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Contributions of natural and anthropogenic forcing to changes in temperature extremes over the United States

Gerald A. Meehl,[1] Julie M. Arblaster,[1,2] and Claudia Tebaldi[1]

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[1] Observations averaged over the U.S. for the second half of the 20th century have shown a decrease of frost days, an increase in growing season length, an increase in the number of warm nights, and an increase in heat wave intensity. For the first three, a nine member multi-model ensemble shows similar changes over the U.S. in 20th century experiments that combine anthropogenic and natural forcings, though the relative contributions of each are unclear. Here we show results from two global coupled climate models run with anthropogenic and natural forcings separately. Averaged over the continental U.S., they show that the observed changes in the four temperature extremes are accounted for with anthropogenic forcings, but not with natural forcings (even though there are some differences in the details of the forcings). This indicates that most of the changes in temperature extremes over the U.S. are likely due to human activity. **Citation:** Meehl, G. A., J. M. Arblaster, and C. Tebaldi (2007), Contributions of natural and anthropogenic forcing to changes in temperature extremes over the United States, *Geophys. Res. Lett.*, *34*, L19709, doi:10.1029/2007GL030948.

1. Introduction

[2] Previous studies have shown that, for globally averaged temperature, the observed increases in the latter part of the 20th century were mostly due to human activity mainly associated with the burning of fossil fuels and the concomitant increases of greenhouse gases in the atmosphere [*Stott et al.*, 2000; *Cubasch et al.*, 2001; *Meehl et al.*, 2004b; *Meehl et al.*, 2007a]. Similar attribution for observed temperature increases has been done for continental-scale averages, as well as for changes in patterns of temperature [*Hegerl et al.*, 2007].

[3] With regards to temperature extremes, there has been less work done on attributing cause and effect for observed changes, as opposed to studies above dealing with changes in mean temperatures. In studying the European heat wave of 2003, it was shown that the estimated likelihood of the risk (probability) of exceedance of a 1.6°C summer season mean threshold (surpassed in 2003 for the first time since the beginning of instrumental record in 1851), is significantly increased within model simulations with both anthropogenic and natural forcings (compared to just natural forcings) [*Schär et al.*, 2004] indicating that the European heat wave of 2003 was made more likely by the presence of increased anthropogenic GHGs. An atmospheric model run with observed 20th century SSTs and no changes in forcing compared to a run with time-varying anthropogenic forcings suggested that the anthropogenic forcings were necessary to get more of the observed pattern of changes in frost days [*Kiktev et al.*, 2003]. In a study looking at changes in warmest night of the year for the period 1980–99 compared to 1950–69 (4 member model ensembles from HadCM3), the increase in warmest nights only occurred in presence of anthropogenic forcing [*Christidis et al.*, 2005]. This is the only study to date that has quantified the changes of these extremes in observations that show an anthropogenic fingerprint. *Kiktev et al.* [2007] compared both the *Alexander et al.* [2006] precipitation and temperature extremes indices from models and observations on the global scale using various pattern correlation measures, and found that the temperature indices were mostly well captured, though there were greater limitations on the precipitation indices. L. V. Alexander and J. M. Arblaster (Assessing trends in observed and modelled climate extremes over Australia in relation to future projections, submitted to *International Journal of Climatology*, 2007) examined indices of extreme temperature and precipitation over Australia from models compared to observations and found qualitative agreement in late 20th century trends for most indices when averaged across the continent. Using a U.S. climate extremes index that combines temperature and precipitation extremes, *Burkholder and Karoly* [2007] detected an anthropogenic influence on trends in the latter part of the 20th century.

[4] Here we focus on four different indices related to temperature extremes, use a nine member multi-model ensemble to compare to the observed trends in temperature extremes, and then show results from two models run with anthropogenic and natural forcings separately to address the main contributing factors to the observed changes in U.S.-averaged frost days, growing season length, warm nights, and heat wave intensity. The index measuring frost days counts the number of days in a year when the temperature goes below freezing. Growing season length is defined as the length of the period between the first spell of five consecutive days with mean temperature above 5°C and the last such spell of the year. Warm nights are defined as the percentage of time in the year when minimum temperature is above the 90th percentile of the climatological distribution for that calendar day. The heat wave intensity index [*Karl and Knight*, 1997] (and applied by *Meehl and Tebaldi* [2004]) has been defined after considering that during the Chicago heat wave of 1995 the worst effects on excess human mortality were observed after three consecutive very hot nights. Therefore, the heat wave intensity index is defined as mean of the annual three consecutive warmest nights.

