Analysis of climate simulations for use in the "Climate-Ready Adaptation Plan for the Delaware Estuary"

Final report to the Partnership for the Delaware Estuary

Raymond Najjar
The Pennsylvania State University
May 25, 2010

Funded by the Partnership for the Delaware Estuary through EPA's Climate Ready Estuary Program

1. Overall goal and general approach

The overall goal of the climate simulation analysis presented here is to provide projections of climate change over the 21st century for the Delaware Estuary and its watershed. These projections will be used by the Partnership for the Delaware Estuary in developing a climate adaptation plan for the Delaware Estuary. To gage the reliability of the projections, an evaluation of the models is also presented.

2. Methods

2.1. Climate models

Global Climate Model (GCM) output was taken from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007). Daily and monthly averages of 2-m temperature and precipitation output of 14 GCMs (Table 1) were used for the 20th and 21st centuries and for two greenhouse gas emissions scenarios (B1 and A2). The emissions scenarios correspond to 2100 CO_2 levels of about 530 ppm (B1) and 820 ppm (A2), which can be compared with the present-day level of about 380 ppm. More than 20 models participated in CMIP3, but the output of only 14 models was available for analysis for the greenhouse gas scenarios and time periods considered here. GCM horizontal resolution varies between roughly 1.5º and 4.5º.

2.2. Observations

Observations of temperature and precipitation for model evaluation were taken from the North American Regional Reanalysis (NARR) and the University of Delaware (Matsuura and Willmot, 2007a, b). The NARR uses data assimilation to determine the state of the atmosphere over North America at high spatial (32 km) and temporal (3 hr) resolution from 1979 to the present (Mesinger et al., 2006). We used 3-hourly and daily averages from the NARR. The University of Delaware data set consists of monthly averages of temperature and precipitation from 1900 to 2006 on a 0.5º grid and is based on multiple station data sets.

2.3. Processing of data sets

GCM output and observational data were interpolated or averaged to a 1º grid within the region of the Delaware Estuary and watershed. The Delaware estuary and its watershed span roughly 3º in latitude and 1º in longitude, so a total of three grid boxes were used (Figure 1). We did not attempt detailed spatial projections for the region, such as those that consider the effects of local orography. We operated under the assumption that climate change will be relatively uniform throughout the region and that this change can be superimposed onto the existing climate of the region. Unless stated otherwise, results presented here are averaged over the three grid boxes in Figure 1.

Six metrics, based on annual cycles in temperature and precipitation, were computed for model evaluation (Table 2). We computed an overall error index for each model based on these metrics, following the approach of Reichler and Kim (2008). Details of the error index calculation can be found in Chapter 5 of Shortle et al. (2009). We also computed a suite of metrics to evaluate the ability of the models to simulate extreme events. The metrics are those developed by Frich et al. (2002) and are also listed in Table 2. The time periods used in the assessment are the same as those used by the Intergovernmental Panel on Climate Change in their Fourth Assessment Report: 1980-1999 (recent past), 2011-2030 (early century), 2046-2065 (mid-century), and 2080-2099 (late century).

3. Results

3.1. Model evaluation of annual cycles

Figure 2 compares the observed and simulated mean annual cycles of monthly mean temperature and precipitation. The multi-model average is seen to capture the observed mean temperature very well, though there is a slight cool bias in winter and summer. The multi-model mean precipitation is close to the observed on the annual mean, but has a wet bias in winter and spring and a dry bias in summer. These biases in the temperature and precipitation, particularly in winter, have been noted in previous climate model evaluations in the Mid-Atlantic Region (Najjar et al., 2009; Shortle et al., 2009).

Interannual variability is a measure of how much the climate varies from year to year. It can be calculated based on annual averages, seasonal averages, or, as presented here, on monthly averages. The observed and simulated interannual variability in monthly mean temperature and precipitation is shown in Figure 3. Here we see that the multi-model mean has slightly too much variability in temperature, on average, but it reproduces the strong annual cycle of relatively high variability in winter compared with summer. Interannual variability in monthly precipitation has a summer peak and a winter minimum, features that are not seen in the multi-model mean, which has little seasonality in precipitation variability.

The final set of metrics based on annual cycles is of intramonthly variability in temperature and precipitation (Figure 4). These metrics are based on daily averages and reflect how variable the atmosphere is within a given month. Variability in temperature and precipitation due to weather events, which have time scales of several days, are roughly captured by this metric. Figure 4 shows that the multi-model mean accurately reproduces the annual cycle in intramonthly temperature variability, though there is a large spread among the models. Intramonthly variability in precipitation is reasonably captured by the multi-model mean but, as with the interannual precipitation variability, is too low in summer. This could reflect the inability of climate models to simulate small-scale convective events (thunderstorms), which contribute significantly to summer precipitation in the Delaware Estuary Watershed.

An overall model evaluation for each GCM in Table 1 and the multi-model mean based on the six annual cycle metrics in Table 2 is shown in Figure 5. An error index of 0 indicates a perfect model whereas an error index of 1 indicates an average model. These results show that the multi-model average is superior to any individual GCM. The top three performing individual GCMs were developed in Norway (BCCR-BCM2.0), Germany (ECHAM5/MPI-OM), and Japan (MIROC3.2).

3.2. Model evaluation of extreme indices

Table 3 shows how the models perform in their simulation of the extreme-event metrics. The first four listed in the table are indices of extremes in precipitation; one is a short-term drought index (consecutive dry days) and the other three are indicators of heavy precipitation. For all of these metrics, the multi-model mean performs well, though there is a slight low bias. The multi-model mean also does well at simulating the growing season length whereas the number of frost days per year is somewhat high due to the anomalously low temperatures simulated by the models in winter (Figure 2).

The multi-model mean appears to do a passable job at simulating extremely hot days, though the spread among the models is so large that the standard deviation exceeds the mean. We suspected that there may be a low bias in the NARR high temperature because the NARR's 3-hourly resolution may not be able to capture the daily peak. To assess this, daily maximum temperature datasets were taken from the Global Historical Climatology Network (GHCN, www.ncdc.noaa.gov/oa/climate/ghcn-daily/) and a gridded dataset described in Maurer et al. (2002). The latter is an interpolation of daily maximum temperature from National Weather Service (NWS) Cooperative Observer Program (COOP) reporting stations to a 1/8° grid. As with the NARR, the GHCN and Maurer et al. (2002) datasets were averaged to each 1° square of the 1° × 3º grid shown in Figure 1. Two grid boxes for the GHCN contained two stations and the other grid box contained eight stations (Figure 6). The number of hot days was calculated by analysis of the mean daily maximum temperature for the entire watershed.

