1.1 A COMPARISON OF MODEL PRODUCED CLIMATE EXTREMES WITH OBSERVED AND PROJECTED TRENDS FOR THE 20TH AND 21ST CENTURIES

David R. Easterling * and Byron Gleason
NOAA National Climatic Data Center, Asheville, North Carolina

Kenneth E. Kunkel
Illinois State Water Survey, Champaign, Illinois

Ronald J. Stouffer
NOAA Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

1. INTRODUCTION

The globally averaged annual temperature has increased approximately 0.7^{o}C over the 20th century, and previous research for the 1950-1993 period (Easterling et al. 1997) showed that, most of this increase was due to a greater increase in daily minimum temperatures than in daily maximum temperatures, resulting in a decrease in the diurnal temperature range (DTR). However, recent research in Vose et al. (2005) that extends previous work through 2004, shows that, although the DTR decreased over the last half of the 20th century, the most recent 20 year period shows little or no decrease with the globally averaged maximum and minimum now increasing at approximately the same rate.

As global climate models have improved in their ability to simulate the observed changes in globally averaged annual temperatures over the 20th century, one question is how well these models simulate observed changes in climate extremes for the same period. This paper examines simulated changes in climate extremes, particularly warm spells (heat waves) for the 20th century using all forcings including observed carbon dioxide and other trace gases (GHGs), and aerosol changes and compares these changes to observed changes. Additionally simulated changes in extremes for the 21st century are also examined for two forcing scenarios, the A2 and B1 scenarios from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4).

Trend values for the model simulations and observations were calculated using the Kendall-Theil (K-T, Kendall 1975, Theil 1950) median of all pairwise slopes non-parametric slope estimator. The K-T method has the advantages of being free of assumptions of any distribution and is a slope estimate that is robust to outliers.

* *Corresponding author address*: David R. Easterling, NOAA National Climatic Data Center, 151 Patton Avenue, Asheville, NC 28801; e-mail: David.Easterling@noaa.gov.

2. MODEL SIMULATIONS

The model simulations used in this study are from the Geophysical Fluid Dynamics Laboratory (GFDL) Climate Model 2.1 (CM2.1) produced for the IPCC AR4. Three simulations are examined: 1. a simulation with 20th century observed forcing, 2. the Special Report on Emissions Scenarios (SRES) A2 (high equivalent CO_2 increase in the 21st century) and 3. SRES B1 (increase to approximately 800 ppmv equivalent CO_2 by the end of the 21st century).

The CM2.1 model is fully documented in Delworth et al. (2006). Here, we will simply highlight the main features of the model. The CM2.1 atmospheric component uses a grid with a 2^o latitude spacing and 18 vertical levels The oceanic component of the uses a 1^o latitude grid with higher resolution in the tropics. The CM2.1 oceanic component uses 50 vertical levels.

The CM2.1 initialization and radiative forcing procedures are outlined in Stouffer et al. (2004) and Delworth et al. (2006). The CM2.1 control integration uses 1860 radiative conditions. The historical integration (1860 to 1990) uses the estimates of the past changes in solar forcing, volcanic aerosols, well mixed greenhouse gases, and other radiatively active constituents. Single realizations of the two different future scenarios are used: SRES A2 and B1.

3. WARM SPELL (HEAT WAVE) DEFINITION.

There are numerous ways to define a warm spell (heat wave), but most have used a number of days above some threshold value with either daytime high temperature (maximum daily temperature) or nighttime low temperature (minimum daily temperature) (Alexander et al. 2006, Kunkel et al. 1999, Meehl and Tebaldi 2004). Here we seek to define warm spells (heat waves) as a combination of threshold exceedances of both maximum and minimum temperatures. Specifically our definition is where at least three days have a maximum temperature above the 80th percentile for that day followed by a minimum temperature above the 80th percentile for that day. This definition is aimed at looking at periods with warm daytime high temperatures that do not cool off much at night. Warm nights after warm days, especially in the context of true heat waves, can have large impacts on human health, as well as ecosystems (Changnon et al. 1996).

Furthermore, we do not restrict this analysis to the summer season, but examine the entire year. Thus in the summer these warm spells are heat waves, but in other parts of the year they may be the same as events like the "January thaw". Warm spells in most times of the year do not have the same deadly effect that a true summertime heat wave might, however there often are profound impacts on ecosystems and society, both good and bad.

For our work, we use the 1971-2000 base period and define the percentile threshold temperature values for each day of the year by using a 30 day running window with 15 days on either side of the day in question. This eliminates any "edge" effects if a warm spell crosses into the next month and any biases in transition months.

The two aspects we examine with respect to warm spells on an annual and seasonal basis are changes in: 1. how many occur, and 2. the duration of the warm spell in days. Figure 1 shows the "anatomy" of a warm spell for a fictional station in the summer, which would be considered a heat wave. The warm spell begins when the maximum temperature rises above the 80th percentile threshold temperature for a given day and the succeeding night's minimum temperature is also above the 80th percentile threshold temperature. The warm spell continues until either the maximum temperature or the minimum temperature falls below the 80th percentile threshold temperature for a given day. The warm spell must also contain at least three consecutive days where both maximum and minimum temperature are above the 80th percentile threshold. The duration is the number of days where the maximum and succeeding minimum temperature are both above the 80th percentile threshold. Here we examine changes in the "maximum" duration, which is the event with the longest duration for any given year.

4. RESULTS FOR THE U.S. OBSERVED RECORD

We examined continental U.S. heat wave changes for the period 1950-2004 using daily station data from the U.S. Cooperative Observer Network. We required stations to have no more than 15% of their data missing for the period which resulted in 3085 stations for the 1950-2005 period. The results for the station data were then gridded to produce the national and regional time series and trends shown.

Figure 2 shows the results for the number of events from the observed record. Annually the number of warm spells is increasing for the country as a whole, however there are large regional differences, with the Southwest, West, Northwest and Northern Plains showing statistically significant increases, and the rest of the country showing no statistically significant change. In fact, the whole eastern U.S. shows almost no trend in the number of warm spells on the annual time scale.

Observed seasonal changes with respect to number of events are also shown in Figure 2. On a national basis all seasons, except the fall, show some small increases in number of events, with the spring showing the largest increase and is only season that is statistically significant. However there are large regional differences in the changes, with the Western and Upper Midwestern parts of the country showing the largest increases, especially in the spring. The rest of the country shows little change.

Figure 3 shows changes in the maximum duration of events. The annual change in duration averaged across the country shows an increase of about ½ day over the period or 1 day per century. Like the frequency of warm spells, the largest increases in duration occur in the Southwest, West, and Northern Plains. The rest of the country shows no statistically significant change, however only Upper Midwest and Southern Plains show small decreases. Seasonally, the largest changes are in the spring, with a statistically significant increase in the national time series and large increases in the West, Southwest, Northwest and Northern Plains. The only other statistically significant changes are in the Upper Midwest in the winter and in the West during summer showing increases and the Upper Midwest in the fall showing a large decrease.

5. MODEL RESULTS, 20TH CENTURY

Figure 4 shows results from the GFDL climate model simulation for the last half of the 20th century for number of events. The annual map shows regional changes that are reasonably consistent with the observed maps. Annually the largest changes occur in the Southwest, West, Northwest and Northern Plains, with the Southeast showing a small negative trend. The model is less consistent with the observed pattern on a seasonal basis with the largest changes occurring in winter followed by the spring where there is a notable spring signal in the observations. Similar patterns are shown with the duration (Figure 5).

6. MODEL PROJECTED CHANGES

We now examine projected changes for the U.S. using two emissions scenarios, the A2 (high GHG) and B1, (low GHG) scenarios. Figure 6 and 7 shows results for the 2001-2100 period from the A2 scenario. We only show the annual and summer maps since all seasons show large increases in both the number and duration of warm spells, with the exception of a couple of regions. The summer map of the number of warm spells (heat waves) shows an interesting pattern in the Southern Plains and Southwest regions and to a lesser extent in other regions. The Southern Plains region best illustrates this pattern, where there is a large increase in number of events to about the middle of the 21st century, where the number begins to taper off and for a few regions actually declines in the latter part of the century. However the duration maps show large increases in the length of these events. This tapering off of numbers of events is due to the fact that as the temperatures warm, the length of events is increasing to the point that most days are above the 80th percentile threshold punctuated by the occasional day with both maximum and minimum temperatures below the threshold. Thus we have fewer, but much longer events.

Results for the B1 emissions scenario (low GHG forcing) for annual and winter are shown in Figures 8 and 9. The other three seasons show similar increases in both number and duration of events. The annual maps show both number and duration increasing although both tend to taper off in the latter half of the 21st century, consistent with the reduction in GHG forcing for the same period. However in winter, for the Eastern part of the country there is little change in either number or duration of warm spells. Analysis of temperature trends for the Southern Plains and Southeast regions during winter for the B1 simulation (not shown) shows little or no warming in either the maximum or minimum temperature for these regions.

7. SUMMARY

We have defined a variation on previous methods of defining warm spells (heat waves) that takes into account threshold temperature exceedances in both the daily maximum (daytime high) and minimum (nighttime low) temperature. Observed changes in warm spells show increases in events mainly in the Western part of the country, with little or no change in the Eastern part. Seasonally the largest changes are in the spring, consistent with other analyses for the same period, such as frost days and the date of the last Spring frost (Easterling 2002).

Model simulated changes for the same period from the GFDL CM2.1 forced with observed changes in climate forcing for the latter half of the 20th century show spatial patterns of changes that are broadly consistent with the observed changes, increases in number and duration of events in the Western portion of the country, with little or no change in the East.

Model projections for the future generally show large increases in number and duration of events with some exceptions. The B1 or low GHG increase scenario shows little change in either number or duration of warm spells in the Eastern part of the country in winter, consistent with a projected lack of wintertime warming. The A2 or high GHG increase show large increases, such that in some regions the number of events actually decreases as the durations increase in the last part of the 21st century.

8. ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy, Office of Biological and Environmental Research under Interagency Agreement DE-AI02-96ER62276 and the NOAA Climate Program Office, Climate Change Data and Detection Element.

9. REFERENCES

Alexander, L., et al., 2006: Global observed changes in daily climate extremes of temperature and precipitation. *J. Geophys. Res*., D05109,doi:10.1029/2005JD006290.

Changnon, S.A., K. Kunkel, and B. Reinke, 1996: Impacts and reponses to the 1995 heat wave: a call to action, ***Bull. Amer. Meteor. Soc.*** **77**, 1497-1506.

Delworth, T., et al. 2006: GFDL's CM2 global coupled climate models, Part I: Formulation and simulation characteristics, ***J. Climate***, 19, 643-674.

Easterling, D.R., 2002: Recent changes in frost days and the frost-free season in the United States, ***Bull. Amer. Meteor. Soc.***, 83, 1327-1332.

Easterling, D.R., B. Horton P.D. Jones, T.C. Peterson, T.R. Karl, M.J. Salinger, D. Parker, V. Razuvayev, N. Plummer, P. Jamason, and C.K. Folland, 1997: Maximum and minimum temperature trends for the globe, ***Science***, V. 277, 364-367***.***

Kendall, M.G., 1975, *Rank Correlation Methods*, 4th edition: Charles Griffin, London. 202 p.

Kunkel, K.E. et al. 1999: Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: a review., ***Bull. Amer. Meteor. Soc.***, **80**, 1077-1098.

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

Stouffer, R., et al. 2004: A method for obtaining pre-twentieth century initial conditions for use in climate change studies. ***Climate Dynamics*, 23**, 327-339.

Theil, H., 1950. A rank-invariant method of linear and polynomial regression analysis, 1, 2, and 3: *Ned. Akad. Wentsch Proc., 53*, 386-392, 521-525, and 1397-1412.

Vose, R.S., D.R. Easterling, and B. Gleason, 2005: Maximum and minimum temperature trends for the globe: An update through 2004. ***Geophys. Res. Lett.***,**32**, L23822, doi:10.1029/2004GL024379.

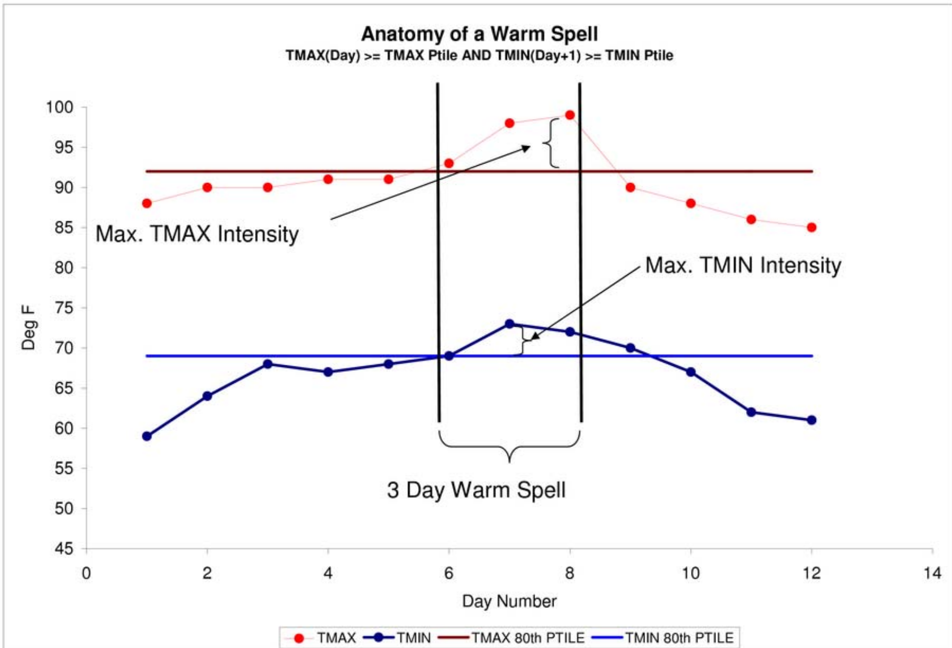


Figure 1. Graph showing the definition of a warm spell for a fictional station. The thick solid lines are the 80th percentile threshold temperature for maximum (red) and minimum (blue) temperatures and the lines with dots are the observed values for a hypothetical warm spell.

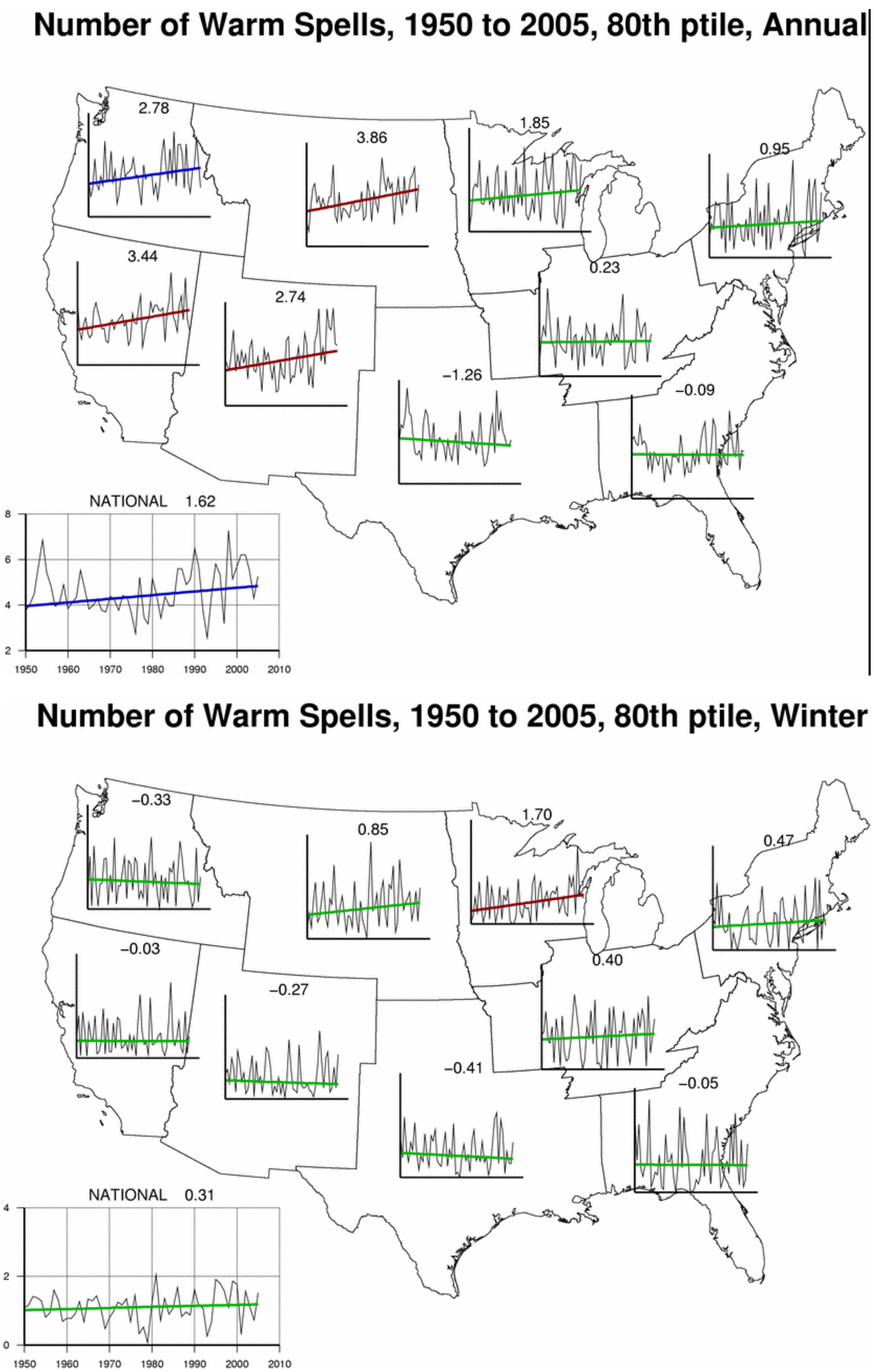
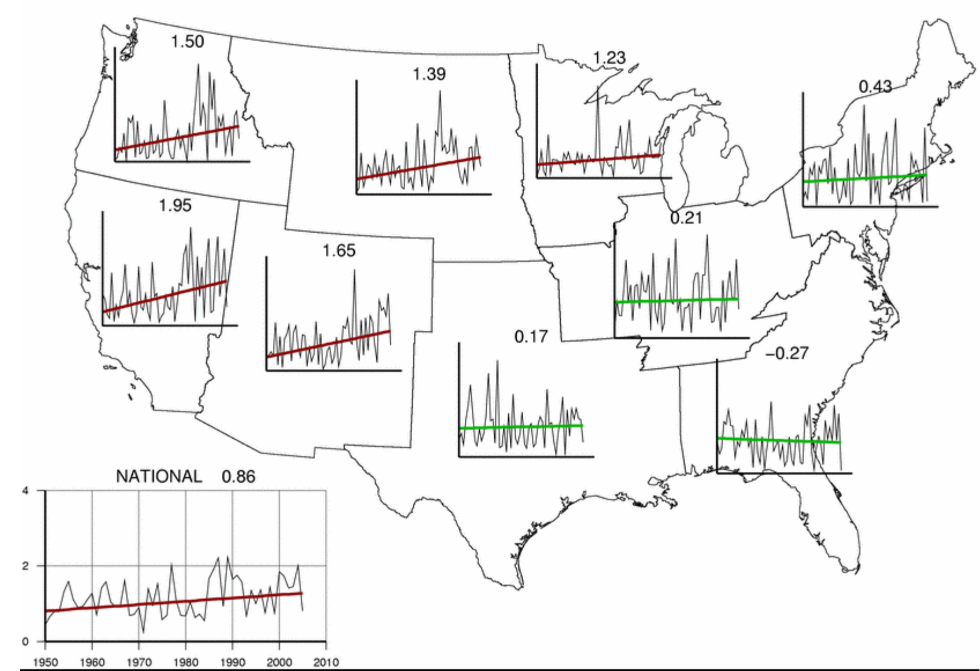
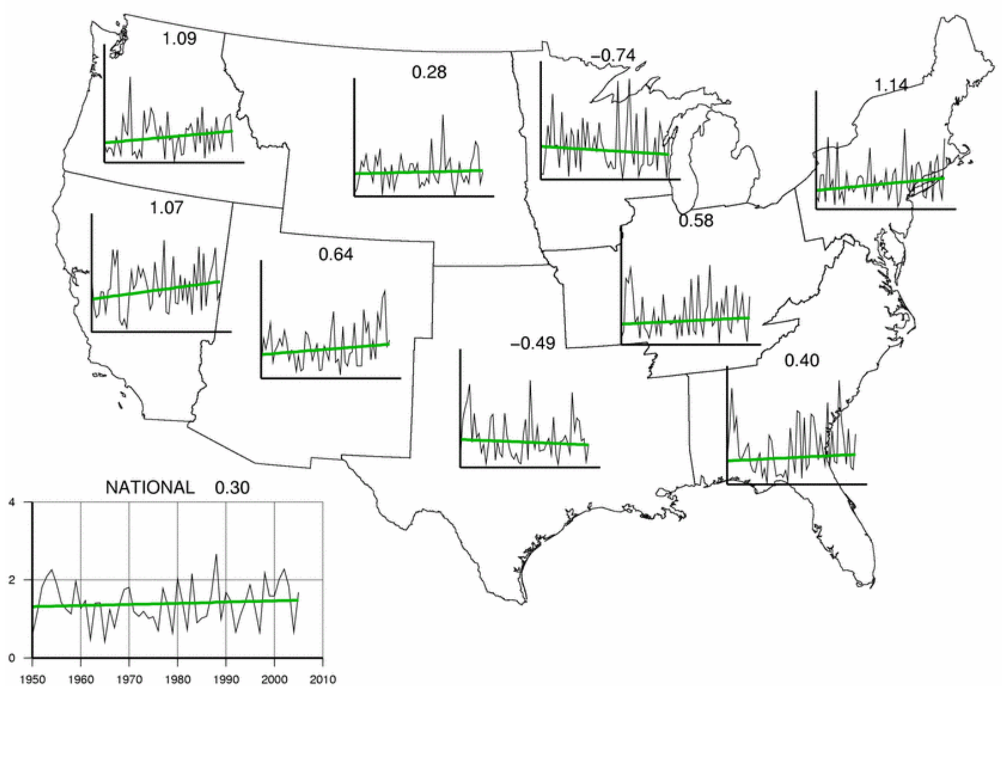


