# Minnesota Climate in Century 21

**Richard H. Skaggs**

## Introduction

Projections the climate of Minnesota for the remainder of this century must be rather general and include rather large uncertainties. In the absence of known quasi-periodic or predictable variations of the external and internal climate forcing functions, GCMs provide the best means of attempting such projections. But using GCM output poses several problems. GCM output is generated for grid points that are located 200 to 300 kilometers apart requiring downscaling to a spatial scale consistent with the size of Minnesota or the use of one or more grid points in or close to the area of interest. GCM output is usually biased, i.e., the values of climate variables such as temperature and precipitation are systematically overestimated or underestimated when compared with observed values. This requires attempting to remove the bias, a difficult task that goes beyond the resources available for this project. Finally, some 22 GCMs participated in the IPCC 4$^{th}$ assessment. Each of the models provided somewhat different projections for the 21$^{st}$ century depending on such things as the spatial scale of the GCM grid, the initial conditions, the land process model used, the coupling scheme to the oceans used, and the parameterizations of sub-grid-scale processes used. The choices available are to either use a composite of the many models or select an individual model to use. Again the resources available precluded the former approach.

In light of the resources available and the issues identified above, this report presents two projections. The first is of temperature, precipitation, and soil moisture on a monthly time scale for four points representing the northwest (NW), northeast (NE), southwest (SW), and southeast (SE) climatological division of Minnesota. The data are part of the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset and are bias-corrected and spatially downscaled climate projections, which were obtained from the CMIP3 data served at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/, as described by Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy (2007), 'Fine-resolution climate projections enhance regional climate change impact studies', *Eos Trans. AGU*, *88*(47), 504. The specific GCM used is the GFDL CM2.1 as run under the A2 (business as usual) scenario for CO2 change over the century.

The second projection uses the GFDL CM2.1 A2 and B1 (rapid control of CO2) scenarios but for daily data for a grid point that is located close to the Twin Cities metropolitan area. These data are used to estimate projected changes in maximum daily precipitation, annual maximum daily temperature, and annual minimum daily temperature for 10 year and 100 year return periods. The results are based on the Generalized Extreme Value (GEV) distribution. The daily data are not bias-corrected. And it is likely that there is residual bias in the monthly data. Therefore, projected changes and not absolute values are presented for both the monthly and daily data analyses.

## Monthly Data Analyses

The monthly temperature and precipitation data are time averaged over three periods: 1950-99, 2000-49, and 2050-99. The average monthly temperature and precipitation data are input to a Thornthwaite water balance model. The Thornthwaite water balance model output includes calculated monthly evapotranspiration and calculated soil moisture values. Calculation of the soil moisture requires knowledge of the field capacity of the soil that is assumed for purposes of easier comparison to be 200 mm for all four locations within Minnesota. Mean monthly temperature change in degrees Celsius between the 2000-49 averaging period and the 1950-99 averaging period and between the 2050-99 averaging period and the 1950-99 averaging period are shown in the first four graphs at the end of this report. It is clear that the temperature change will be greatest in the second half of the 21$^{st}$ century. Monthly temperature increases in the 2000-49 period are generally less than 2 degrees Celsius and generally well above 2 degrees Celsius in the second half of the century. There is an annual cycle of the monthly temperature increases with the largest increases occurring in the late summer and in the winter. The late summer temperature increases are larger than the winter increases in the southern part of the state but in the northern part of the state the two increases are comparable in magnitude. The late summer peak in temperature increase is very important when combined with the projected changes in precipitation.

Changes in precipitation are shown as per cent change in the next four graphs at the end of this report. Precipitation is projected to increase in most months with peaks of increase occurring in the late fall and early winter and in the spring. However, the months of July, August, and September are projected to have precipitation decreases or little change, which is crucial when combined with the temperature increase peak in the same months. In general, the projected precipitation changes are larger in the second half of the 21$^{st}$ century. Also the projected precipitation changes appear to be more erratic than the projected temperature changes. It is likely that using per cent change is partially responsible, but it also the case that GMCs have a much harder time projecting precipitation.

The combination of the projected late summer increases in temperature and decreases in precipitation is crucial for soil moisture. The higher temperatures imply larger amounts of water loss (evapotranspiration) at the same time water supply is reduced. The last four graphs at the end of this report present the projected per changes in soil moisture. With rare exceptions, soil moisture is projected to decrease throughout the year. And the soil moisture decreases in the late summer are projected to be very large. In general, the soil moisture results demonstrate that the projected increases in precipitation are well short of what are required to offset the projected temperature increases and the associated projected increases in evapotranspiration. The soil moisture changes are shown as constant for four to six months depending on the location, scenario, and time averaging period, as the result of frozen soil.