The results of our analysis show that the NARR does, in fact, underestimate the number of hot days, which indicates that the agreement between the NARR and the GCMs is fortuitous (Figure 7). We do not think agreement is fortuitous for the other metrics in Table 2 because they are all based on daily and monthly averages, except for the number of frost days, which is computed from the daily low temperature. As noted earlier, frost days are overestimated by the GCM ensemble average (Table 3), which we suspect is related to the cold bias of the GCMs. Future work should more closely evaluate the NARR's ability to capture the daily low temperature.

3.3. Model projections

Figure 8 shows that all models project warming and most models project precipitation increases throughout the 21st century. Median projected warming by late century for the two scenarios (B1 and A2) is 1.9 and 3.7º C and the corresponding precipitation increase is 7 and 9%. The model spread in temperature change is smaller than that of the precipitation change, which suggests greater confidence in the temperature projections. Also seen in Figure 8 is that the scenario makes little difference in the projection in the early 21st century, but is important by the late 21st century. Figures 9 and 10 show how the projected changes vary between summer and winter, with the models showing substantially greater warming in summer and substantially greater precipitation increases in winter when compared with the annual changes.

Figures 11 and 12 show projected changes in some of the extremes indices. Projected frost days are seen to decline and projected growing season length to increase, both substantially (Figure 11). Increases in precipitation extremes are also seen to be substantial, though a small fraction of the models, typically less than ¼, show declines (Figure 12). Extreme high temperature changes are not shown because the model evaluation showed poor performance for this metric. Other studies show substantial increases in the number of hot days in the vicinity of the Delaware River Basin. For example, Union of Concerned Scientists (2008) show roughly a doubling to a quadrupling of the number of days above 90º F by the late 21st century, depending on the emissions scenario.

4. Summary

The analysis presented here shows that global climate models plausibly simulate the climate of the Delaware Estuary Watershed when evaluated with metrics based on the annual cycles of mean temperature and precipitation, as well as with metrics that describe submonthly and interannual variability of these variables. The GCMs also capture a number of hydrological extremes but do poorly for extreme high temperatures. The multi-model average is seen to be more skillful than any individual model. For the greenhouse gas scenarios considered (B1 and A2) the projected climate by the end of the 21st century is warmer by about 2-4º C and wetter by 7-9%. Summer warming and winter precipitation increases are substantially larger than the annual-mean changes. Also projected are substantially longer growing seasons, fewer frost days, and more intense precipitation.

Acknowledgements. Many thanks to Matthew Rydzik and Andrew Ross, who made all of the calculations and graphics for this analysis.

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Table 1. Global climate models used for this study.

Originating Group(s)	Country	CMIP3 I.D.
Bjerknes Centre for Climate Research	Norway	BCCR-BCM2.0
National Center for Atmospheric Research	USA	CCSM3
Canadian Centre for Climate Modelling & Analysis	Canada	CGCM3.1(T47)
Météo-France / Centre National de Recherches Météorologiques	France	CNRM-CM3
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.0
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.5
Max Planck Institute for Meteorology	Germany	ECHAM5/MPI-OM
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group.	Germany / Korea	ECHO-G
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM2.0
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM2.1
Institute for Numerical Mathematics	Russia	INM-CM3.0
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan	MIROC3.2(medres)
Meteorological Research Institute	Japan	MRI-CGCM2.3.2
National Center for Atmospheric Research	USA	PCM

Table 2. Metrics for the evaluation of the climate models.

Annual cycles

(1) Monthly mean temperature
(2) Monthly mean precipitation
(3) Interannual temperature variability (standard deviation of monthly mean)
(4) Interannual precipitation variability (standard deviation of monthly mean)
(5) Intramonthly temperature variability (standard deviation of daily mean)
(6) Intramonthly precipitation variability (standard deviation of daily mean)

Extreme events

(1) Maximum consecutive dry days in a year
(2) Maximum 5-day precipitation total in a year
(3) Days per year with precipitation > 10 mm
(4) Percent of annual precipitation due to daily events above the 95th percentile
(5) Number of frost days per year
(6) Growing season length
(7) Days per year with maximum temperature above 80º F ($T_{max} > 80$)
(8) $T_{max} > 85$
(9) $T_{max} > 90$
(10) $T_{max} > 95$

Table 3. Evaluation of GCM simulation of extreme event indices using the North American Regional Reanalysis (NARR).

Metric	**NARR**	**Model average ± 1 standard deviation**
Maximum consecutive dry days in a year	17	14 ± 3
Maximum 5-day precipitation total in a year (mm)	69	63 ± 6
Days per year with precipitation > 10 mm	31	27 ± 4
Percent of annual precipitation due to daily events above the 95th percentile	37	33 ± 5
Number of frost days per year	114	123 ± 28
Growing season length (days)	198	197 ± 25
Days per year with maximum temperature above 80º F ($T_{max} > 80$)	52	34 ± 30
$T_{max} > 85$	19	13 ± 14
$T_{max} > 90$	3.3	3.3 ± 3.9
$T_{max} > 95$	0.21	0.34 ± 0.72

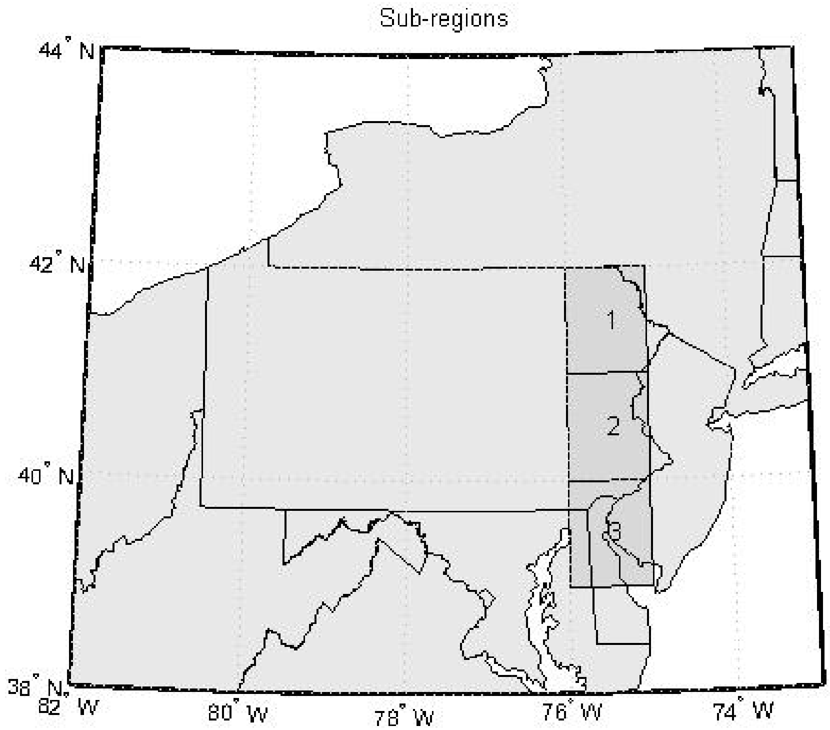


Fig. 1. Location of grid boxes used for analysis of climate model output and observations.

