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6 Contributions of natural and anthropogenic  
7 forcing to changes in temperature extremes  
8 over the U.S.

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1 **Abstract**

2 Observations averaged over the U.S. for the second half of the 20<sup>th</sup> century have shown a  
3 decrease of frost days, an increase in growing season length, an increase in warm nights,  
4 and an increase in heat wave intensity. A nine member multi-model ensemble shows  
5 similar changes over the U.S. for the first three of those extremes indices resulting from  
6 experiments under a 20<sup>th</sup> century scenario combining anthropogenic and natural forcings,  
7 though the relative contributions of each are unclear. Here we show results from two  
8 global coupled climate models run with anthropogenic and natural forcings separately.  
9 Averaged over the continental U.S., the models show that the observed changes in the  
10 four temperature extremes are accounted for with anthropogenic forcings, but not with  
11 natural forcings. This indicates that most of the changes in temperature extremes over  
12 the U.S. are likely due to human activity.

13

14

15 **1. Introduction**

16 Previous studies have shown that, for globally averaged temperature, the observed  
17 increases in the latter part of the 20<sup>th</sup> century were mostly due to human activity mainly  
18 associated with the burning of fossil fuels and the concomitant increases of greenhouse  
19 gases in the atmosphere (Stott et al., 2001; Cubasch et al., 2001; Meehl et al., 2004a,  
20 2007a). Similar attribution for observed temperature increases has been done for  
21 continental-scale averages, as well as for changes in patterns of temperature (Hegerl et  
22 al., 2007).

23

1 With regards to temperature extremes, there has been less work done on attributing cause  
2 and effect for observed changes, as opposed to studies above dealing with changes in  
3 mean temperatures. In studying the European heat wave of 2003, it was shown that the  
4 estimated likelihood of the risk (probability) of exceedance of a 1.6°C summer season  
5 mean threshold (surpassed in 2003 for the first time since the beginning of instrumental  
6 record in 1851), is significantly increased within model simulations with both  
7 anthropogenic and natural forcings (compared to just natural forcings, Stott et al, 2004)  
8 indicating that the European heat wave of 2003 was made more likely by the presence  
9 of increased anthropogenic GHGs. An atmospheric model run with observed 20th  
10 century SSTs and no changes in forcing compared to a run with time-varying  
11 anthropogenic forcings suggested that the anthropogenic forcings were necessary to get  
12 more of the observed pattern of changes in frost days (Kiktev et al., 2003). In a study  
13 looking at changes in warmest night of the year for the period 1980-99 compared to  
14 1950-69 (4 member model ensembles from HadCM3), the increase in warmest nights  
15 only occurred in presence of anthropogenic forcing (Christidis et al., 2005). Kiktev et al.  
16 (2007) compared both the Alexander et al. (2006) precipitation and temperature extremes  
17 indices from models and observations on the global scale using various pattern  
18 correlations measures, and found that the temperature indices were mostly well captured,  
19 though there were greater limitations on the precipitation indices. Alexander and  
20 Arblaster (2007) examined indices of extreme temperature and precipitation over  
21 Australia from models compared to observations and found qualitative agreement in late  
22 20<sup>th</sup> century trends for most indices when averaged across the continent. Using a U.S.  
23 climate extremes index that combines temperature and precipitation extremes,

1 Burkholder and Karoly (2007) detected an anthropogenic influence on trends in the latter  
2 part of the 20<sup>th</sup> century.

3

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

19

20 Note that Zhang et al. (2005) found that for temperature extremes indices based on  
21 percentiles from a base period (such as warm nights which uses a 1961-1990  
22 climatology), discontinuities are introduced at the boundaries of the base period. This  
23 tends to lead to an overestimation of the magnitude of the trends calculated across it.

1 Zhang et al. (2005) developed a bootstrapping method to eliminate this bias. The HadEX  
2 observations of Alexander et al. (2006) in the present paper use this new definition,  
3 whereas the models do not. This distinction does not change the fundamental  
4 conclusions of the present paper.