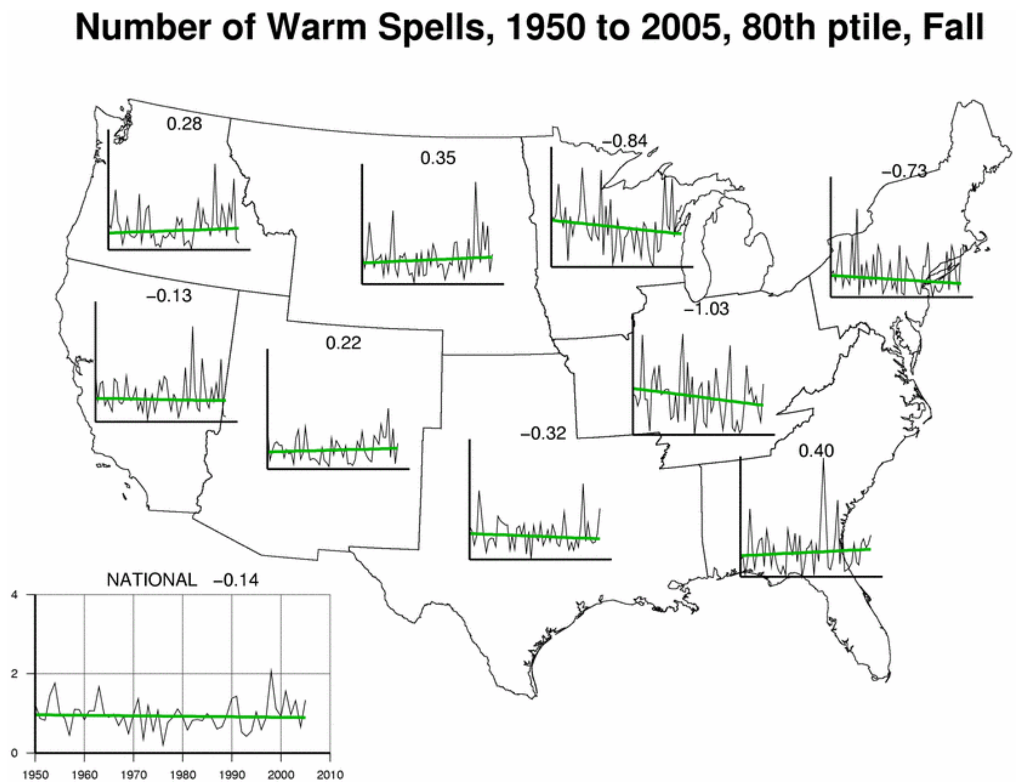
Figure 2. Observed number of warm spells for Annual, Fall, Winter, Spring, Summer. Trends are shown for each region and Nationally in events/Century. Green trend line is not significant, blue is significant at the 90% level and red is significant at the 95% level.

Number of Warm Spells, 1950 to 2005, 80th ptile, Spring



Number of Warm Spells, 1950 to 2005, 80th ptile, Summer





Number of Warm Spells, 1950 to 2005, 80th ptile, Fall
0.28
0.35
−0.84
−0.73
−0.13
0.22
−1.03
−0.32
0.40
NATIONAL −0.14
4
2
0
1950
1960
1970
1980
1990
2000
2010

Figure 2, end.

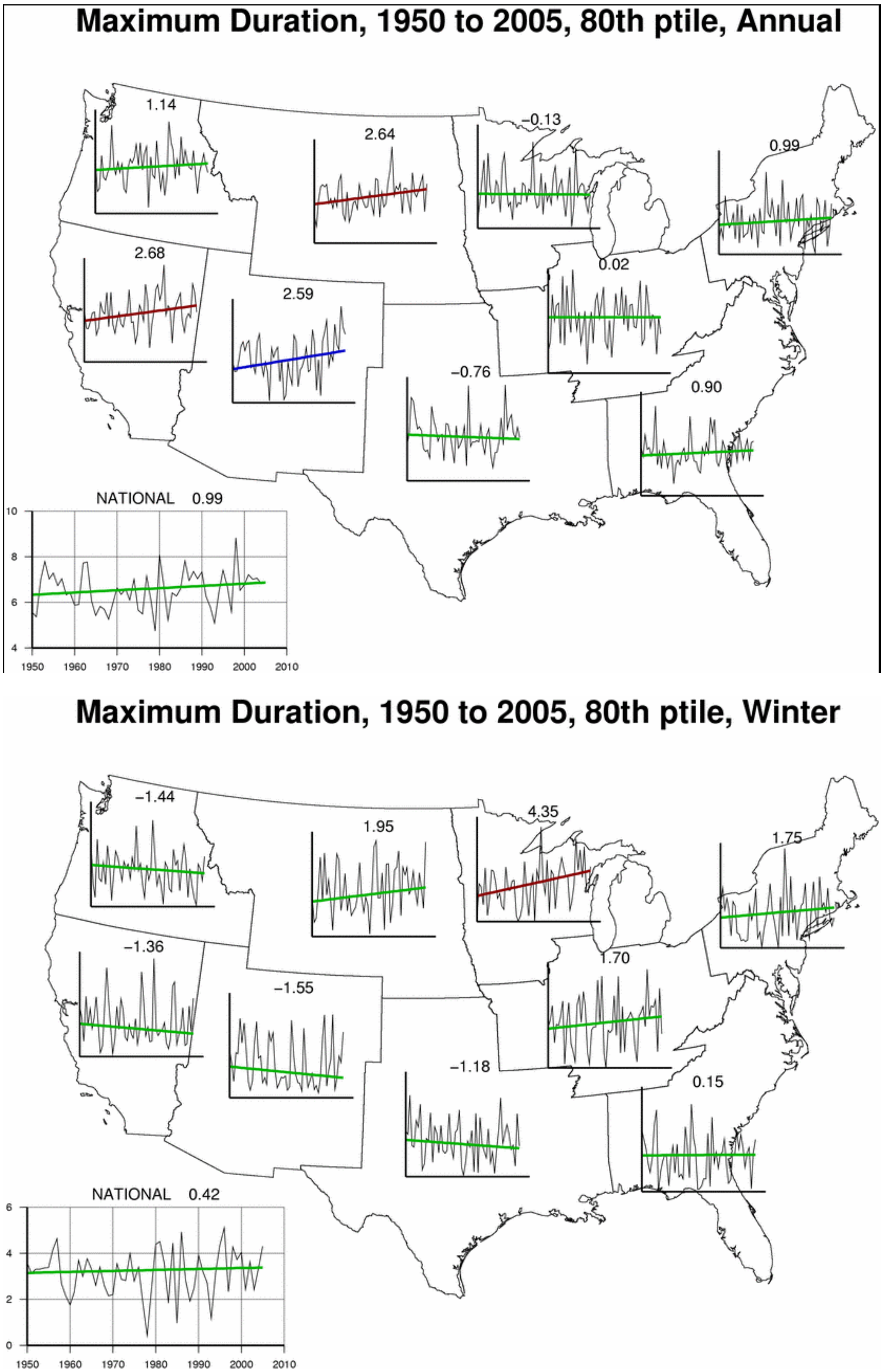


Figure 3. Trend in observed duration of warm spells in days/century. Trend line colors same as Figure 2.