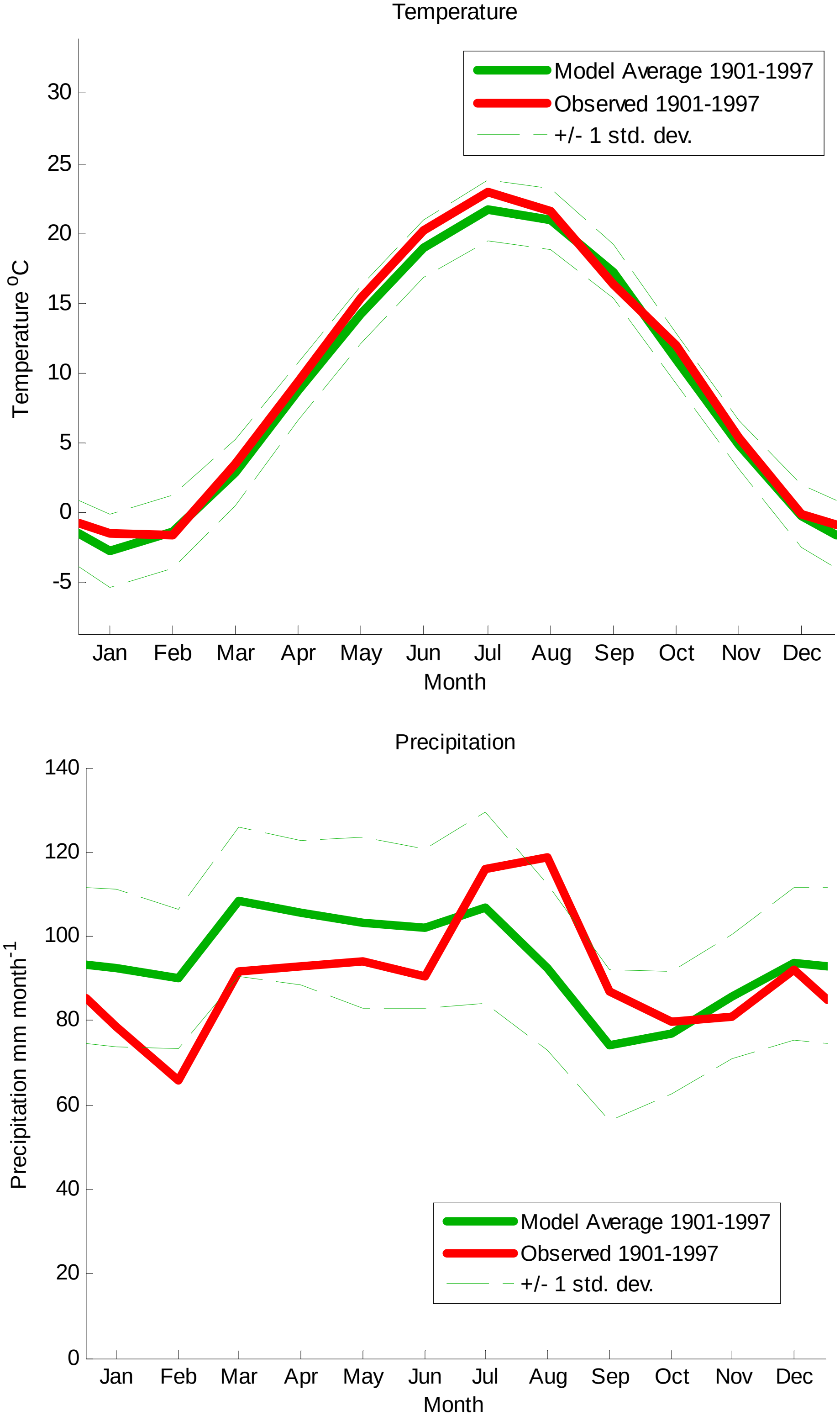


Fig. 2. Observed and modeled mean annual cycles of monthly mean temperature and precipitation over the Delaware Estuary Watershed.