[1]National Center for Atmospheric Research, Boulder, Colorado, USA.
[2]Also at Bureau of Meteorology Research Centre, Melbourne, Victoria, Australia.

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[5] Note that *Zhang et al.* [2005] found that for temperature extremes indices based on percentiles from a base period (such as warm nights which uses a 1961–1990 climatology), discontinuities are introduced at the boundaries of the base period. This tends to lead to an overestimation of the magnitude of the trends calculated across it. *Zhang et al.* [2005] developed a bootstrapping method to eliminate this bias. The HadEX observations of *Alexander et al.* [2006] in the present paper use this new definition, whereas the models do not. This distinction does not change the fundamental conclusions of the present paper.

[6] All trends are calculated as ordinary least squares except for warm nights, which uses generalized least squares due to significant autocorrelation of order one in the residuals of the linear fit.

2. Models and Observed Data

[7] As noted above, modeling groups have calculated the extremes indices that have been archived in the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset at PCMDI [*Meehl et al.*, 2007b], and results from nine models are analyzed here. The models are: PCM, CCSM3, GFDL-CM2.0, GFDL-CM2.1, MIROC3.2-hires, MIROC3.2-medres, CNRM-CM3, MRI-CGCM2.3.2, and INMCM3_0. *Tebaldi et al.* [2006] show globally averaged results and geographic maps of 20th and 21st century extremes indices from these models. A more full description of the models as well as additional details regarding the WCRP CMIP3 multi-model archive at PCMDI can be found at: http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php.

[8] We also analyze results from two global coupled climate models. The first, the Parallel Climate Model (PCM), has been described and used in the studies of temperature and precipitation extremes of *Meehl et al.* [2004a, 2005] and *Meehl and Tebaldi* [2004]. The resolution of the atmosphere is T42, or roughly $2.8^\circ \times 2.8^\circ$, with 18 levels in the vertical. Resolution in the ocean is about $^2/_3$ degree tapering down to $^1/_2$ degree in the equatorial tropics, with 32 levels. No flux adjustments are used in the model, and, at least in terms of global-mean temperature, a relatively stable climate is simulated.

[9] The second global coupled model is the Community Climate System Model version 3 (CCSM3) described by *Collins et al.* [2006]. We analyze 20th century simulations from the T85 version of CCSM3, with grid points in the atmosphere roughly every 1.4° latitude and longitude, and 26 levels in the vertical. The ocean is a version of the Parallel Ocean Program (POP) with a nominal latitude-longitude resolution of 1° (1/2° Equation Tropics) and 40 levels in the vertical. No flux adjustments are used in the CCSM3.

[10] Both PCM and CCSM3 were run for a pre-industrial (1870) control run which provided initial states for the 20th century simulations. Five member ensembles of CCSM3 and four member ensembles of PCM 20th century climate experiments were run with first anthropogenic and then natural forcings (note that black carbon aerosols are included in the anthropogenic forcings in CCSM3 but not in PCM [see *Meehl et al.*, 2006]). In both models, the 20th century simulations were started from different times in the 1870 control run separated by 10 to 20 years. The natural and anthropogenic forcings for PCM and CCSM3 are described by *Meehl et al.* [2004b] and *Meehl et al.* [2006], respectively. They use the same GHG forcings and volcanic aerosols, have similar ozone changes (though CCSM3 uses a time-varying 3-D tropospheric ozone dataset), differ in solar forcing (though those differences are small as discussed by *Meehl et al.* [2006]), and different sulfate aerosol forcing since PCM uses specified time and space varying concentrations, and CCSM3 generates concentrations internally with a coupled sulfur cycle model. Additionally, CCSM3 includes specified time-varying black carbon aerosols [*Meehl et al.*, 2007c]. However, for the area-averages over the U.S., though these differences in forcing produce some small discrepancies in the overall forcing and thus the pattern of response, other factors such as model sensitivity and systematic errors unique to each model also contribute to the differences in response.

[11] The observed data are the extremes indices [*Frich et al.*, 2002] derived from daily data, updated and described by *Alexander et al.* [2006], and called the HadEX dataset. Thomas Peterson supplied a version of HadEX with errors corrected in the growing season length calculation and the addition of the heat wave intensity index of *Karl and Knight* [1997].

3. Multi-model Temperature Extremes Indices

[12] Time series from the nine models described above for the second half of the 20th century, compared to observations, averaged over the continental United States are shown in Figure 1. For the time period when the globally averaged temperatures in observations and models started to dramatically increase (from the mid-1970s onward) [e.g., *Meehl et al.*, 2004b], linear trends are computed for the multi-model average compared to the observed trend for each. There is qualitative agreement of the trends comparing the multi-model average to the observations, with frost days decreasing, growing season length increasing, and number of warm nights increasing (Table 1).

