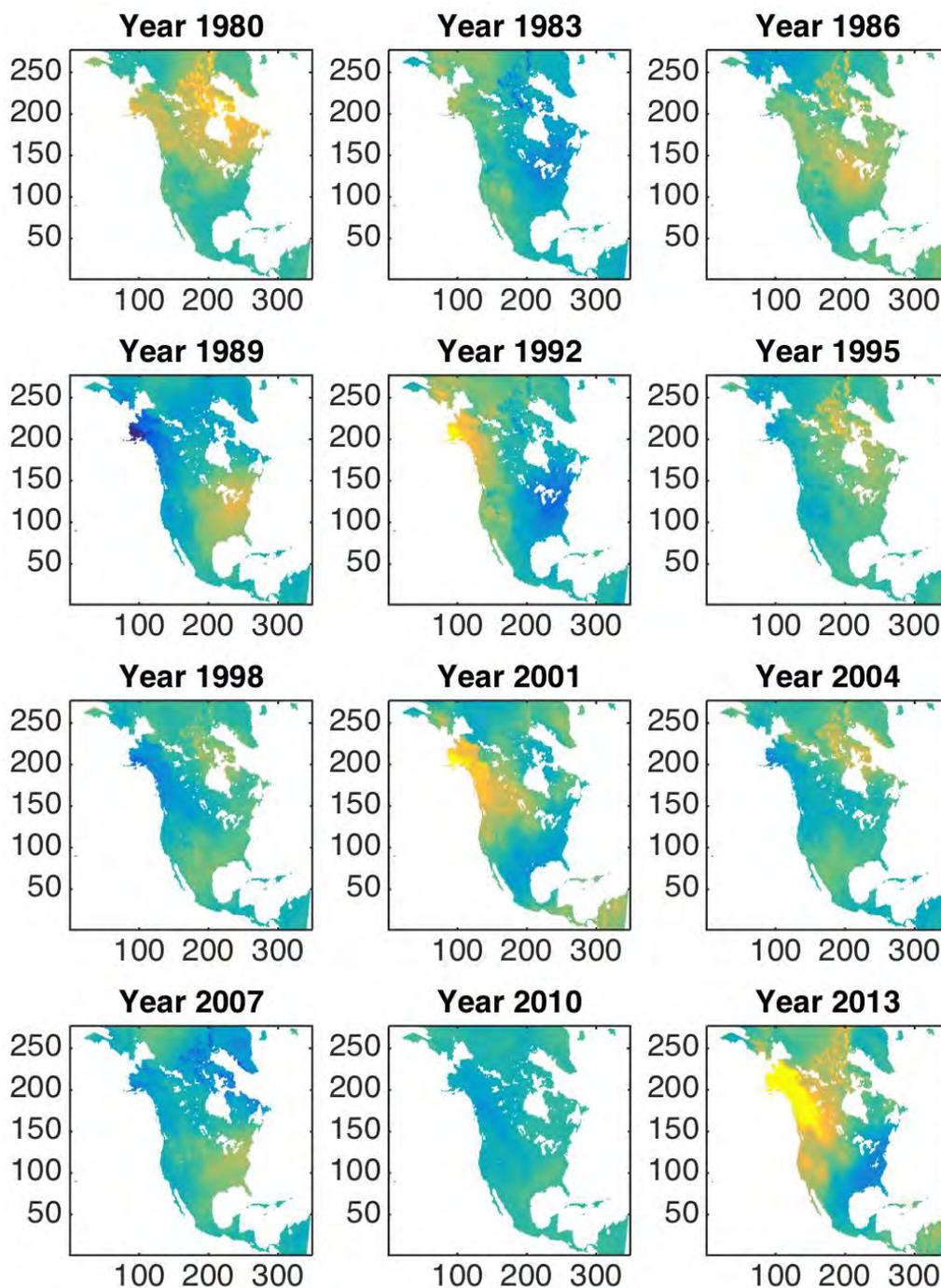Figure 4: The same as in Fig. 3, but for the JJA season.