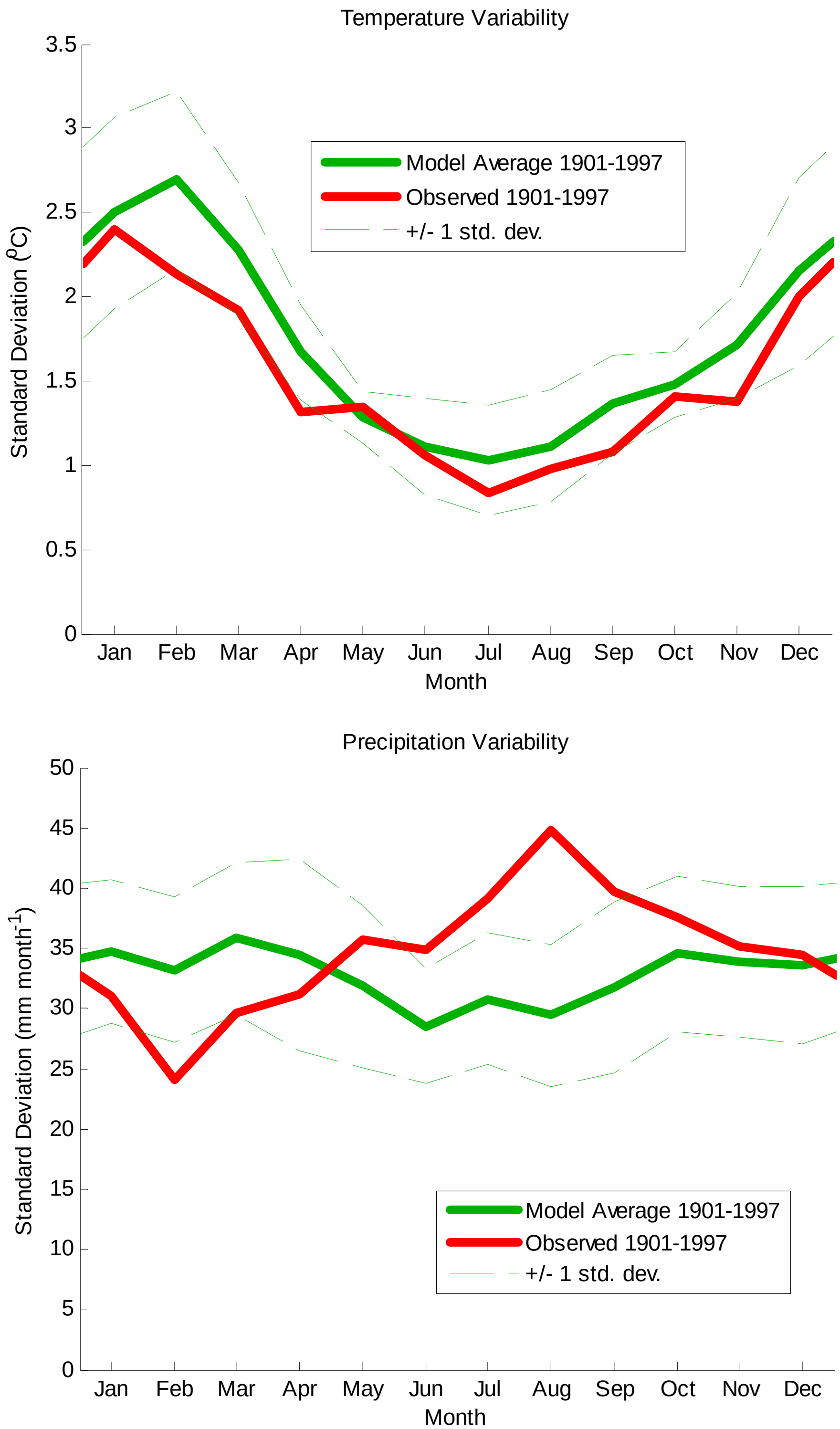


Fig. 3. Observed and modeled mean annual cycles of the interannual variability in temperature and precipitation over the Delaware Estuary Watershed.

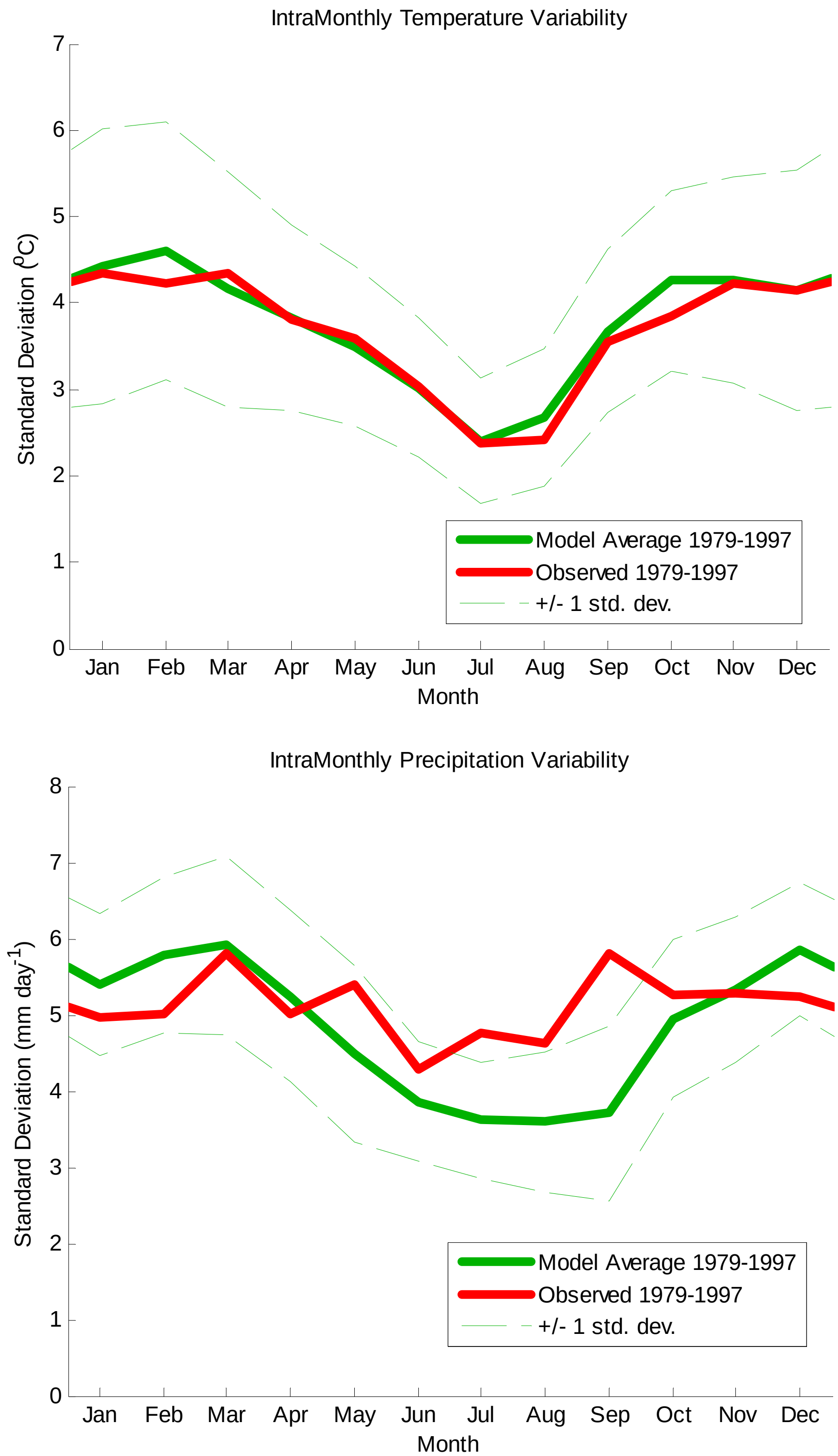


Fig. 4. Observed and modeled mean annual cycles of the intramonthly variability in temperature and precipitation over the Delaware Estuary Watershed.