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## 7 **2. Models and observed data**

8

9 As noted above, modeling groups have calculated the extremes indices that have been  
10 archived in the World Climate Research Programme's (WCRP's) Coupled Model  
11 Intercomparison Project phase 3 (CMIP3) multi-model dataset at PCMDI (Meehl et al.,  
12 2007b), and results from nine models are analyzed here. The models are:  
13 PCM, CCSM3, GFDL-CM2.0, GFDL-CM2.1, MIROC3.2-hires, MIROC3.2-medres,  
14 CNRM-CM3, MRI-CGCM2.3.2, and INMCM3\_0. Tebaldi et al. (2006) show globally  
15 averaged results and geographic maps of 20<sup>th</sup> and 21<sup>st</sup> century extremes indices from  
16 these models. A more full description of the models as well as additional details  
17 regarding the WCRP CMIP3 multi-model archive at PCMDI can be found at:

18 [http://www-pcmdi.llnl.gov/ipcc/about\\_ipcc.php](http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php)

19

20 We also analyze results from two global coupled climate models. The first, the Parallel  
21 Climate Model (PCM), has been described and used in the studies of temperature and  
22 precipitation extremes of Meehl et al., (2004b,c; 2005). The resolution of the  
23 atmosphere is T42, or roughly 2.8° x 2.8°, with 18 levels in the vertical. Resolution in

1 the ocean is about  $\frac{2}{3}$  degree tapering down to  $\frac{1}{2}$  degree in the equatorial tropics, with 32  
2 levels. No flux adjustments are used in the model, and, at least in terms of global-mean  
3 temperature, a relatively stable climate is simulated.

4

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

11

12 Both PCM and CCSM3 were run for a pre-industrial (1870) control run which provided  
13 initial states for the 20<sup>th</sup> century simulations. Five member ensembles of CCSM3 and  
14 four member ensembles of PCM 20<sup>th</sup> century climate experiments were run with first  
15 anthropogenic and then natural forcings (note that black carbon aerosols are included in  
16 the anthropogenic forcings in CCSM3 but not in PCM, see Meehl et al., 2006). In both  
17 models, the 20<sup>th</sup> century simulations were started from different times in the 1870 control  
18 run separated by 10 to 20 years. The natural and anthropogenic forcings for PCM and  
19 CCSM3 are described in Meehl et al. (2004a) and Meehl et al. (2006), respectively.

20

21 The observed data are the extremes indices (Frich et al., 2002) derived from daily data,  
22 updated and described by Alexander et al. (2006), and called the HadEX dataset.

23 Thomas Peterson supplied a version of HadEX with errors corrected in the growing

1 season length calculation and the addition of the heat wave intensity index of Karl and  
2 Knight (1997).

3

### 4 **3. Multi-model temperature extremes indices**

5 Time series from the nine models described above for the second half of the 20<sup>th</sup> century,  
6 compared to observations, averaged over the continental United States are shown in Fig.  
7 1. For the time period when the globally averaged temperatures in observations and  
8 models started to dramatically increase (from the mid-1970s onward, e.g. Meehl et al.,  
9 2004a), linear trends are computed for the multi-model average compared to the observed  
10 trend for each. There is qualitative agreement of the trends comparing the multi-model  
11 average to the observations, with frost days decreasing, growing season length increasing,  
12 and warm nights increasing (Table 1).

13

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

17

### 18 **4. Natural vs. anthropogenic effects on U.S. temperature extremes**

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

23

1 For all four of these temperature-related indices, the anthropogenic forcings experiments  
2 capture the recent trends in the observations, but not the natural forcings experiments.  
3 Table 1 shows linear trends calculated as above for the multi-model ensemble, but for the  
4 PCM and CCSM3 anthropogenic and natural forcings separately. Clearly the models  
5 with anthropogenic forcings only do much better in capturing the qualitative trend in the  
6 observations for the period after 1975 (Table 1).

7  
8 Frost days (Fig. 2a,b) show the clearest separation of the anthropogenic from natural  
9 forcings, with the ranges from the ensemble experiment separating around 1980, and the  
10 observed trend in decreasing frost days following the anthropogenic forcings ensemble  
11 mean. Also for growing season length the recent observed increasing trend is captured  
12 only in the anthropogenic forcings experiments as noted in Table 1.

13  
14 The recent observed increases in warm nights (Fig. 2e,f) are also captured only in the  
15 anthropogenic forcings experiments, with the range of ensemble members of the  
16 anthropogenic forcing experiments separating from the range of the natural forcings in  
17 the late 1970s. The heat waves index also shows large interannual variability in the  
18 model ensemble members (large range across ensemble members). The CCSM3  
19 anthropogenic forcings experiment captures the recent observed increase in heat wave  
20 intensity, and these experiments separate from the natural forcings experiments around  
21 1980 (Fig. 2 g). However, the PCM shows less of this separation, though the ensemble  
22 mean anthropogenic forcings lies above the ensemble mean natural forcings, and reflects

1 somewhat better the recent increase of observed heat wave intensity (Fig. 2h and Table  
2 1).