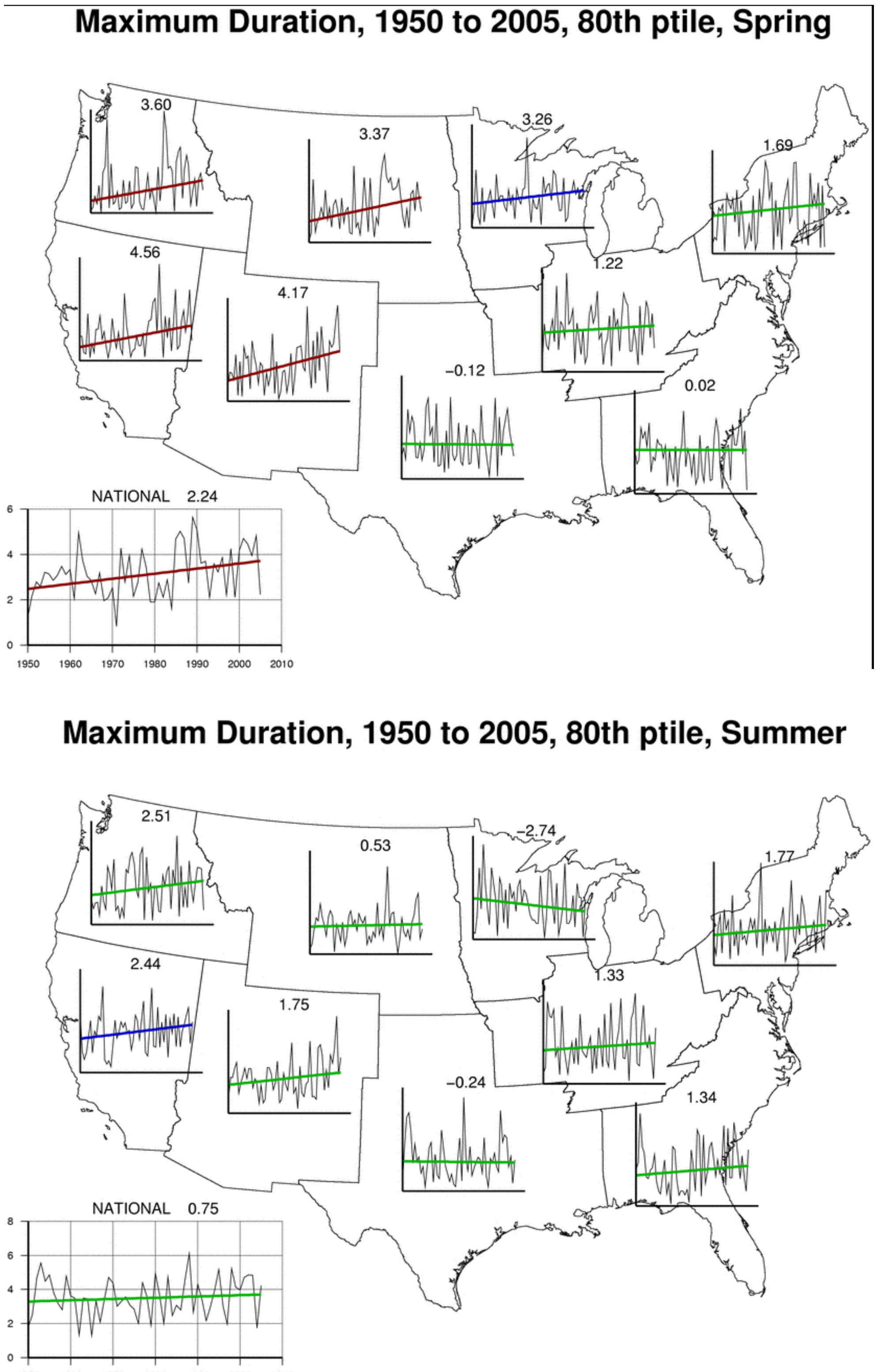


Figure 3, cont.

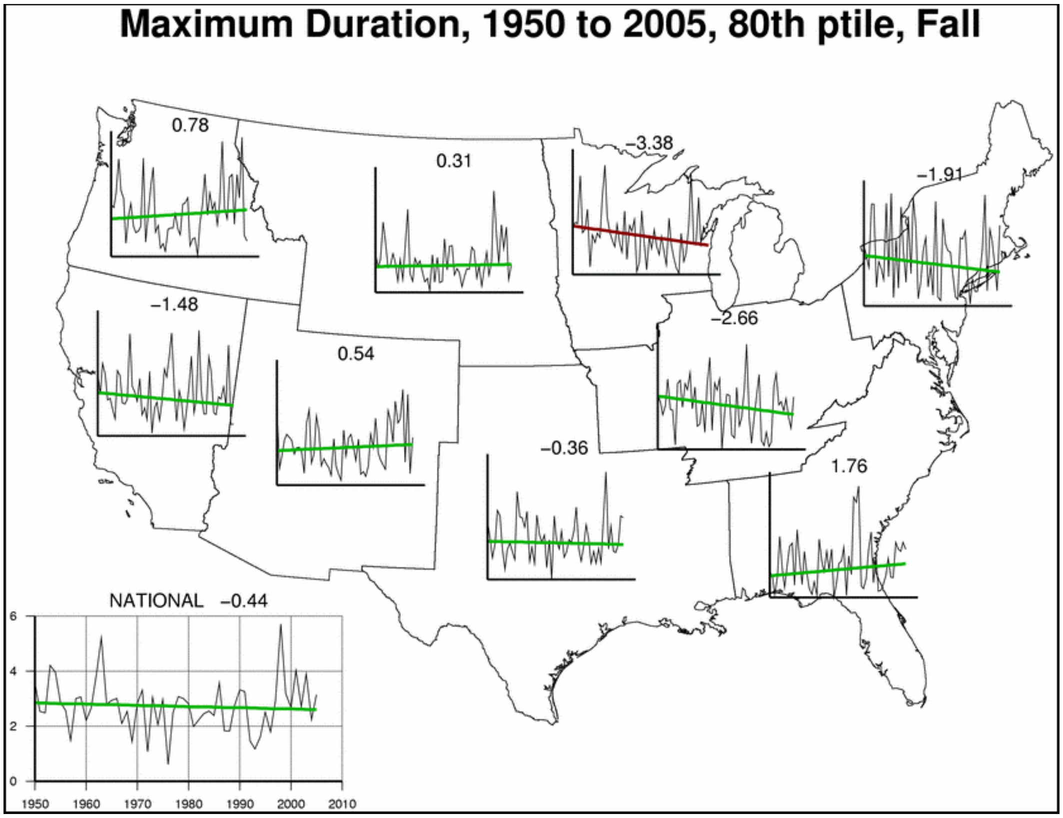
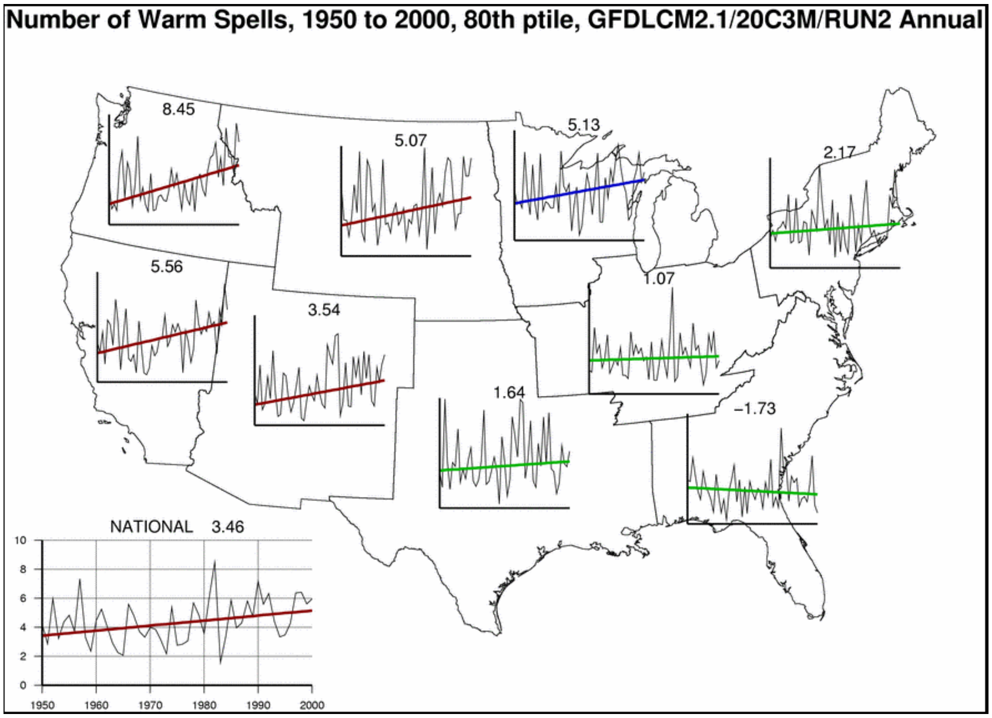

Maximum Duration, 1950 to 2005, 80th ptile, Fall
0.78
0.31
−3.38
−1.91
−1.48
0.54
−2.66
−0.36
1.76
NATIONAL −0.44
6
4
2
0
1950
1960
1970
1980
1990
2000
2010

Figure 3, end.