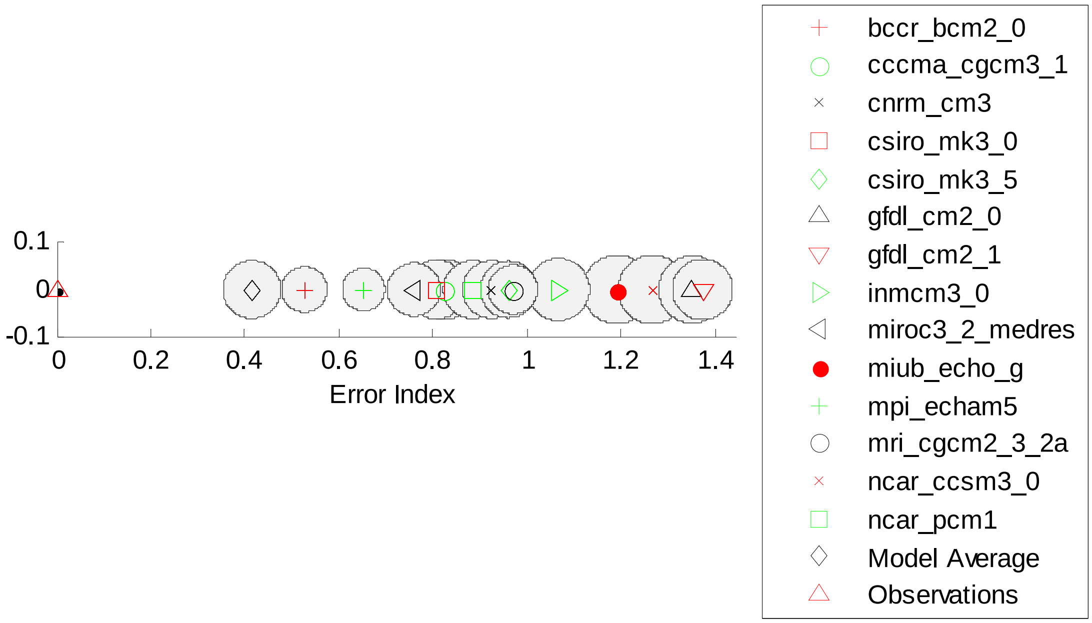


Fig. 5. Symbols show the error index calculate for each GCM in Table 1 and the multimodel average. The circles reflect 95% confidence intervals.

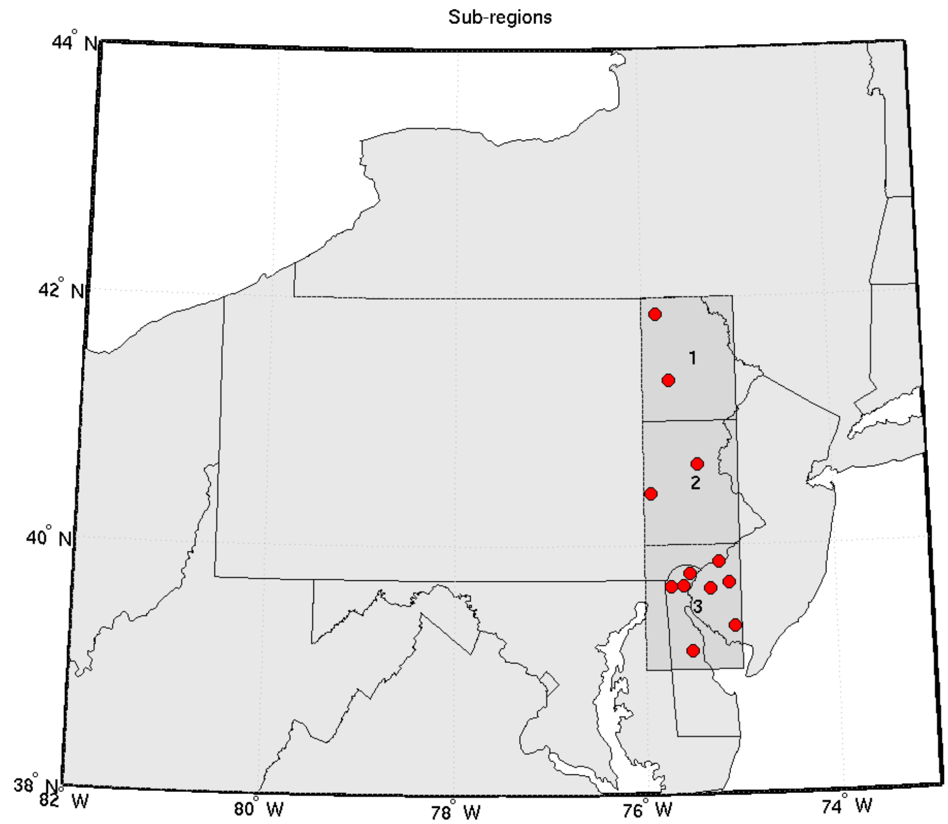


Fig. 6. Locations of the GHCN reporting sites averaged to create values for each of the 1° grids.