3

#### 4 **5. Conclusions**

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

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1 **References**

2

3 Alexander, L.V., and co-authors (2006) Global observed changes in daily climate  
4 extremes of temperature and precipitation. *J. Geophys. Res.*, *111*, D05109,  
5 doi:10.1029/2005JD006290

6

7 Alexander L.V. and J.M. Arblaster (2007) Assessing trends in observed and modelled  
8 climate extremes over Australia in relation to future projections, *Clim. Dyn.*, submitted.

9

10 Burkholder, B.A., and D.J. Karoly, 2007: An assessment of U.S. climate variability  
11 using the climate extremes index. *American Meteorological Society Pre-print Volume*,  
12 2B.9.

13

14 Christidis, N., P.A. Stott, S. Brown, G.C. Hegerl and J. Caesar (2005), Detection of  
15 changes in temperature extremes during the second half of the 20<sup>th</sup> century, *Geophys.*  
16 *Res. Lett.*, **32**, L20716, doi:10.1029/2005GL023885

17

18 Collins, W.D., and co-authors, 2006: The Community Climate system Model version 3  
19 (CCSM3). *J. Climate*, *19*, 2122—2143.

20

21 Cubasch, U., and coauthors (2001), Projections of future climate change. In: Climate  
22 Change 2001: The Scientific Basis. Contribution of Working Group I to the Third  
23 Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J. T.,

1 Y. Ding, D. J. Griggs, M. Noguer, P. van der Linden, X. Dai, K. Maskell, C. I. Johnson  
2 (eds.)]. Cambridge University Press, 525--582.  
3  
4 Frich, P., L.V. Alexander, P. Della-Marta, B. Gleason, M. Haylock, A.M.G. Klein Tank,  
5 and T. Peterson (2002), Observed coherent changes in climatic extremes during the  
6 second half of the twentieth century. *Clim. Res.*, *19*, 193--212.  
7  
8 Hegerl, G.C. and co-authors (2007) Understanding and attributing climate change. In:  
9 *Climate Change 2007: The Scientific Basis*. Contribution of Working Group I to the  
10 Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S.  
11 Solomon, Q. Dahe, and M. Manning, Eds., Cambridge University Press, in press.  
12  
13 Karl, T.R., and R.W. Knight (1997) The 1995 Chicago heat wave: How likely is a  
14 recurrence? *Bull. Amer. Meteorol. Soc.*, *78*, 1107—1119.  
15  
16 Kiktev, D., D.M.H. Sexton, L. Alexander, and C.K. Folland (2003) Comparison of  
17 modeled and observed trends in indices of daily climate extremes. *J. Climate*, *16*,  
18 3560—3571.  
19  
20 Kiktev, D., J. Caesar, L. V Alexander, H. Shiogama and M. Collier (2007) Comparison  
21 of observed and multimodeled trends in annual extremes of temperature and  
22 precipitation. *Geophys. Res. Lett.*, *34*, L10702, doi:10.1029/2007GL029539.  
23

1 Meehl, G.A., and C. Tebaldi (2004), More intense, more frequent and longer lasting heat  
2 waves in the 21st century. *Science*, 305, 994--997.

3

4 Meehl, G.A., C. Tebaldi, and D. Nychka (2004b) Changes in frost days in simulations of  
5 21st century climate. *Clim. Dyn.*, 23, 495--511.

6

7 Meehl, G. A., W. M. Washington, C. Amman, J. M. Arblaster, T. M. L. Wigley, and C.  
8 Tebaldi (2004c) Combinations of natural and anthropogenic forcings and 20<sup>th</sup> century  
9 climate. *Journal of Climate*, 17, 3721–3727.

10

11 Meehl, G. A., J. M. Arblaster, and C. Tebaldi (2005) Understanding future patterns of  
12 precipitation extremes in climate model simulations. *Geophysical Research Letters*, 32,  
13 No. 18, L18719, doi: 10.1029/2005GL023680.