While these monthly analyses are instructive, they do not provide insight into combinations of months into important seasons. For a look at seasons, we analyzed mean seasonal temperature and total seasonal precipitation for each year, for the two seasons of summer (June, July, and August) and winter (November through March), for the four climatological divisions, and for two carbon dioxide scenarios A2 (business as usual) and B1 (rapid emissions reductions). 20th century means and standard deviations were then calculated. Five categories of temperature and precipitation were constructed for each climatological division and season based on standard deviations from the mean as indicated in this table.

| Limits | Temperature | Precipitation |
|---|---|---|
| -2 sds or greater below the mean | Very Cold | Very Dry |
| -1 to -2 sds below the mean | Cold | Dry |
| -1 to +1 sds around the mean | Normal | Normal |
| 1 to 2 sds above mean | Warm | Wet |
| 2 sds or more above the mean | Very Warm | Very Wet |

For each division and season the value of the boundaries of these categories were determined and the output of the A2 and B1 scenarios results were compared with the critical values to produce a frequency count of seasons in each category, season, and division in 50 year increments from 1950 through 2100.  These frequency counts are contained in the following tables.

## Northwest Division, Summer

| Temperature | Very Cool | Cool | Normal | Warm | Very Warm |
|---|---|---|---|---|---|
| 1951-2000 | 0 | 3 | 28 | 12 | 7 |
| A2: 2000-2049 | 0 | 0 | 7 | 11 | 32 |
| B1: 2000-2049 | 0 | 0 | 6 | 18 | 26 |
| A2: 2050-2099 | 0 | 0 | 0 | 2 | 48 |
| B1: 2050-2099 | 0 | 0 | 1 | 4 | 45 |
| | | | | | |
| Precipitation | Very Dry | Dry | Normal | Wet | Very Wet |
| 1951-2000 | 3 | 8 | 23 | 10 | 6 |
| A2: 2000-2049 | 4 | 6 | 26 | 8 | 6 |
| B1: 2000-2049 | 4 | 4 | 30 | 5 | 7 |
| A2: 2050-2099 | 3 | 9 | 26 | 4 | 8 |
| B1: 2050-2099 | 3 | 7 | 21 | 12 | 7 |

Northeast Division, Summer

| Temperature | Very Cool | Cool | Normal | Warm | Very Warm |
|---|---|---|---|---|---|
| 1951-2000 | 2 | 7 | 33 | 8 | 0 |
| A2: 2000-2049 | 0 | 0 | 16 | 17 | 17 |
| B1: 2000-2049 | 0 | 0 | 16 | 16 | 18 |
| A2: 2050-2099 | 0 | 0 | 1 | 3 | 46 |
| B1: 2050-2099 | 0 | 0 | 3 | 8 | 39 |
| | | | | | |
| Precipitation | Very Dry | Dry | Normal | Wet | Very Wet |
| 1951-2000 | 1 | 6 | 26 | 10 | 7 |
| A2: 2000-2049 | 0 | 8 | 18 | 18 | 6 |
| B1: 2000-2049 | 1 | 9 | 19 | 14 | 7 |
| A2: 2050-2099 | 2 | 9 | 22 | 10 | 7 |
| B1: 2050-2099 | 0 | 9 | 19 | 16 | 6 |

Southwest Division, Summer

| Temperature | Very Cool | Cool | Normal | Warm | Very Warm |
|---|---|---|---|---|---|
| 1951-2000 | 1 | 5 | 36 | 6 | 2 |
| A2: 2000-2049 | 0 | 0 | 14 | 17 | 19 |
| B1: 2000-2049 | 0 | 0 | 19 | 11 | 20 |
| A2: 2050-2099 | 0 | 0 | 0 | 3 | 47 |
| B1: 2050-2099 | 0 | 0 | 3 | 12 | 35 |
| | | | | | |
| Precipitation | Very Dry | Dry | Normal | Wet | Very Wet |
| 1951-2000 | 0 | 10 | 34 | 5 | 1 |
| A2: 2000-2049 | 1 | 10 | 26 | 10 | 3 |
| B1: 2000-2049 | 2 | 9 | 29 | 6 | 4 |
| A2: 2050-2099 | 6 | 10 | 29 | 4 | 1 |
| B1: 2050-2099 | 3 | 4 | 31 | 8 | 4 |