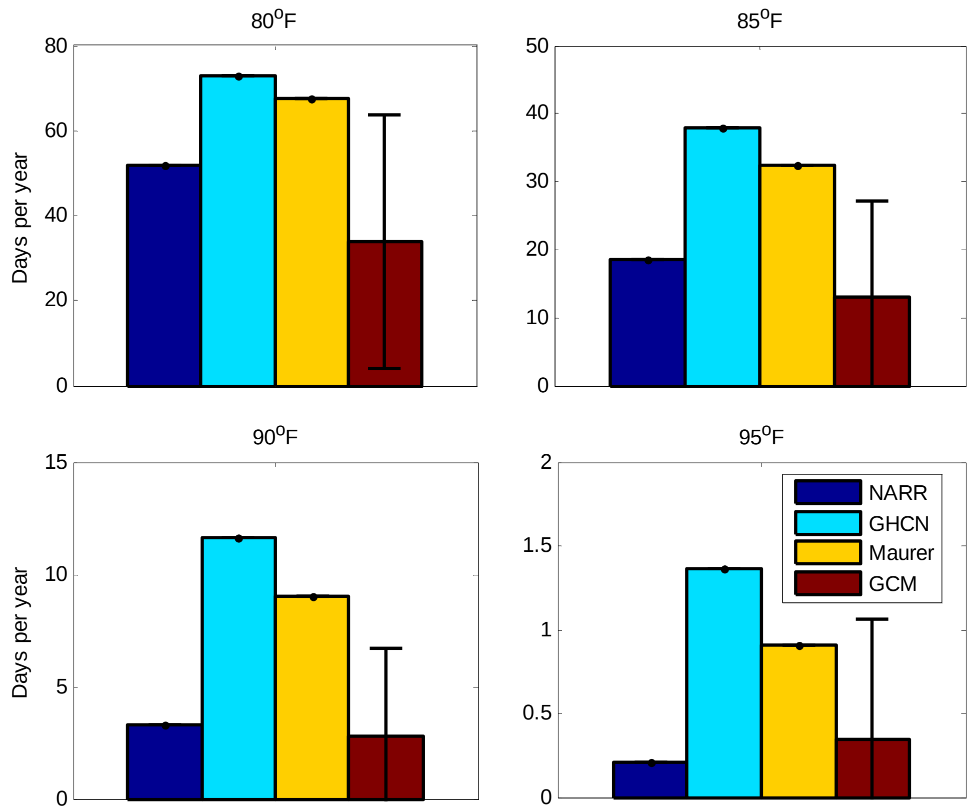
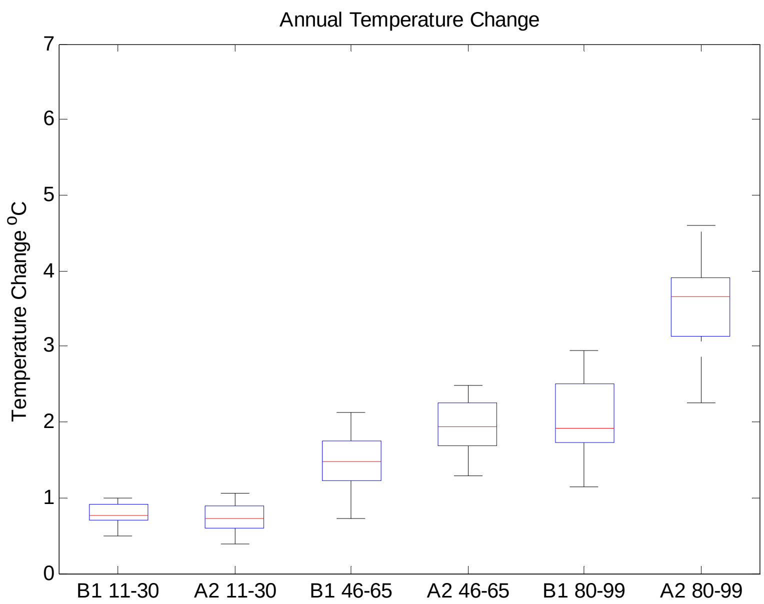


Fig. 7. Average number of hot days per year, defined as the number of days in which the high temperature exceeds 80, 85, 90, and 95° F. Shown are this metric computed for the North American Regional Reanalysis (NARR), the Global Historical Climate Network (GHCN), the Maurer et al. (2002) data set, and the Global Climate Model (GCM) multi-model average (and standard deviation).



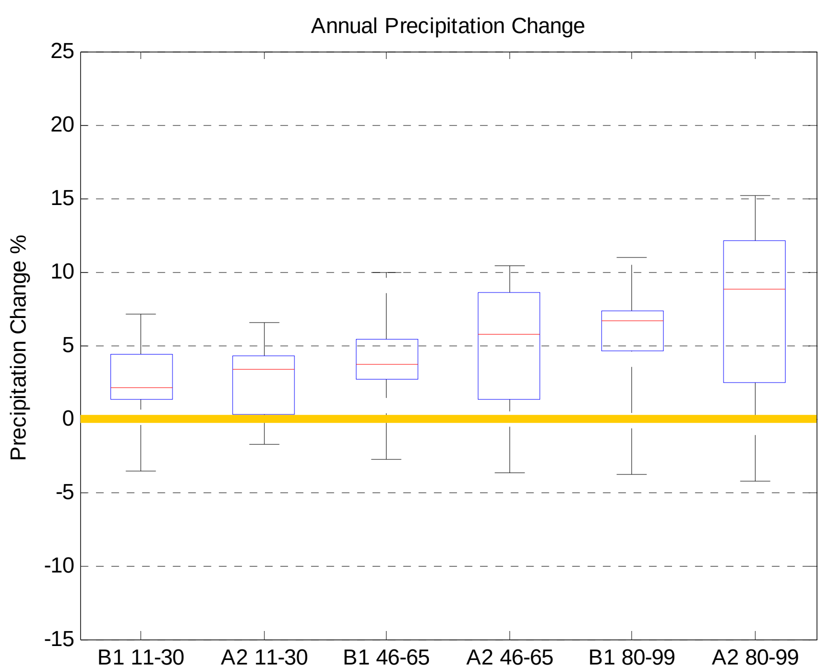


Fig. 8. Projected changes in annual-mean temperature and precipitation for the 14 global climate models listed in Table 1. The projections are changes with respect to 1980-1999 for two greenhouse gas emissions scenarios (B1 and A2) and three time periods (2011-2030, 2046-2065, and 2080-2099). The red line is the median projection, the blue box shows the 25th to 75th percentile range, and the black lines show the maximum and minimum projections.