14

15 Meehl, G. A., W. M. Washington, B. D. Santer, W. D. Collins, J. M. Arblaster, A. Hu,  
16 D. Lawrence, H. Teng, L. E. Buja, and W. G. Strand (2006) Climate change projections  
17 for twenty-first century and climate change commitment in the CCSM3. *Journal of*  
18 *Climate*, 19, 2597–2616.

19

20 Meehl, G. A. and coauthors (2007a) Global Climate Projections, In: *Climate Change*  
21 *2007: The Scientific Basis*. Contribution of Working Group I to the Fourth Assessment  
22 Report of the Intergovernmental Panel on Climate Change, S. Solomon, Q. Dahe, and M.  
23 Manning, Eds., Cambridge University Press, in press.

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Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor (2007b) The WCRP CMIP3 multi-model dataset: A new era in climate change research, *Bulletin of the American Meteorological Society*, in press.

Tebaldi, C., J.M. Arblaster, K. Hayhoe, and G.A. Meehl (2006) Going to the extremes: An intercomparison of model-simulated historical and future changes in extreme events. *Clim. Change*, 79, doi 10.1007/s10584-006-9051-4.

Zhang, X., G. Hegerl, F. Zwiers, and J. Kenyon (2005), Avoiding inhomogeneity in percentile-based indices of temperature extremes, *J. Climate*, 18, 1641-1651.

1 **Figure captions**

2

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

8

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

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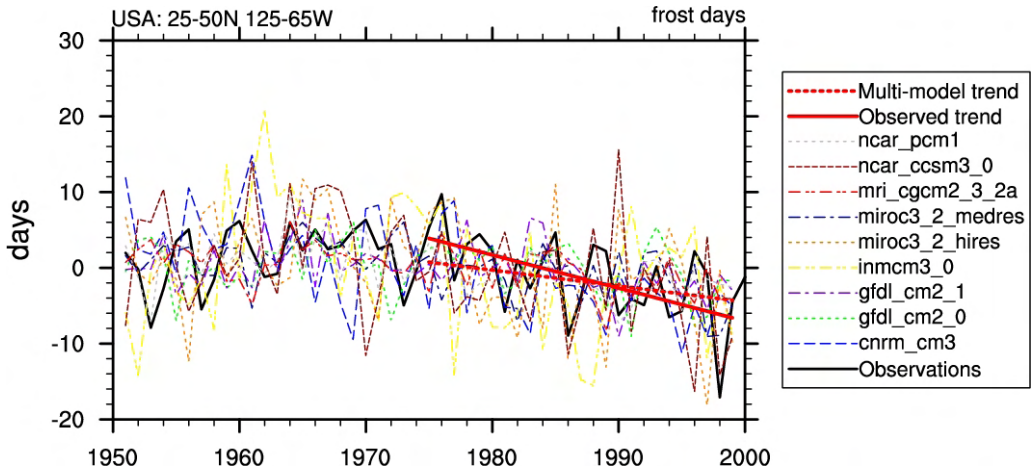
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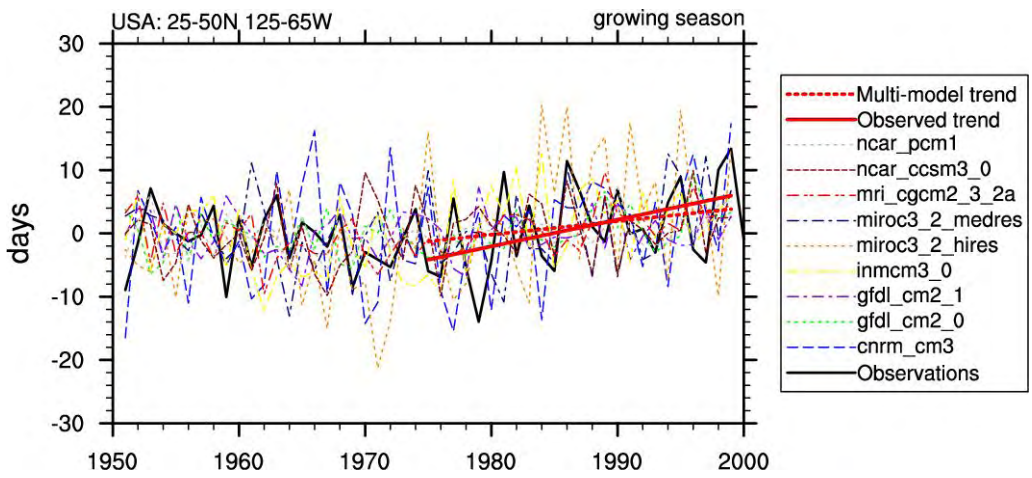
Table 1: Linear trends for the four temperature extremes indices, 1975-99, averaged over the continental U.S., units given in left column. Note that the heat wave intensity index was not calculated or made available in the CMIP3 multi-model ensemble. An asterisk signifies that the trends are significant at the 95% level.