Figure 5: Three-year tendencies of the daily minimum DJF surface-temperature mean. Panel captions give the year corresponding to the middle of the three-year period. For example, the first panel, labeled 1980, shows the difference in the mean DJF temperature between 1981 and 1979, the second panel (1983) the difference between 1984 and 1982, and so forth. The color scale corresponds to the range between ±5°C, from saturated navy blue to bright yellow.
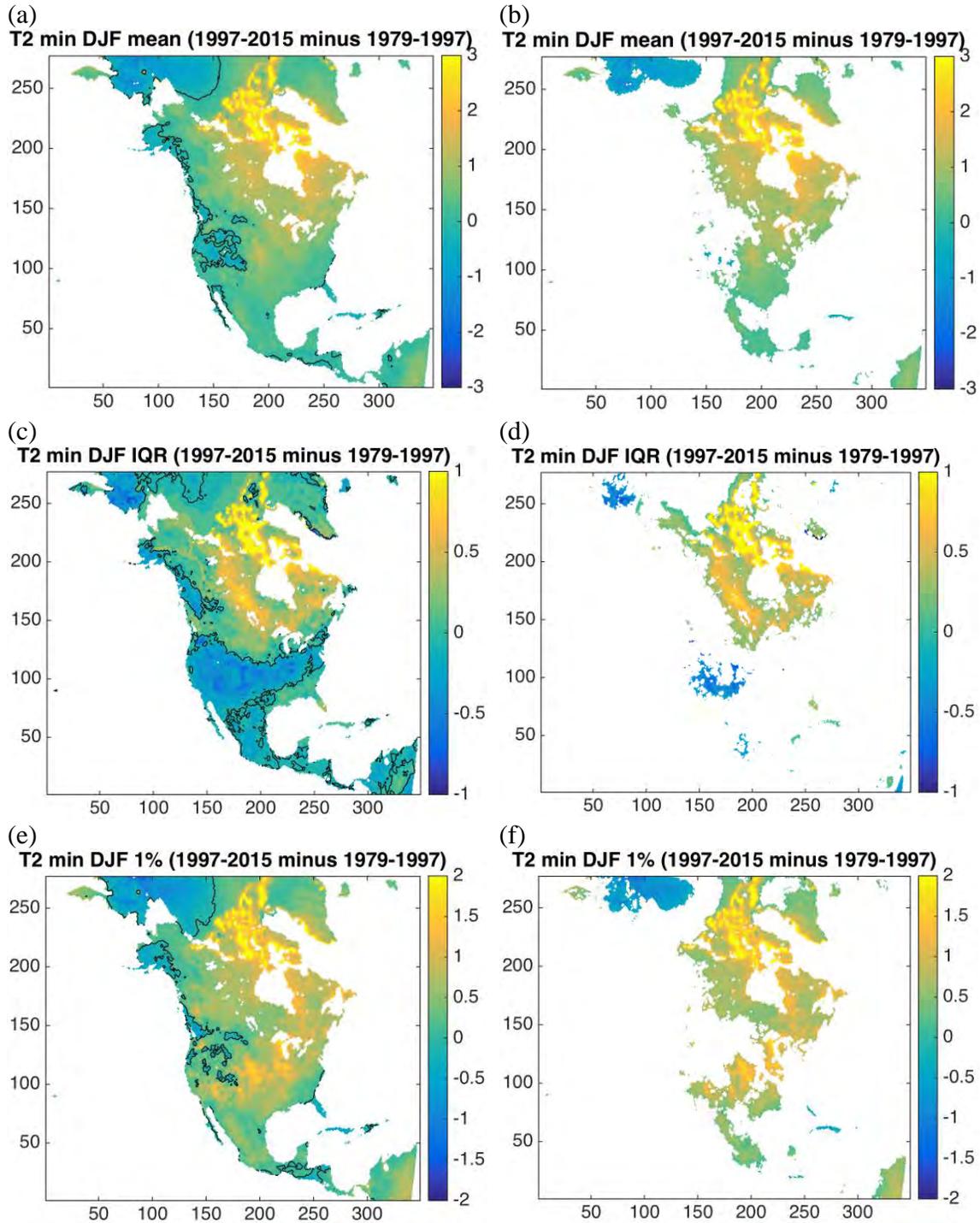
Figure 6: The change in climatological characteristics of the daily minimum DJF surface temperature between the 1997–2015 and 1979–1997 periods, for the three quantities displayed in Fig. 3a–c (mean, IQR, and 99th percentile). Left panels show all surface locations, and right panels show only the locations exhibiting statistically significant climate change (according to the two-sided Student's *t*-test). Black contour corresponds to 0°C.
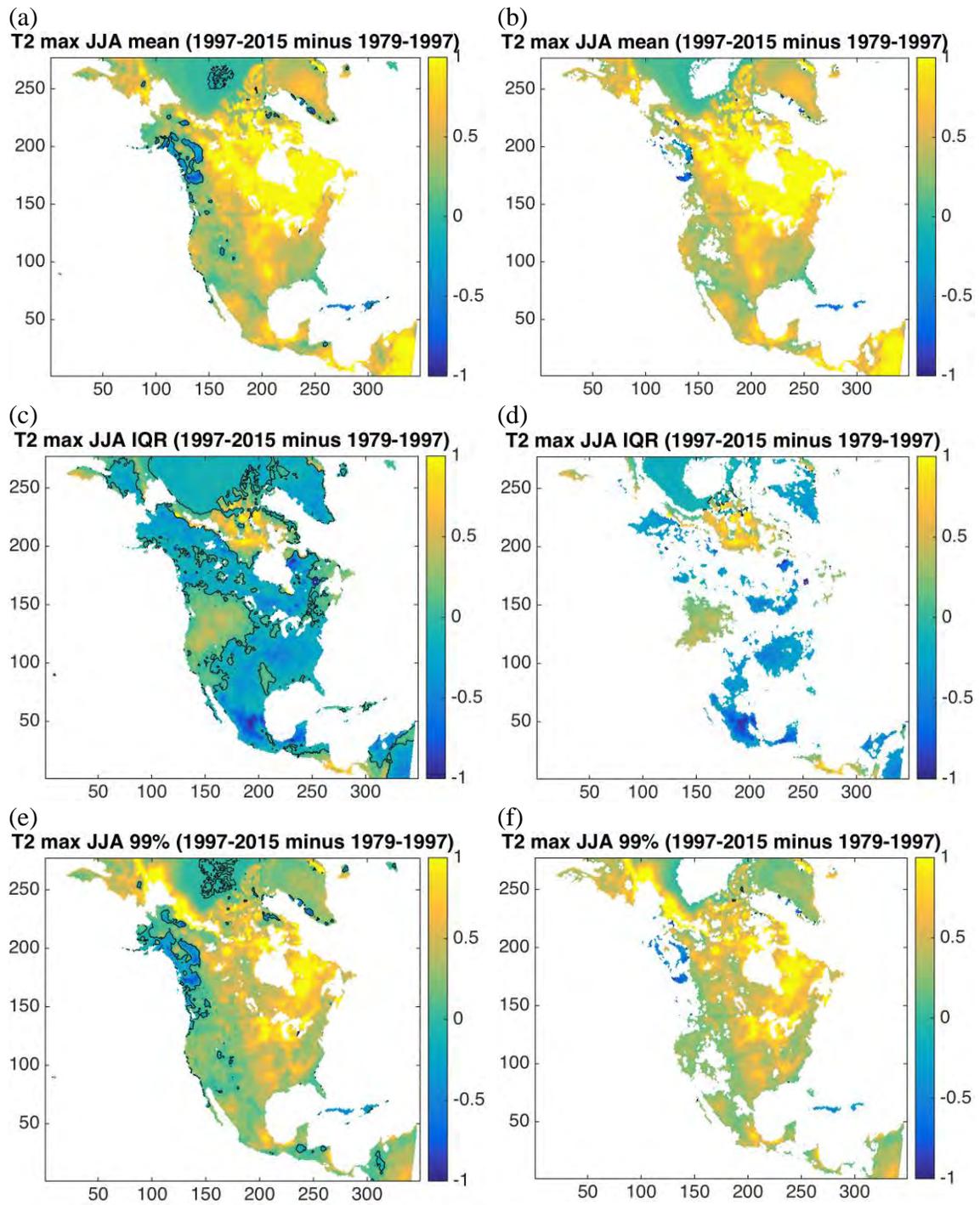
Figure 7: The same as in Fig. 6, but for the change in the JJA maximum daily temperature characteristics (see Fig. 4d–f for the corresponding 1979–2015 climatological fields).