## Southeast Division, Summer

| Temperature | Very Cool | Cool | Normal | Warm | Very Warm |
|---|---|---|---|---|---|
| 1951-2000 | 1 | 3 | 32 | 11 | 3 |
| A2: 2000-2049 | 0 | 0 | 7 | 13 | 30 |
| B1: 2000-2049 | 0 | 0 | 6 | 20 | 24 |
| A2: 2050-2099 | 0 | 0 | 0 | 0 | 50 |
| B1: 2050-2099 | 0 | 0 | 0 | 4 | 46 |
| | | | | | |
| Precipitation | Very Dry | Dry | Normal | Wet | Very Wet |
| 1951-2000 | 0 | 7 | 35 | 8 | 0 |
| A2: 2000-2049 | 2 | 8 | 26 | 13 | 1 |
| B1: 2000-2049 | 1 | 9 | 31 | 6 | 3 |
| A2: 2050-2099 | 7 | 9 | 27 | 6 | 1 |
| B1: 2050-2099 | 3 | 6 | 29 | 10 | 2 |

## Northwest Division, Winter

| Temperature | Very Cool | Cool | Normal | Warm | Very Warm |
|---|---|---|---|---|---|
| 1951-2000 | 0 | 0 | 41 | 7 | 1 |
| A2: 2000-2049 | 0 | 0 | 33 | 13 | 4 |
| B1: 2000-2049 | 0 | 0 | 26 | 16 | 8 |
| A2: 2050-2099 | 0 | 0 | 6 | 18 | 26 |
| B1: 2050-2099 | 0 | 0 | 14 | 20 | 16 |

| Precipitation | Very Dry | Dry | Normal | Wet | Very Wet |
|---|---|---|---|---|---|
| 1951-2000 | 0 | 7 | 36 | 5 | 1 |
| A2: 2000-2049 | 0 | 6 | 38 | 5 | 1 |
| B1: 2000-2049 | 0 | 3 | 33 | 9 | 5 |
| A2: 2050-2099 | 0 | 2 | 27 | 13 | 8 |
| B1: 2050-2099 | 0 | 1 | 38 | 8 | 3 |

## Northeast Division, Winter

| Temperature | Very Cool | Cool | Normal | Warm | Very Warm |
|---|---|---|---|---|---|
| 1951-2000 | 1 | 7 | 33 | 7 | 1 |
| A2: 2000-2049 | 0 | 1 | 23 | 19 | 7 |
| B1: 2000-2049 | 0 | 3 | 17 | 17 | 13 |
| A2: 2050-2099 | 0 | 0 | 1 | 9 | 40 |
| B1: 2050-2099 | 0 | 0 | 6 | 17 | 27 |

| Precipitation | Very Dry | Dry | Normal | Wet | Very Wet |
|---|---|---|---|---|---|
| 1951-2000 | 1 | 7 | 34 | 5 | 2 |
| A2: 2000-2049 | 0 | 7 | 38 | 5 | 0 |
| B1: 2000-2049 | 0 | 5 | 32 | 9 | 4 |
| A2: 2050-2099 | 0 | 2 | 28 | 11 | 9 |
| B1: 2050-2099 | 0 | 7 | 28 | 13 | 2 |

## Southwest Division, Winter

| Temperature | Very Cool | Cool | Normal | Warm | Very Warm |
|---|---|---|---|---|---|
| 1951-2000 | 0 | 9 | 30 | 10 | 1 |
| A2: 2000-2049 | 0 | 1 | 28 | 17 | 4 |
| B1: 2000-2049 | 0 | 3 | 24 | 18 | 5 |
| A2: 2050-2099 | 0 | 0 | 7 | 19 | 24 |
| B1: 2050-2099 | 0 | 0 | 12 | 27 | 11 |

| Precipitation | Very Dry | Dry | Normal | Wet | Very Wet |
|---|---|---|---|---|---|
| 1951-2000 | 0 | 9 | 32 | 6 | 3 |
| A2: 2000-2049 | 0 | 2 | 32 | 9 | 7 |
| B1: 2000-2049 | 0 | 2 | 32 | 12 | 4 |
| A2: 2050-2099 | 0 | 2 | 23 | 15 | 10 |
| B1: 2050-2099 | 0 | 3 | 35 | 9 | 3 |