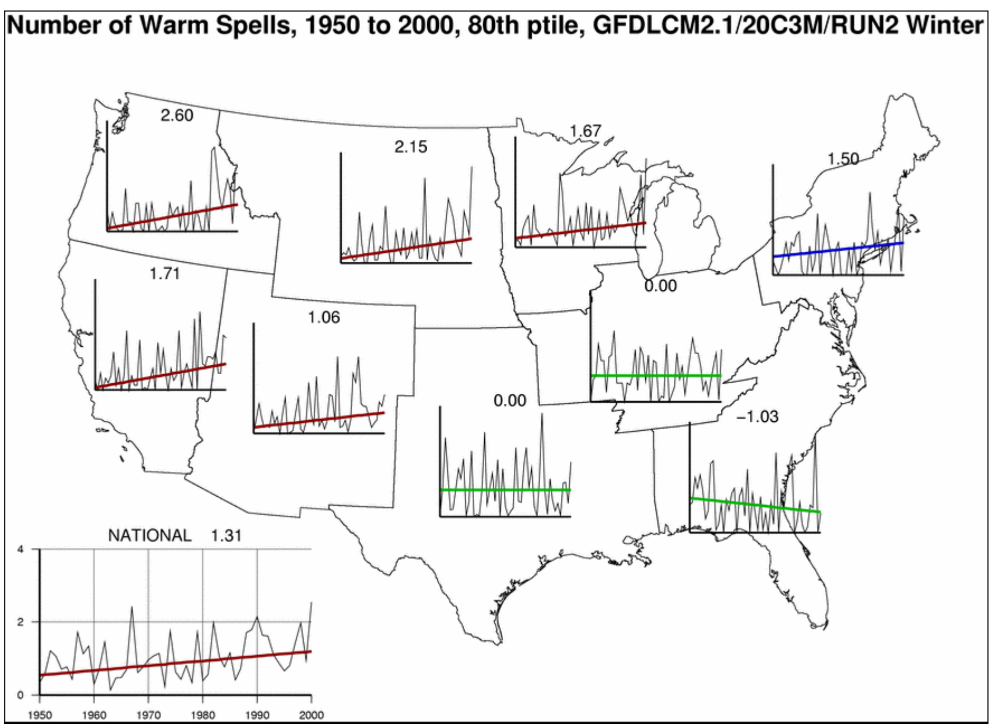
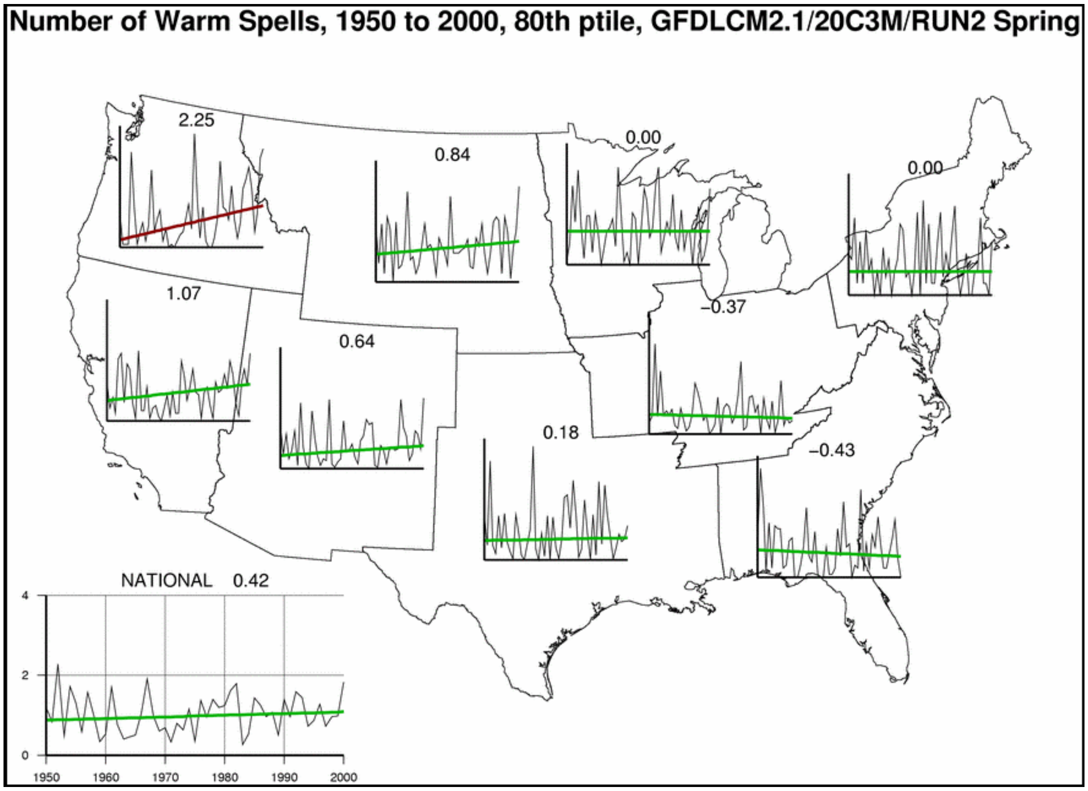


Figure 4. Number of warm spells for 20th century simulation. Line colors same as Figure 2.



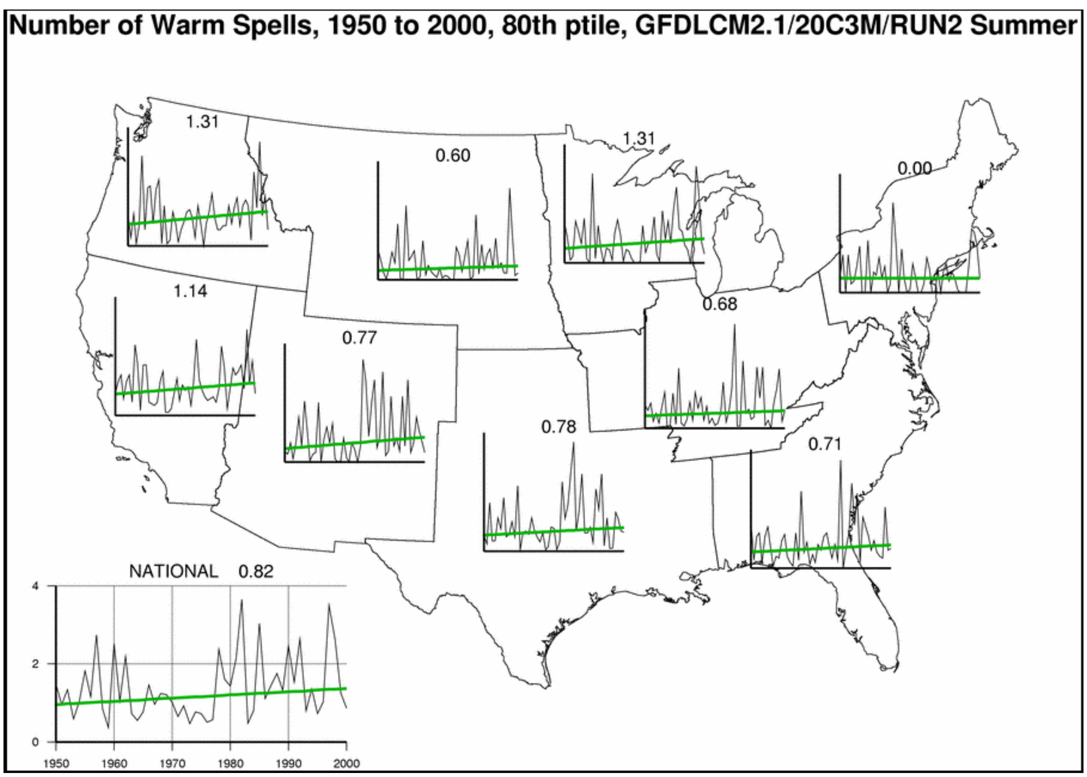


Figure 4, cont.

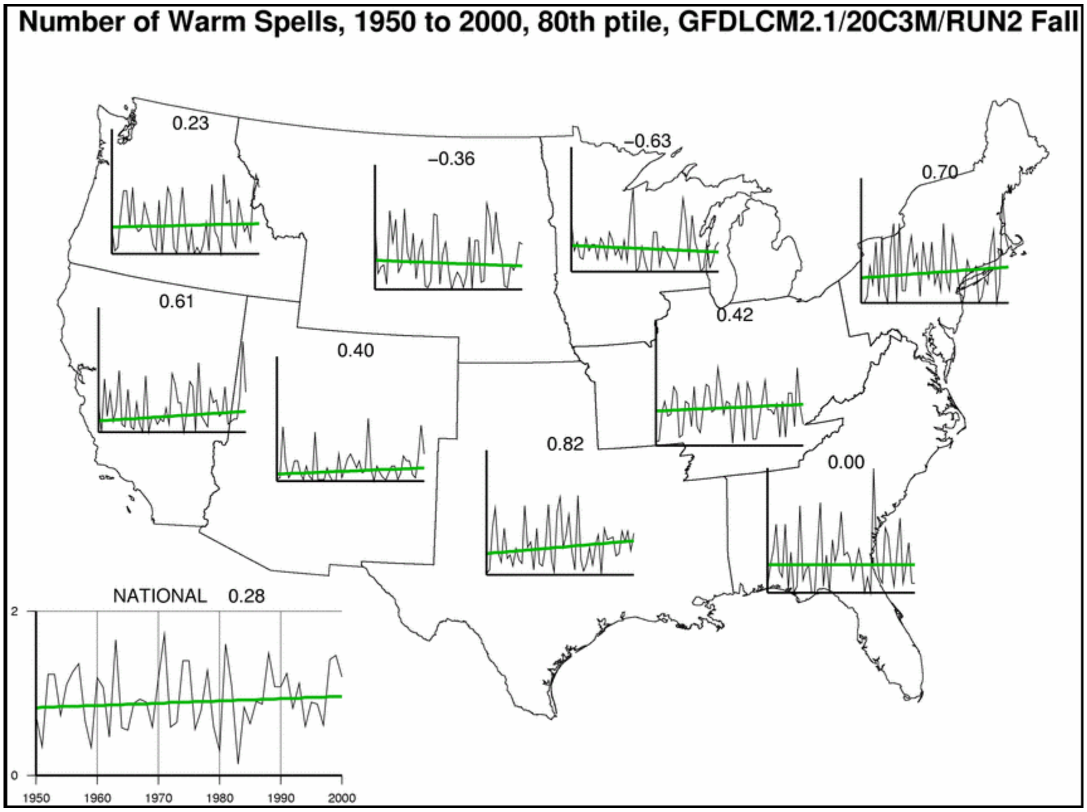
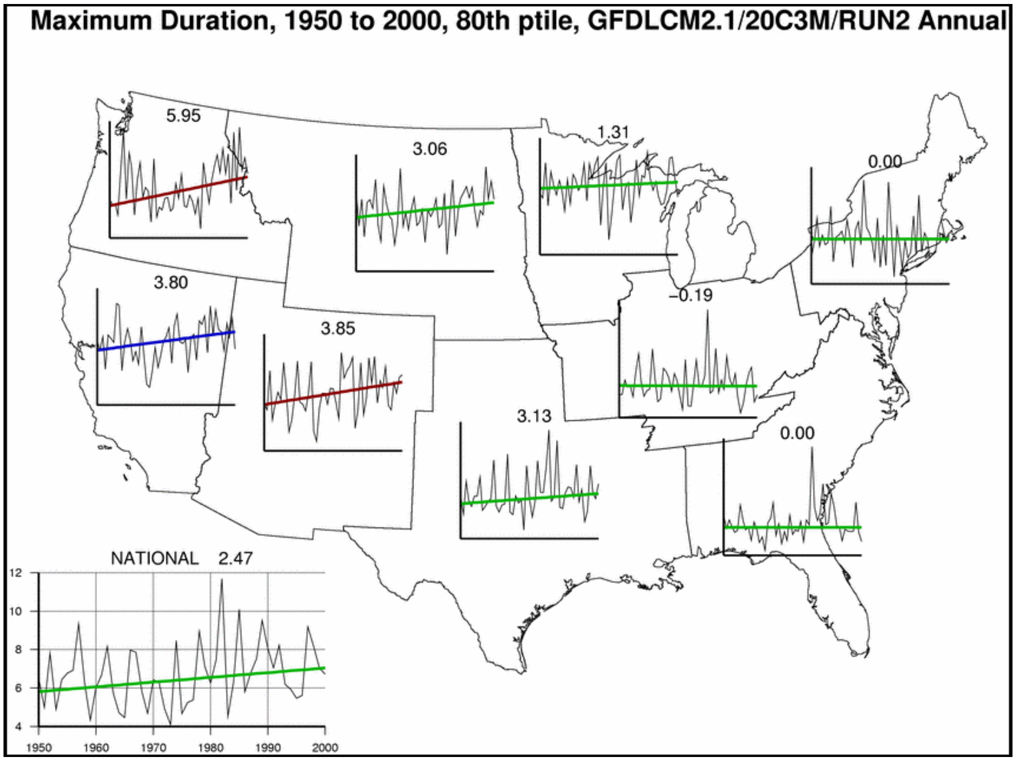