About The Society of Actuaries

The Society of Actuaries (SOA), formed in 1949, is one of the largest actuarial professional organizations in the world dedicated to serving 28,000 actuarial members and the public in the United States, Canada and worldwide. In line with the SOA Vision Statement, actuaries act as business leaders who develop and use mathematical models to measure and manage risk in support of financial security for individuals, organizations and the public.

The SOA supports actuaries and advances knowledge through research and education. As part of its work, the SOA seeks to inform public policy development and public understanding through research. The SOA aspires to be a trusted source of objective, data-driven research and analysis with an actuarial perspective for its members, industry, policymakers and the public. This distinct perspective comes from the SOA as an association of actuaries, who have a rigorous formal education and direct experience as practitioners as they perform applied research. The SOA also welcomes the opportunity to partner with other organizations in our work where appropriate.

The SOA has a history of working with public policymakers and regulators in developing historical experience studies and projection techniques as well as individual reports on health care, retirement and other topics. The SOA's research is intended to aid the work of policymakers and regulators and follow certain core principles:

Objectivity: The SOA's research informs and provides analysis that can be relied upon by other individuals or organizations involved in public policy discussions. The SOA does not take advocacy positions or lobby specific policy proposals.

Quality: The SOA aspires to the highest ethical and quality standards in all of its research and analysis. Our research process is overseen by experienced actuaries and nonactuaries from a range of industry sectors and organizations. A rigorous peer-review process ensures the quality and integrity of our work.

Relevance: The SOA provides timely research on public policy issues. Our research advances actuarial knowledge while providing critical insights on key policy issues, and thereby provides value to stakeholders and decision makers.

Quantification: The SOA leverages the diverse skill sets of actuaries to provide research and findings that are driven by the best available data and methods. Actuaries use detailed modeling to analyze financial risk and provide distinct insight and quantification. Further, actuarial standards require transparency and the disclosure of the assumptions and analytic approach underlying the work.

Society of Actuaries
475 N. Martingale Road, Suite 600
Schaumburg, Illinois 60173
www.SOA.org