Southeast Division, Winter

| Temperature | Very Cool | Cool | Normal | Warm | Very Warm |
|---|---|---|---|---|---|
| 1951-2000 | 0 | 9 | 31 | 8 | 1 |
| A2: 2000-2049 | 0 | 1 | 26 | 18 | 5 |
| B1: 2000-2049 | 0 | 3 | 21 | 18 | 8 |
| A2: 2050-2099 | 0 | 0 | 4 | 16 | 30 |
| B1: 2050-2099 | 0 | 0 | 11 | 22 | 17 |

| Precipitation | Very Dry | Dry | Normal | Wet | Very Wet |
|---|---|---|---|---|---|
| 1951-2000 | 0 | 9 | 31 | 7 | 2 |
| A2: 2000-2049 | 0 | 5 | 32 | 9 | 4 |
| B1: 2000-2049 | 0 | 1 | 36 | 10 | 3 |
| A2: 2050-2099 | 0 | 1 | 28 | 9 | 12 |
| B1: 2050-2099 | 0 | 2 | 37 | 9 | 2 |

Conclusions drawn from these tables include:

- The models, after removing the bias, reproduce the 20th century temperature and precipitation regimes as the second half of the century is well known to have been slightly warmer and wetter.
- The summer temperatures in the 21st century, especially in the last half, are projected to be much warmer for all divisions with most of the summer seasons being in the 20th century category of very warm.
- The winter temperature also are projected to be warmer but not to the degree of summer temperatures.
- Precipitation will not change to the degree that temperature changes; the changes are toward slightly wetter conditions but not significantly so.
- The largest changes in both temperature and precipitation occur in the second half of the current century.
- The combination of much high temperatures and little change in precipitation imply that summers will be much drier than was experienced in the 20th century leading to a reduction in lake volume and stream flow and an increase in moisture stress for plants.

**Daily Data Analyses**

The GFDL CM2.1 daily data are for the period 1961 through 2099. Daily time series of maximum temperature, minimum temperature, and precipitation were acquired for the A2 and the B1 scenarios. The total time period was divided into segments: 1961-2000, 2000-49, and 2050-99. Within each time segment and each scenario, time series of the maximum temperature each year, the minimum temperature each year, and maximum daily precipitation each year were extracted. The GEV distribution was fit to each of the 18 time series. It is necessary to express the results as changes rather than absolute values because the input data from the models are biased. In Tables 1 and 2, the 24 hour, 10 year and 100 year return period maximum daily precipitation for the A2 and B1 scenarios are presented. But it is clear that the absolute values for the 1961-2000 base period are underestimates by nearly 50 per cent. Thus it is necessary to focus attention on the per cent increases, which range from about 1 per cent for the B1 10 year return period to about 24 per cent for the B1 100 year return period.

Table 1
24 Hour, 10 Year Return Period

| Period | A2 GEV | Per Cent Increase | B1 GEV | Per Cent Increase |
|---|---|---|---|---|
| 1961-2000 | 49.5 | | 49.5 | |
| 2001-2050 | 55.7 | 11.1 | 49.8 | 0.6 |
| 2051-2100 | 59.8 | 17.2 | 54.4 | 9.0 |

Table 2
24 Hour, 100 Year Return Period

| Period | A2 GEV | Per Cent Increase | B1 GEV | Per Cent Increase |
|---|---|---|---|---|
| 1961-2000 | 64.9 | | 64.9 | |
| 2001-2050 | 70.3 | 7.7 | 66.8 | 2.9 |
| 2051-2100 | 80.3 | 19.2 | 85.4 | 24.0 |

Tables 3 and 4 and Tables 5 and 6 present similar information for annual maximum temperature and annual minimum temperature respectively. Once again the absolute values are biased estimates and focus should be on the differences.

Table 3
Annual Maximum Temperature, 10 Year Return Period

| Period | A2 GEV | Increase | B1 GEV | Increase |
|---|---|---|---|---|
| 1961-2000 | 42.4 | | 42.4 | |
| 2001-2050 | 45.5 | 3.1 | 46.0 | 3.6 |
| 2051-2100 | 51.7 | 9.3 | 48.1 | 5.7 |

Table 4
Annual Maximum Temperature, 100 Year Return Period

| Period | A2 GEV | Increase | B1 GEV | Increase |
|---|---|---|---|---|
| 1961-2000 | 45.6 | | 45.6 | |
| 2001-2050 | 51.2 | 5.7 | 47.8 | 2.2 |
| 2051-2100 | 53.6 | 8.1 | 51.5 | 5.9 |