[13] Therefore, for these temperature-related indices, the models are qualitatively capturing the observed trends over the U.S. However, this still does not tell us if these trends are due to natural or anthropogenic forcings.

4. Natural Versus Anthropogenic Effects on U.S. Temperature Extremes

[14] Results from the two AOGCMs considered here (PCM and CCSM3) for ensemble experiments with natural and anthropogenic forcings separately are shown for the three temperature-related indices from the multi-models in Figure 1, with the addition of the heat wave intensity index in Figure 2.

[15] For all four of these temperature-related indices, the anthropogenic forcings experiments capture the recent trends in the observations, but not the natural forcings experiments. Table 1 shows linear ordinary least squares trends calculated as above for the multi-model ensemble (except for warm nights where the calculation is a generalized least squares trend due to autocorrelation effects), but for the PCM and CCSM3 anthropogenic and natural forc-

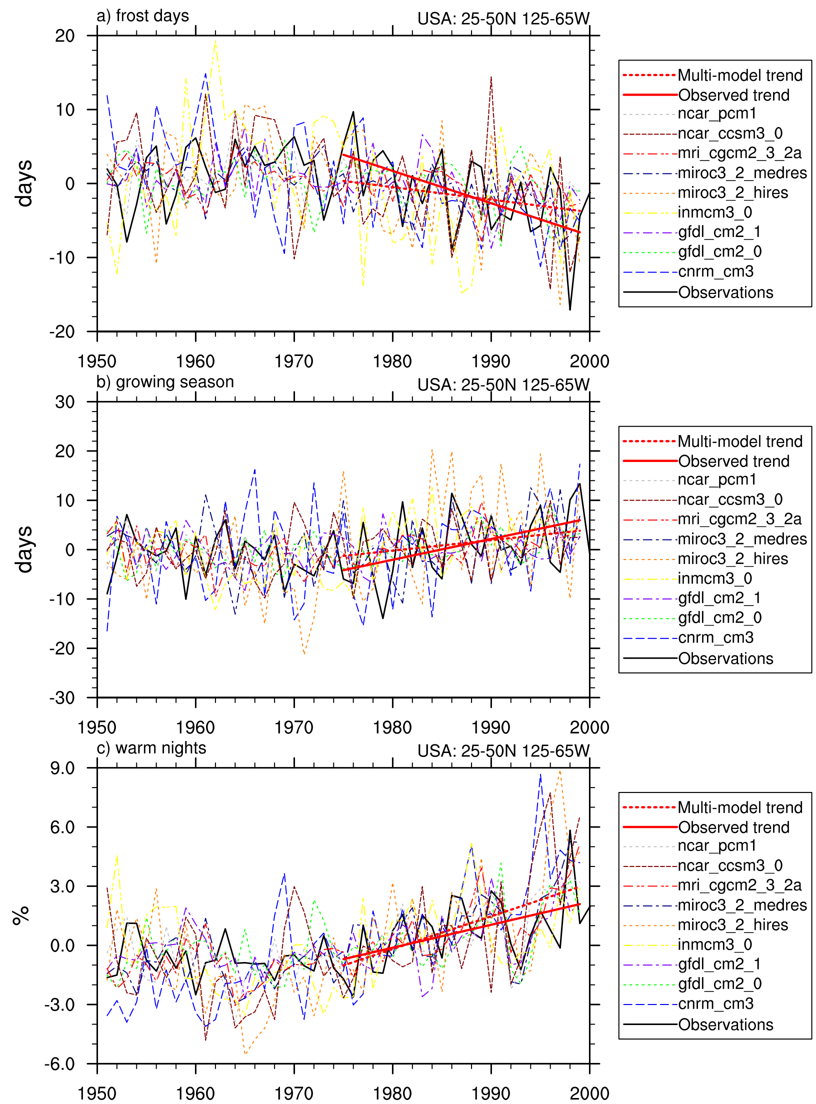

Figure 1. Three temperature-related extremes indices available for nine models in the WCRP CMIP3 multi-model dataset at PCMDI averaged for the continental U.S., annual means, anomalies from 1951–99. The models are interpolated to the HadEX grid and only grid points with valid observations are included in the area-weighted average: (a) frost days (in days), (b) growing season length (in days), and (c) warm nights (in %).

ings separately. Clearly the models with anthropogenic forcings-only do much better in capturing the trend in the observations for the period after 1975 (Table 1), with a significant trend (at the 95% level) for all four indices for CCSM3, and for growing season length and warm nights from PCM. Additionally, the 5% and 95% confidence limits are shown for the significant trends from observations and models.