Linear trend 1975-99	Observations	Multi-model average	CCSM3 anthropogenic	CCSM3 natural	PCM anthropogenic	PCM natural
Frost days (days/25 yrs)	-10.9*	-5.2*	-8.8*	+0.0	-3.1	+0.6
Growing season length (days/25 yrs)	+10.5*	+5.3*	+7.6*	-1.0	+3.6*	-1.0
Warm nights (%/25 yrs)	+2.9*	+4.2*	+5.1*	+0.9	+3.8*	+0.8
Heat wave intensity (°C/25 yrs)	+0.4	---	+0.7*	-0.2	+0.0	-0.1

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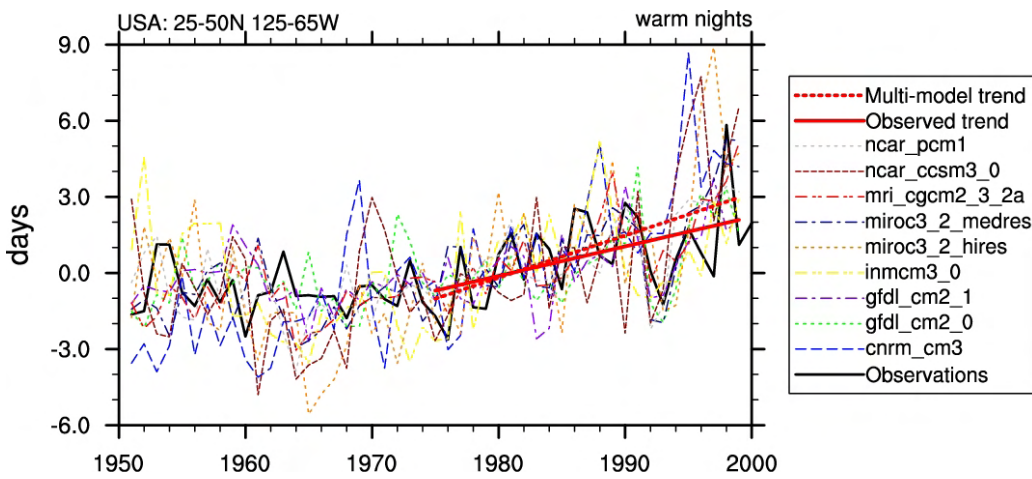