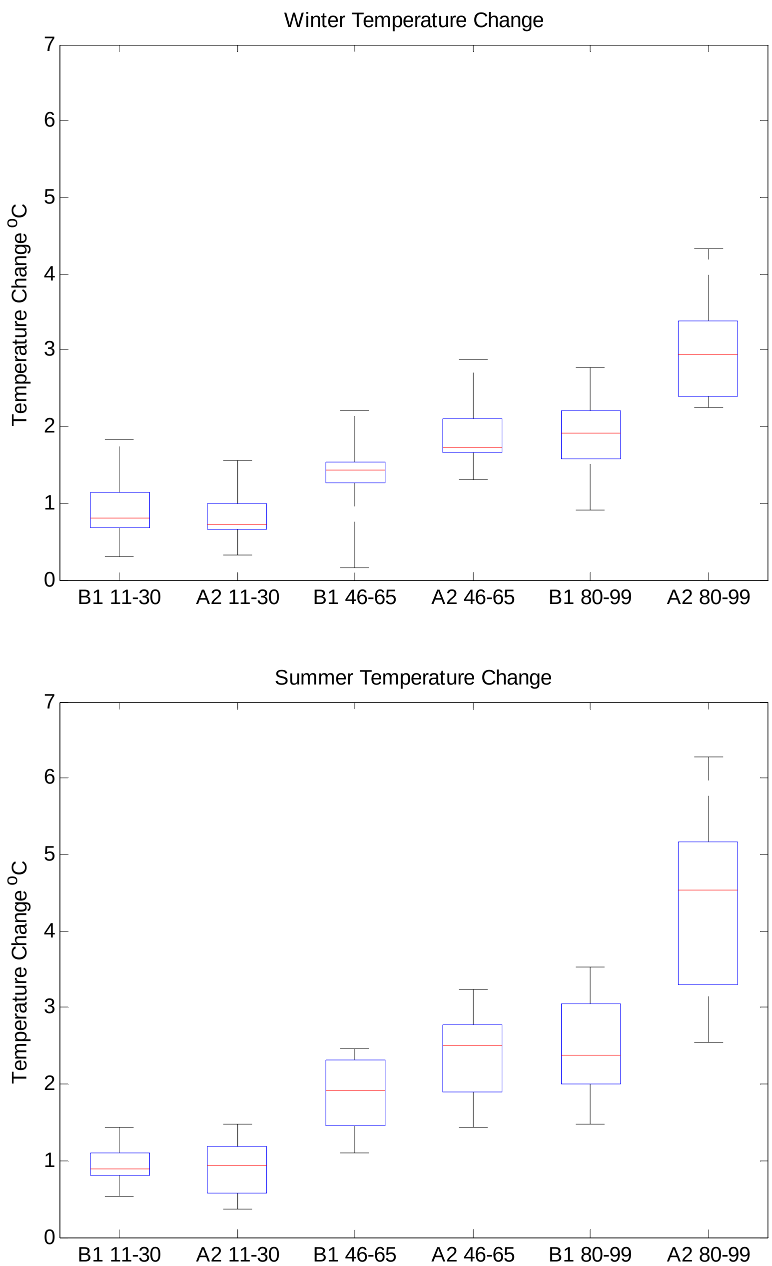


Fig. 9. Same as Figure 8 but for winter and summer temperature.

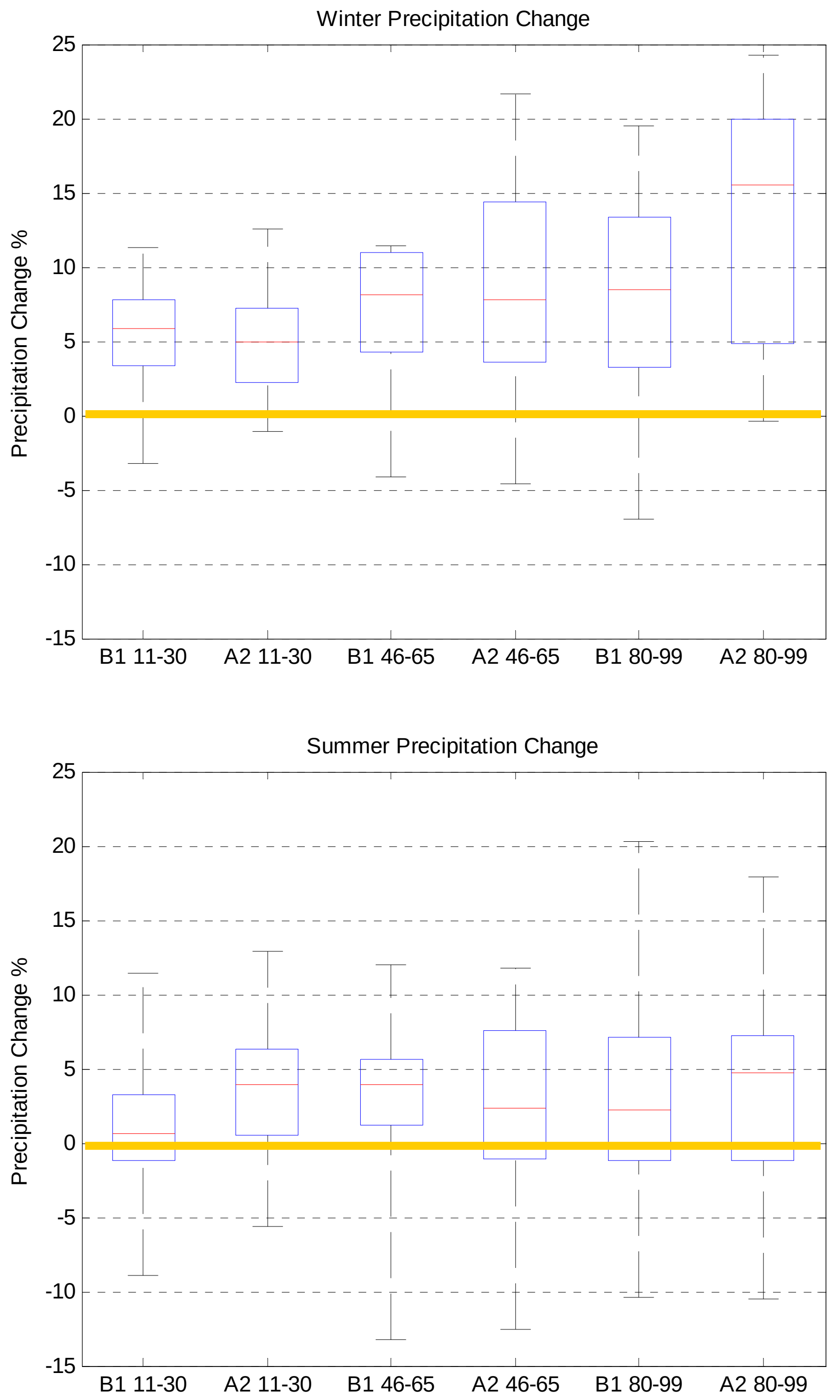


Fig. 10. Same as Figure 8 but for winter and summer precipitation.