Number of Warm Spells, 1950 to 2000, 80th ptile, GFDLCM2.1/20C3M/RUN2 Fall
0.23
−0.36
−0.63
0.70
0.61
0.40
0.42
0.82
0.00
NATIONAL 0.28
2
0
1950
1960
1970
1980
1990
2000

Figure 4, end.



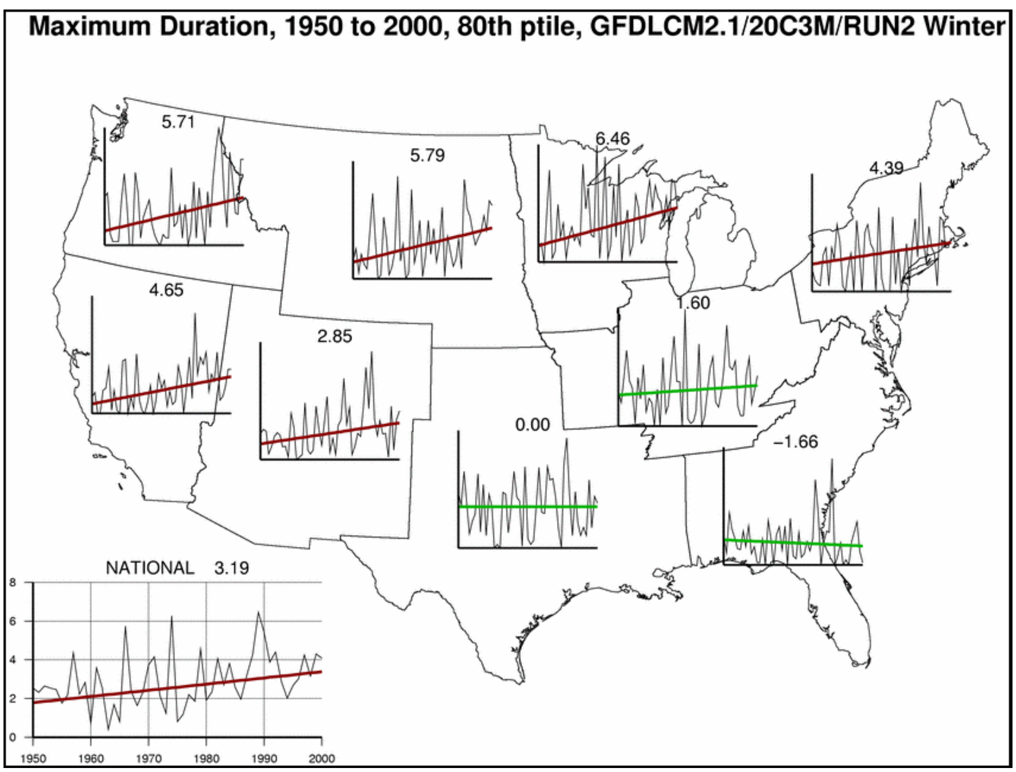


Figure 5. Warm spell duration changes for 20th century simulation. Line colors same as Figure 2.

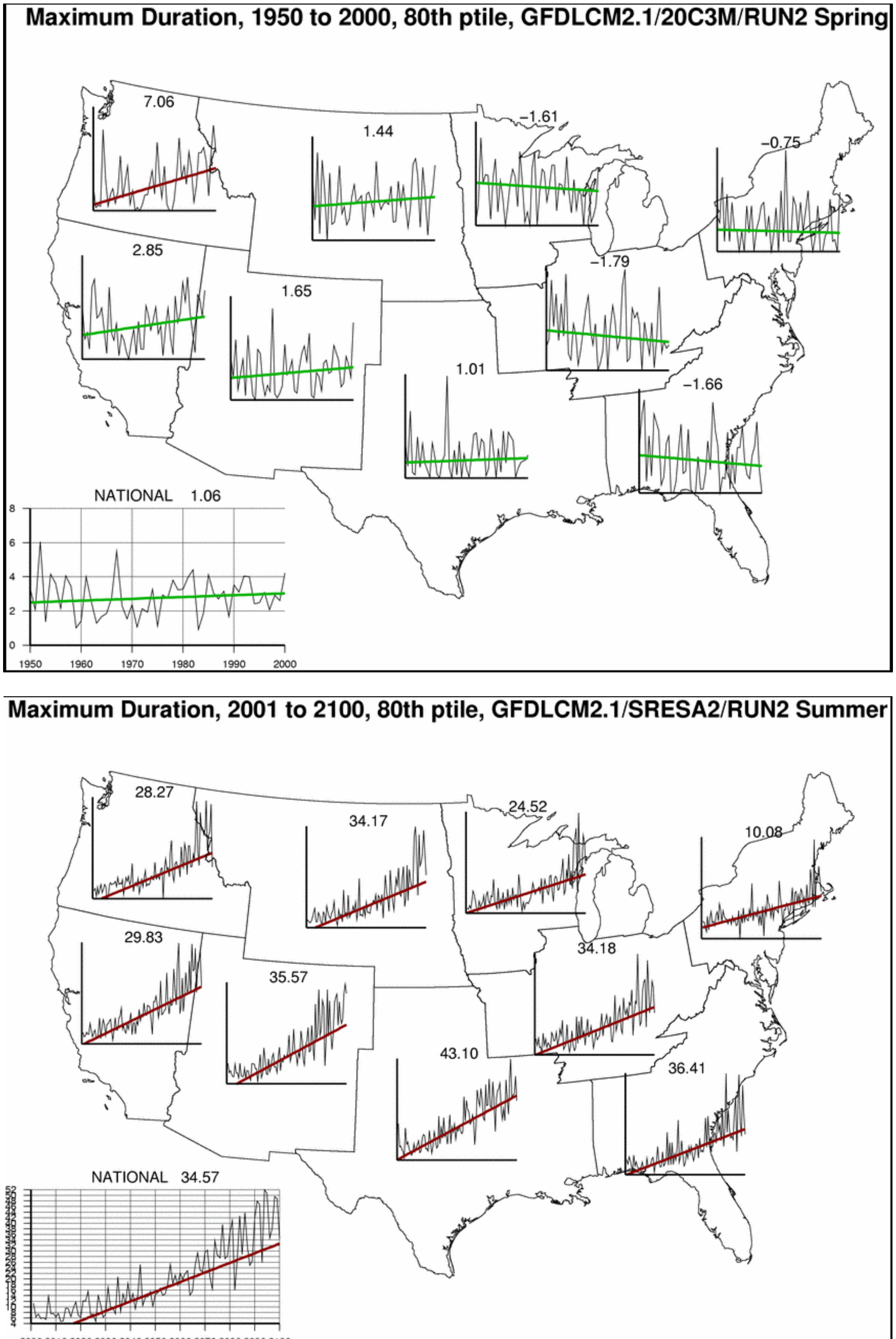


Figure 5, cont.