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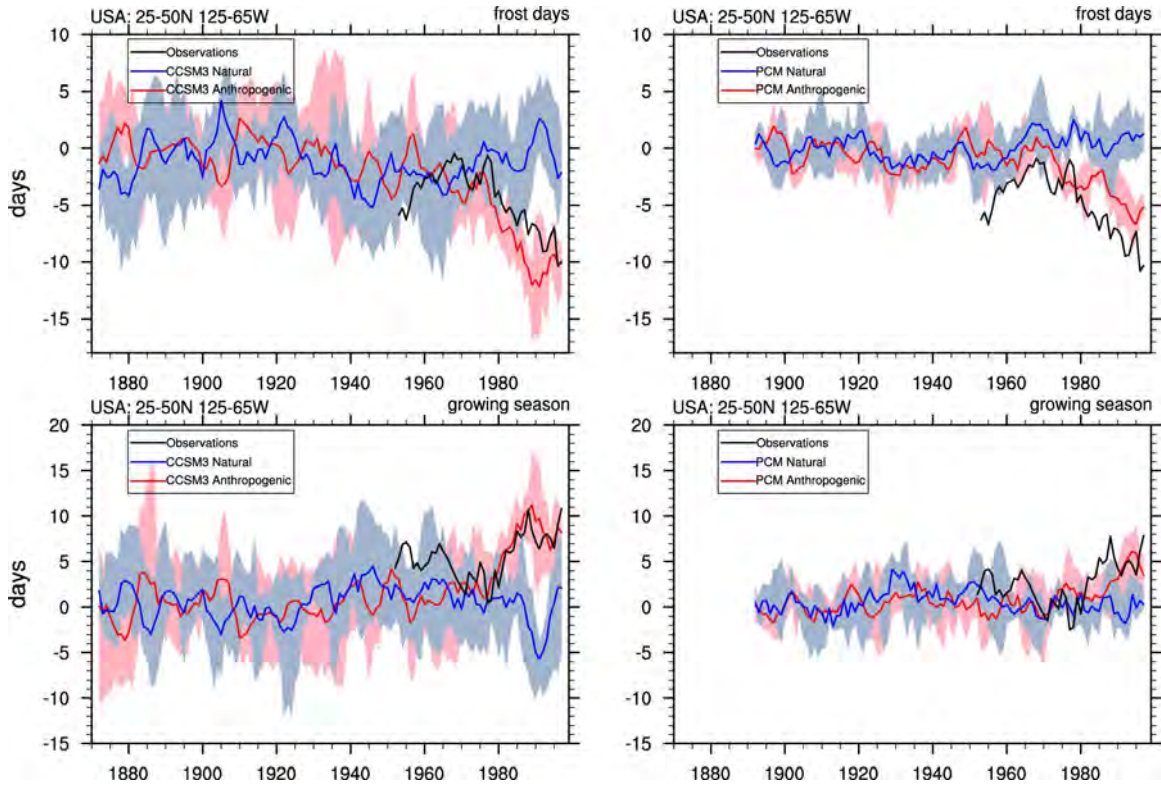
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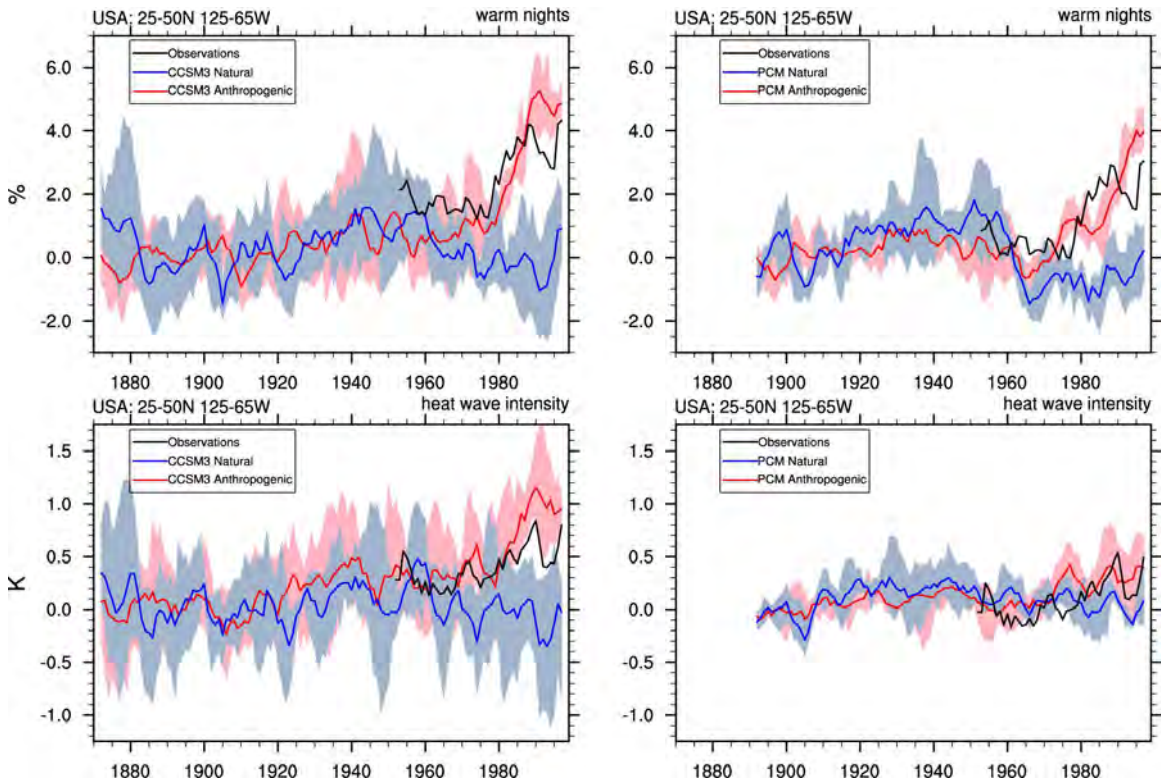
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5 Figure 1

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4 Figure 2