Table 5
Annual Minimum Temperature, 10 Year Return Period

| Period | A2 GEV | Increase | B1 GEV | Increase |
|---|---|---|---|---|
| 1961-2000 | -38.9 | | -38.9 | |
| 2001-2050 | -36.9 | 2.0 | -39.6 | -0.7 |
| 2051-2100 | -32.4 | 6.5 | -34.7 | 4.2 |

Table 6
Annual Minimum Temperature, 100 Year Return Period

| Period | A2 GEV | Increase | B1 GEV | Increase |
|---|---|---|---|---|
| 1961-2000 | -43.3 | | -43.3 | |
| 2001-2050 | -40.5 | 2.8 | -45.3 | -2.0 |
| 2051-2100 | -36.7 | 6.6 | -37.1 | 6.2 |

An approximation of the absolute values can be obtained by applying the changes in the tables above to observed data for the Twin Cities. The full 20th century records for annual maximum temperature, annual minimum temperature, and annual daily precipitation were analyzed by fitting the GEV to the appropriate annual time series. The differences were then applied to the results for the observed 20th century climate (Tables 7, 8, and 9).

Table 7
Annual Maximum Temperature

| | 10 Year Return Period | | 100 Year Return Period | |
|---|---|---|---|---|
| | A2 | B1 | A2 | B1 |
| 20th Cent. | 38.9 | 38.9 | 41.1 | 41.1 |
| 2001-2050 | 42.0 | 42.5 | 46.8 | 43.3 |
| 2051-2100 | 48.2 | 44.6 | 49.2 | 47.0 |

Table 8
Annual Minimum Temperature

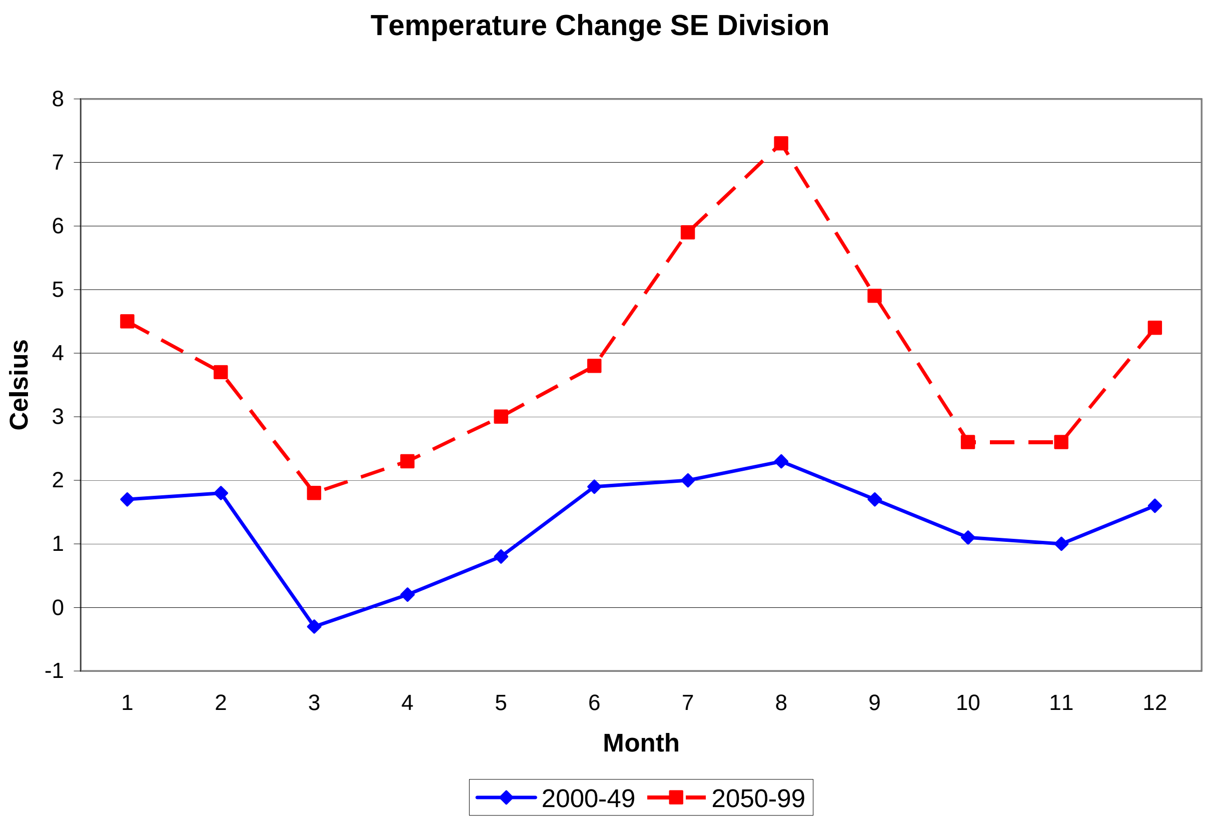
| | 10 Year Return Period | | 100 Year Return Period | |
|---|---|---|---|---|
| | A2 | B1 | A2 | B1 |
| 20th Cent. | -34.2 | -34.2 | -36.8 | -36.8 |
| 2001-2050 | -32.2 | -34.9 | -34.0 | -38.8 |
| 2051-2100 | -27.2 | -30.0 | -30.2 | -30.6 |