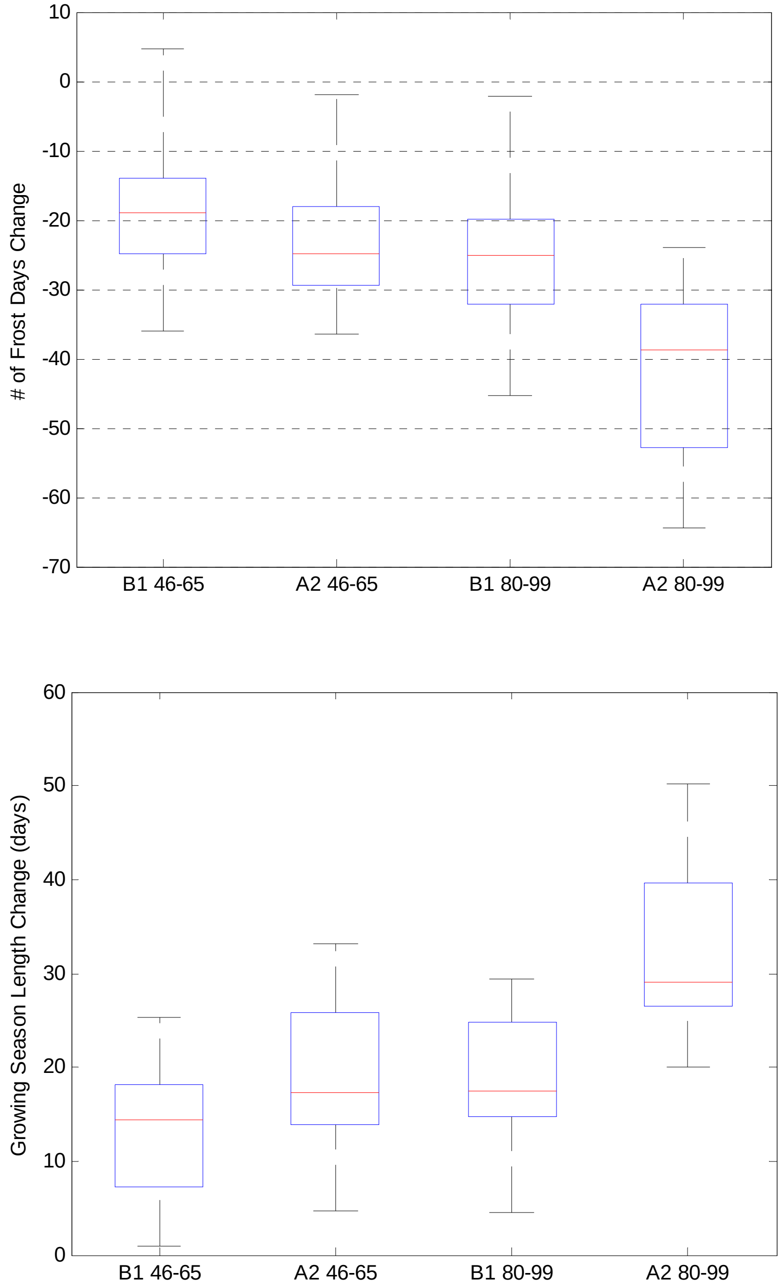
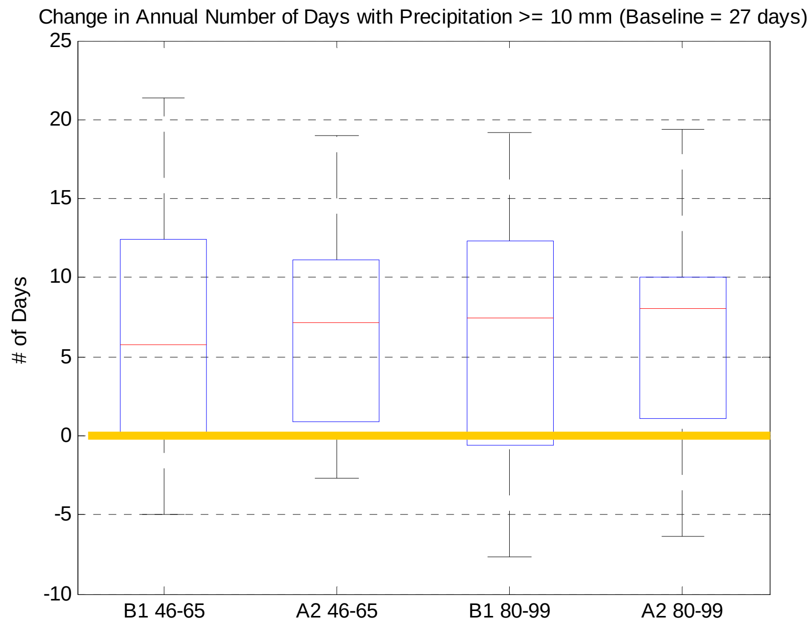


Fig. 11. Projected changes in frost days per year (top) and growing season length (bottom).



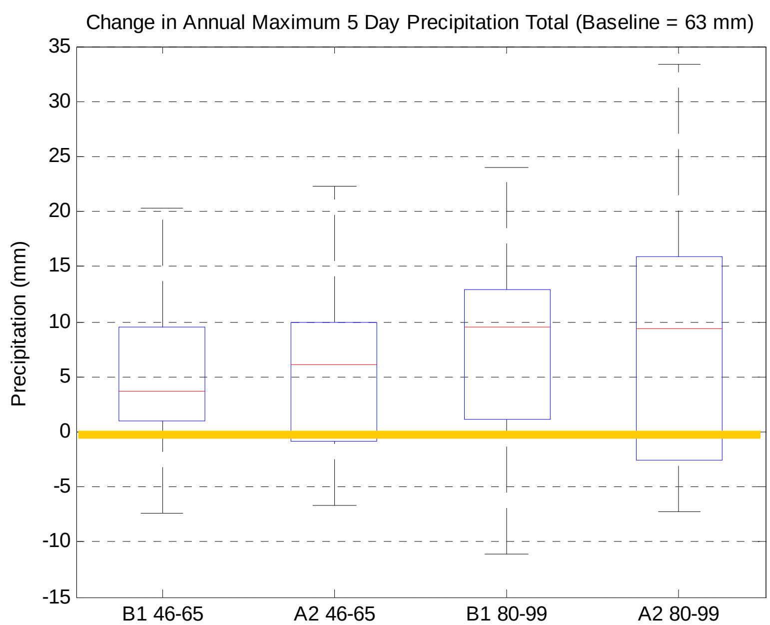


Fig. 12. Projected changes in heavy precipitation. Top is the change in the number of days per year with daily precipitation greater than 10 mm; bottom is the change in the annual maximum 5-day precipitation total.