[16] Frost days (Figures 2a and 2b) show the clearest separation of the anthropogenic from natural forcings, with the ranges from the ensemble experiment separating around 1980, and the significant observed trend in decreasing frost days following the anthropogenic forcings ensemble mean. Also for growing season length the recent significant observed increasing trend is captured only in the anthropogenic forcings experiments (Figures 2c and 2d) as noted in Table 1.

[17] The recent significant observed increases in warm nights (Figures 2e and 2f) are also captured only in the anthropogenic forcings experiments, with the range of

Table 1. Linear trends for the Four Temperature Extremes Indices, 1975–99, Averaged Over the Continental U.S.[a]

Linear Trend 1975–99	Observations	Multi-model Average	CCSM3 Anthropogenic	CCSM3 Natural	PCM Anthropogenic	PCM Natural
Frost days, days/25 yrs	−10.9* (−17.7, −4.2)	−5.2* (−7.0, −1.4)	−8.8* (−13.5, −4.2)	+0.0	−3.1	+0.6
Growing season length, days/25 yrs	+10.5* (1.4, 19.6)	+5.3* (1.8, 8.8)	+7.6* (2.2, 13.1)	−1.0	+3.6* (0.1, 7.0)	−1.0
Warm nights, %/25 yrs	+2.9* (0.6, 5.2)	+4.2* (2.7, 5.6)	+5.1* (2.6, 6.9)	+0.9	+3.8* (2.1, 5.6)	+0.8
Heat wave intensity, °C/25 yrs	+0.4	—	+0.7* (0.2, 1.2)	−0.2	+0.0	−0.1

[a]Note that the heat wave intensity index was not calculated or made available in the CMIP3 multi-model ensemble. An asterisk signifies that the trends are significant at the 95% level. The 95% confidence intervals are included in parentheses for the significant trends.