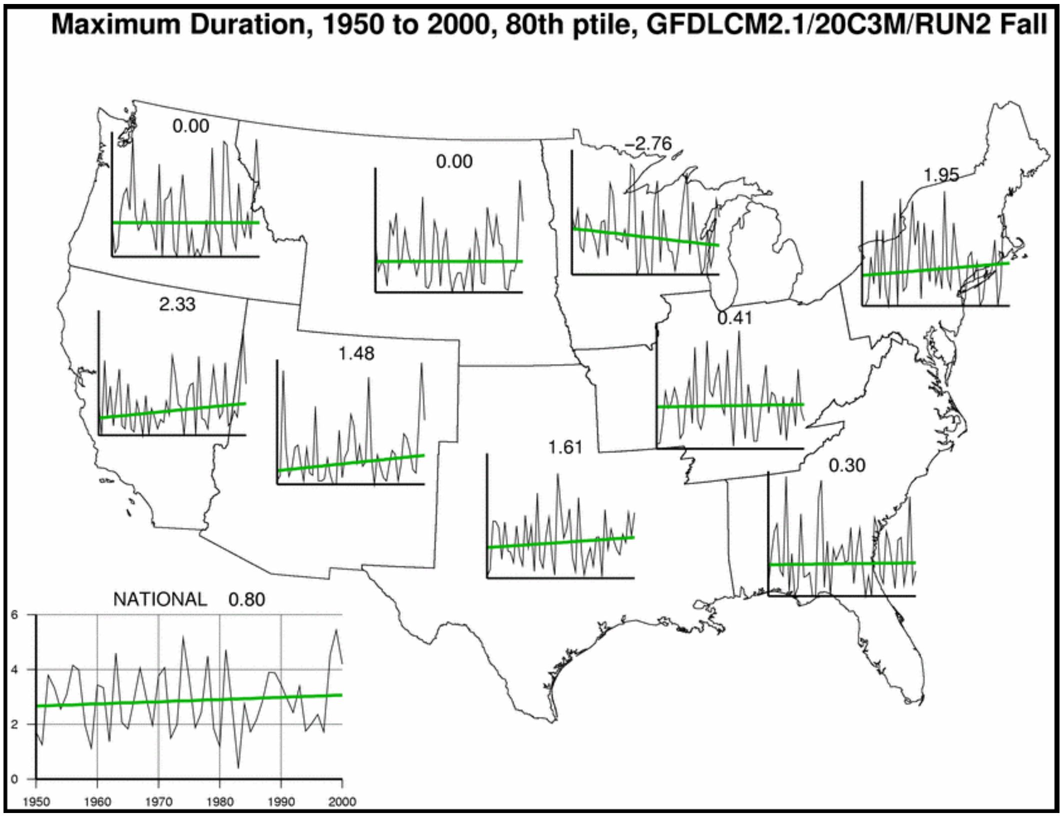
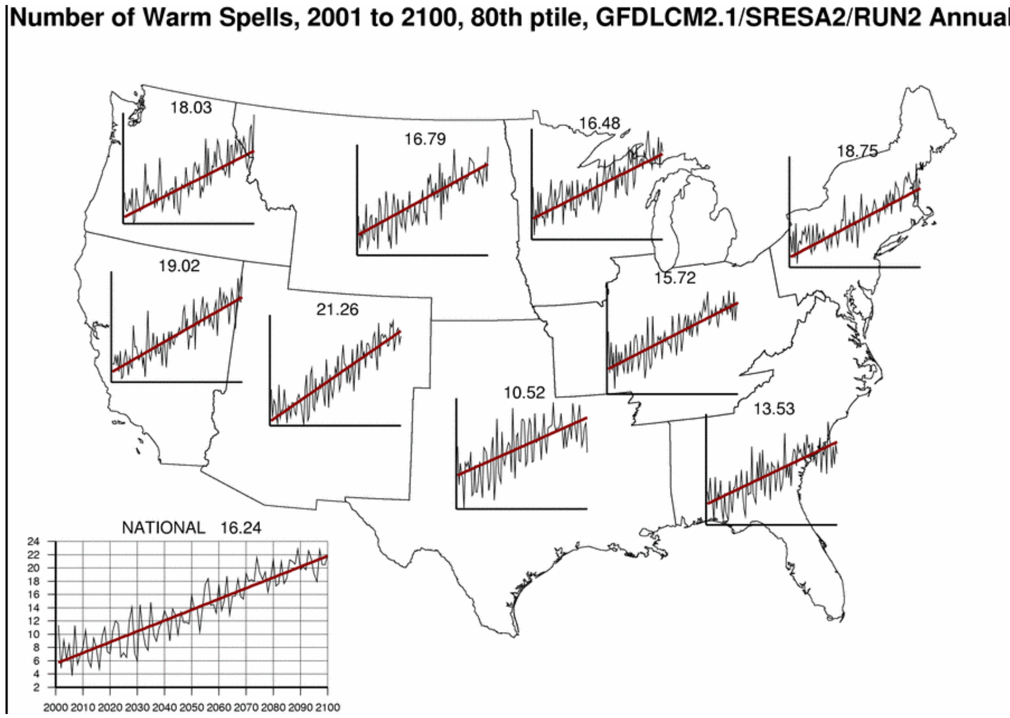

Maximum Duration, 1950 to 2000, 80th ptile, GFDLCM2.1/20C3M/RUN2 Fall
0.00
0.00
-2.76
1.95
2.33
1.48
0.41
1.61
0.30
NATIONAL 0.80
6
4
2
0
1950
1960
1970
1980
1990
2000

Figure 5, end.



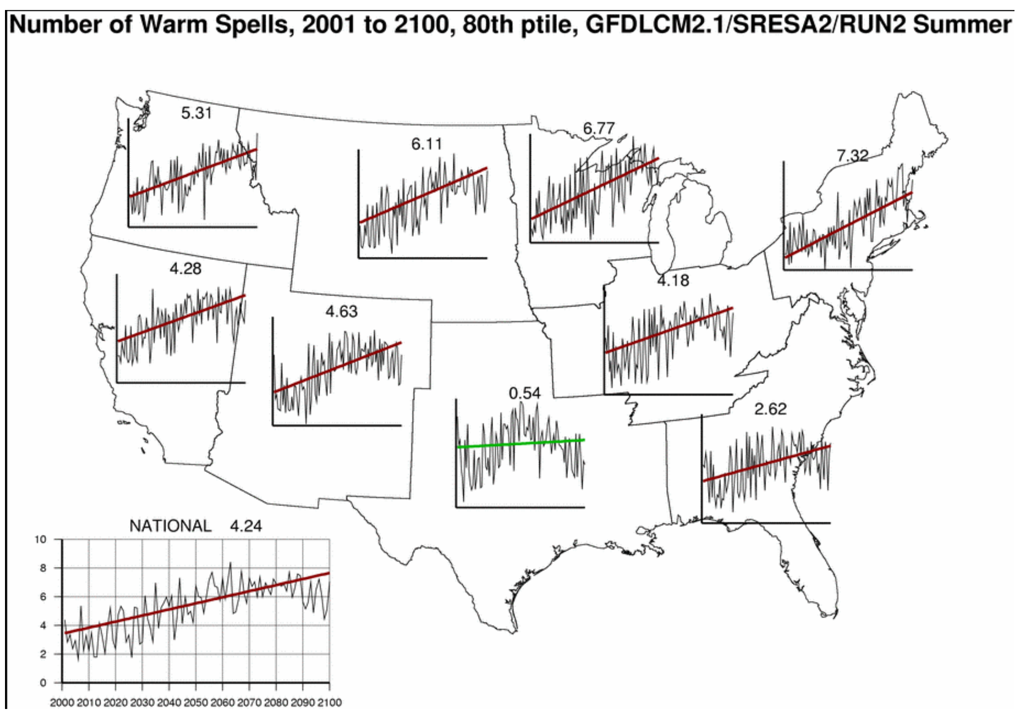


Figure 6. Model projected number of events for Annual and Summer for the 2001-2100 period from the A2 emissions scenario.