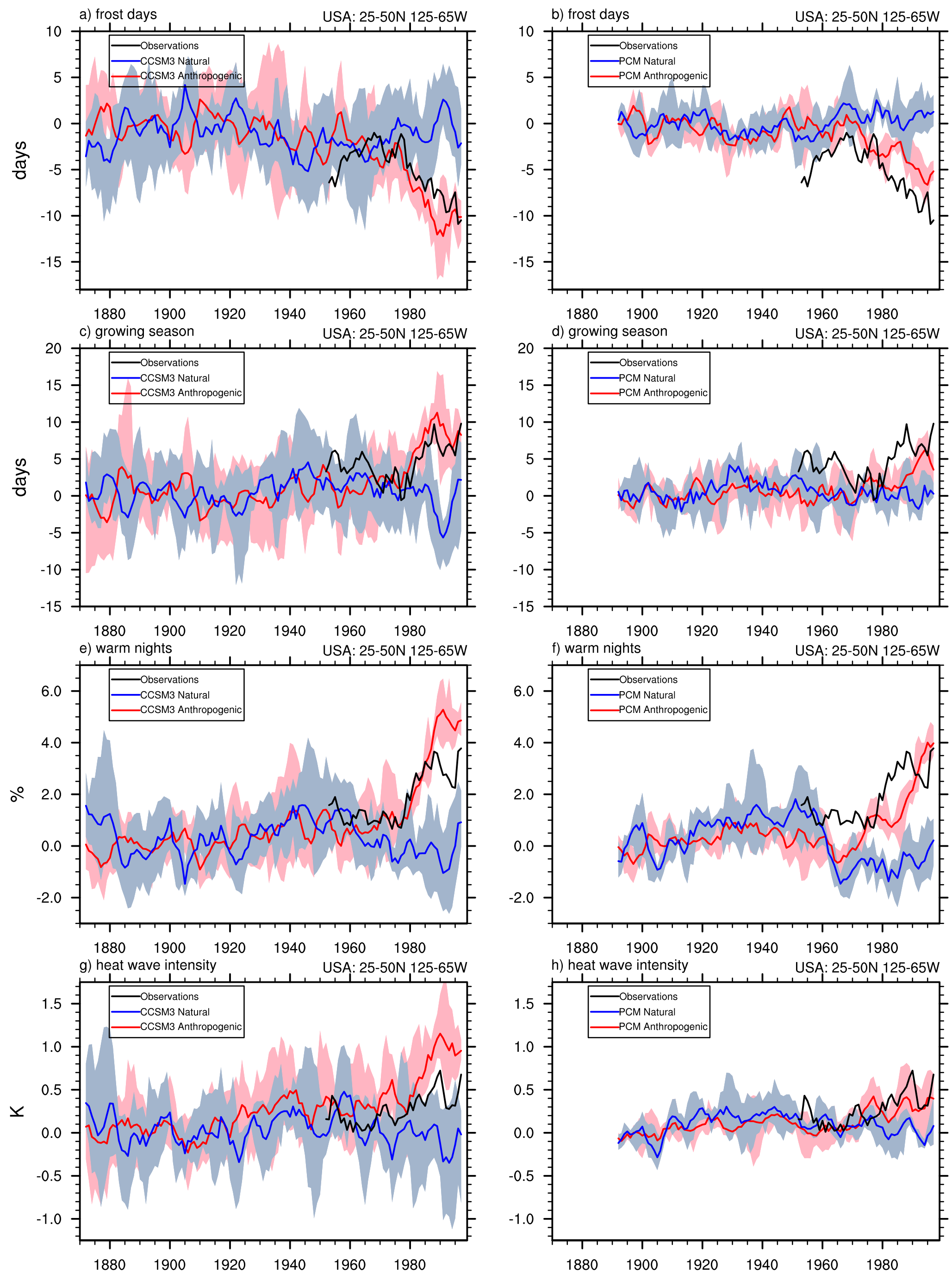

Figure 2. Four temperature-related extremes indices averaged over the continental U.S. for model experiments with only natural forcings (blue line is multi-member ensemble average, blue shading is range across the ensembles), and only anthropogenic forcings (red line is multi-member ensemble average, red shading is range across the ensembles), four member ensembles for the PCM experiments, and five member ensembles for CCSM3. Each line is smoothed with a 5 year running mean. For the models, the 1890–1919 mean from each ensemble member is subtracted to form anomalies. An 1890–1919 mean is not available for the observations, so they are instead centered on the 1960–1999 mean of the anthropogenic runs from the models, the models are interpolated to the HadEX grid and only grid points with valid observations are used: (a) frost days for CCSM3, (b) frost days for PCM, (c) growing season length for CCSM3, (d) growing season length for PCM, (e) warm nights for CCSM3, (f) warm nights for PCM, (g) heat wave intensity for CCSM3, and (h) heat wave intensity for PCM.

ensemble members of the anthropogenic forcing experiments separating from the range of the natural forcings in the late 1970s. The heat waves index also shows large interannual variability in the model ensemble members (large range across ensemble members). The CCSM3 anthropogenic forcings experiment captures the recent observed increase in heat wave intensity, and these experiments separate from the natural forcings experiments around 1980 (Figure 2g). However, the PCM shows less of this separation, though the ensemble mean anthropogenic forcings lies above the ensemble mean natural forcings, and reflects somewhat better the recent increase of observed heat wave intensity (Figure 2h and Table 1).

[18] To assess how unusual the statistically significant observed changes in Table 1 are in relation to inherent low frequency climate variability ("detection"), periods from the PCM and CCSM3 control runs are analyzed. A 650 year period from the PCM pre-industrial control run (with no time varying changes in forcings), is first de-trended to eliminate a small drift, then 25 year trends are calculated from the model for the three significant observed indices, advancing the calculation by 13 years for each iteration so there is 50% overlap in the trends (providing 49 trends). The 2.5th and 97.5th percentile of trends for these indices are −6.6 and 4.8 for frost days, −6.6 and 4.7 for growing season length, and −2.0 and 2.3 for warm nights. Following a similar procedure for a 270 year period in the CCSM3 pre-industrial control run, the 2.5th and 97.5th percentile of trends for these indices are −6.7 and 5.7 for frost days, −7.8 and 7.1 for growing season length, and −2.4 and 2.6 for warm nights. The significant observed trends (frost days, growing season length, and warm nights, first column of Table 1) lie well outside those limits of inherent variability from both model control runs, indicating a detectible signal.

5. Conclusions

[19] Trends in temperature extremes indices computed from nine AOGCMs averaged over the continental United States show qualitative agreement with observations for the latter part of the 20th century, with decreases in frost days, increases in growing season length, and increases in warm nights. To address the relative contributions from anthropogenic vs. natural factors, two AOGCMs (the CCSM3 and PCM) show agreement with the observations since 1975 for decreases in frost days, increases in growing season length, increases in warm nights, and increases in heat wave intensity for the anthropogenic forcings experiments only. The natural forcings experiments (including only solar and volcanoes) show little change in these extremes indices for the latter part of the 20th century. This indicates that the recent observed changes in temperature extremes over the U.S. have been mostly due to changes in anthropogenic forcings associated with increases of GHGs.

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J. M. Arblaster, G. A. Meehl, and C. Tebaldi, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307, USA. (meehl@ncar.ucar.edu)