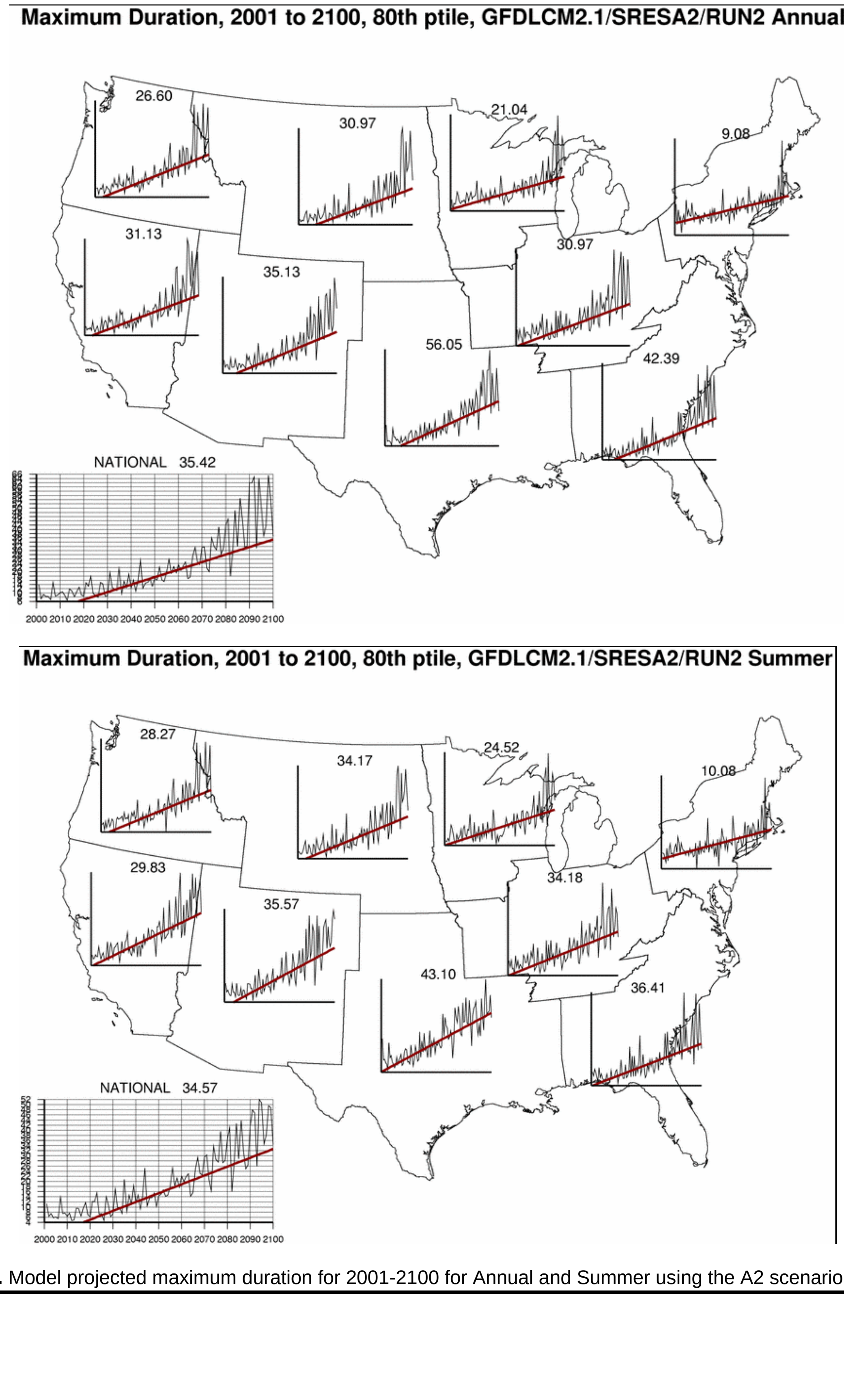
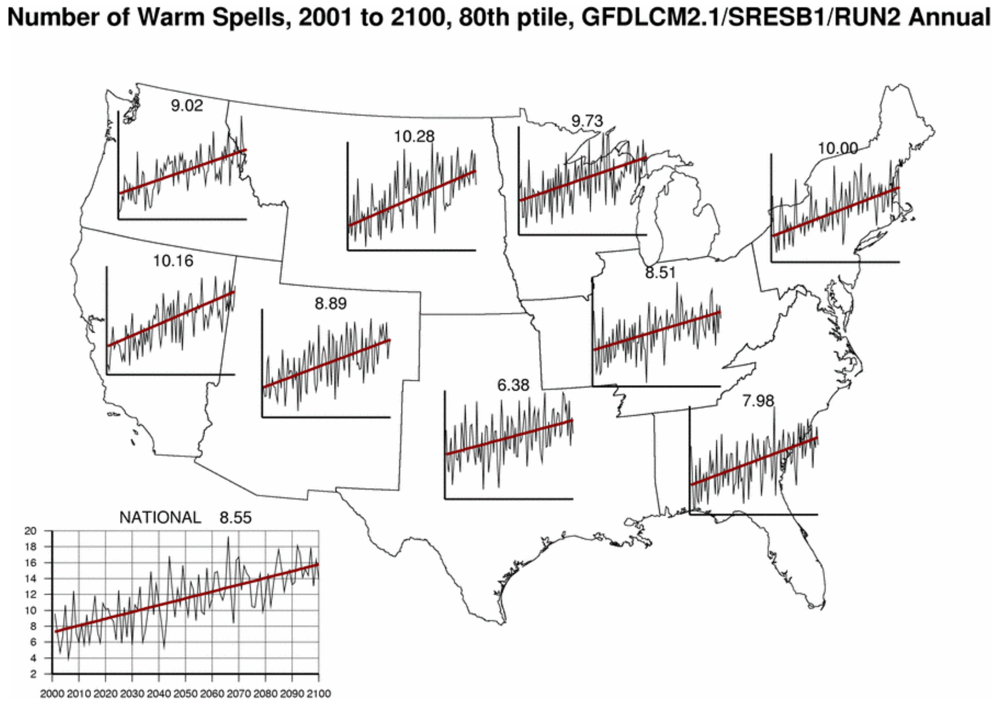


Figure 7. Model projected maximum duration for 2001-2100 for Annual and Summer using the A2 scenario.



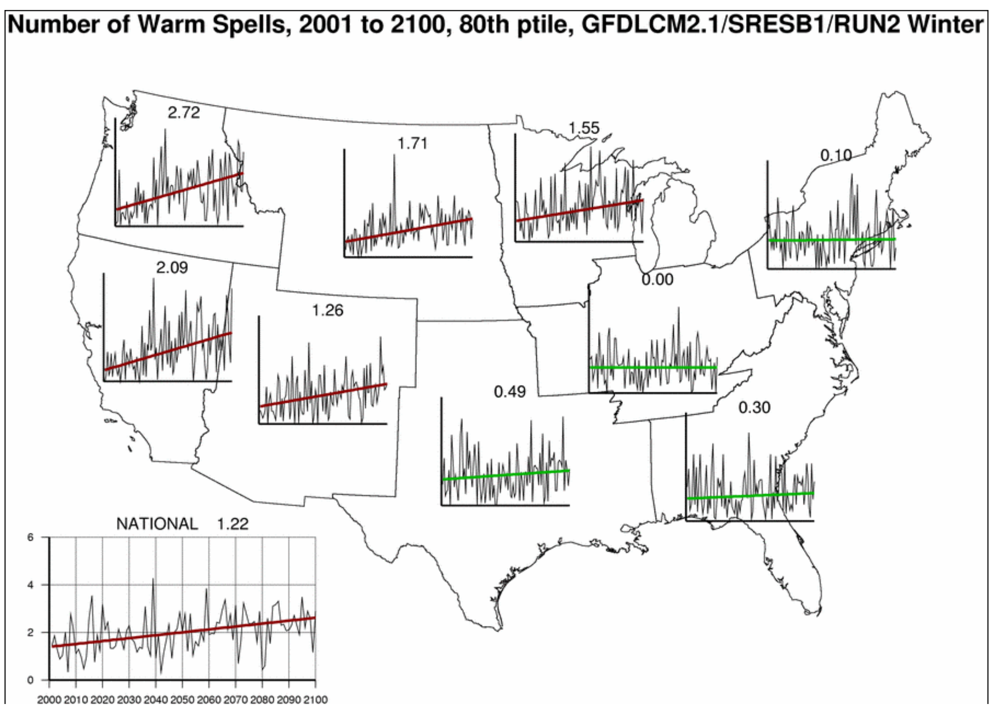


Figure 8. Model projected changes in the number of events using the B1 emissions scenario for Annual and Winter.

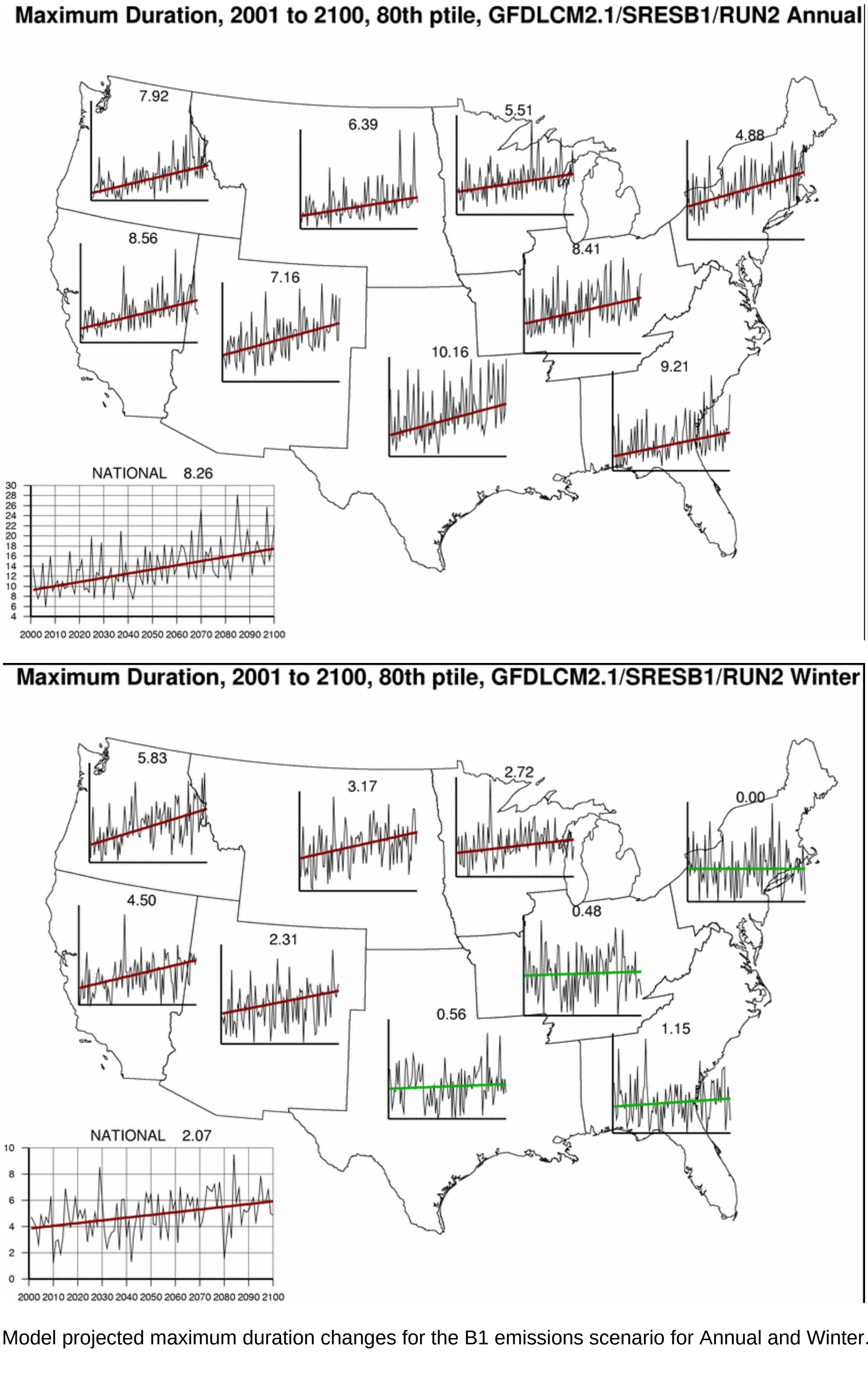


Figure 9. Model projected maximum duration changes for the B1 emissions scenario for Annual and Winter.