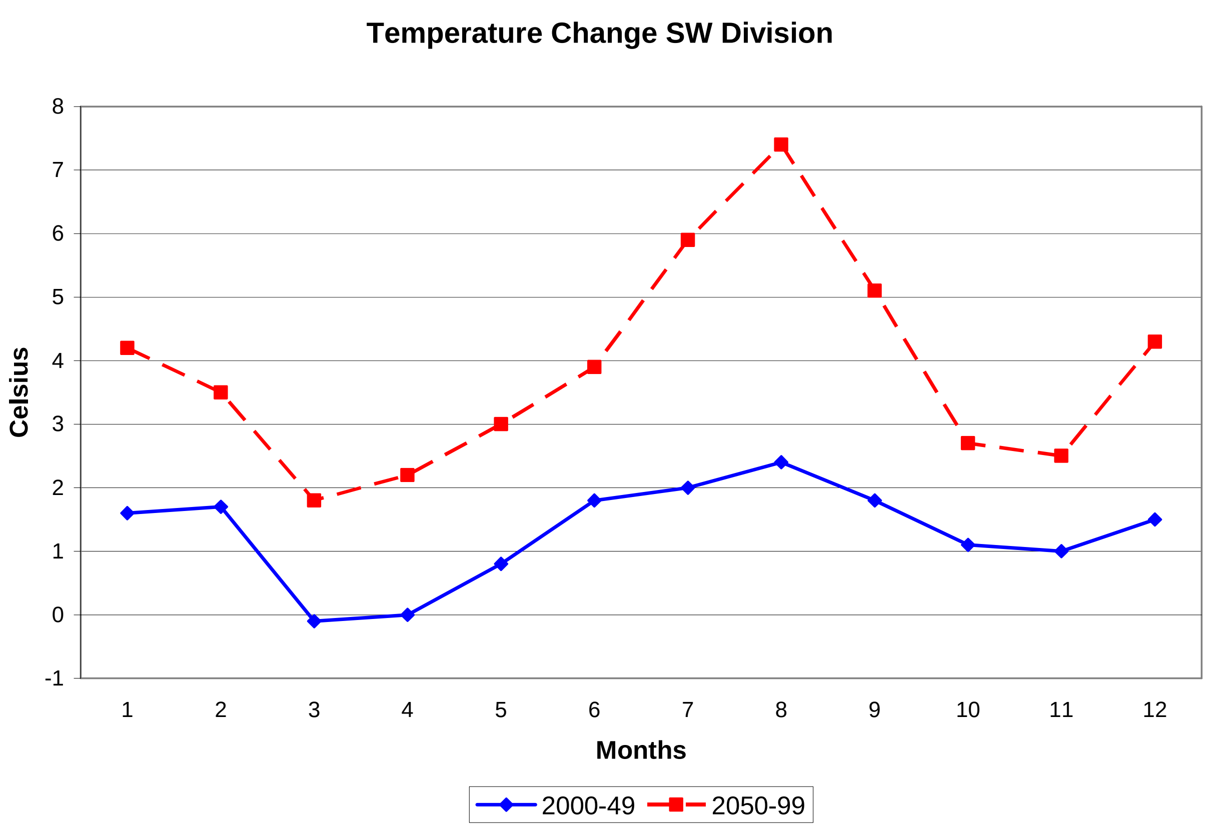
Table 9
Annual Maximum Precipitation

| | 10 Year Return Period | | 100 Year Return Period | |
|---|---|---|---|---|
| | A2 | B1 | A2 | B1 |
| 20th Cent. | 87.9 | 87.9 | 155.5 | 155.5 |
| 2001-2050 | 97.7 | 88.4 | 167.5 | 160.0 |
| 2051-2100 | 103.0 | 95.8 | 185.4 | 192.8 |

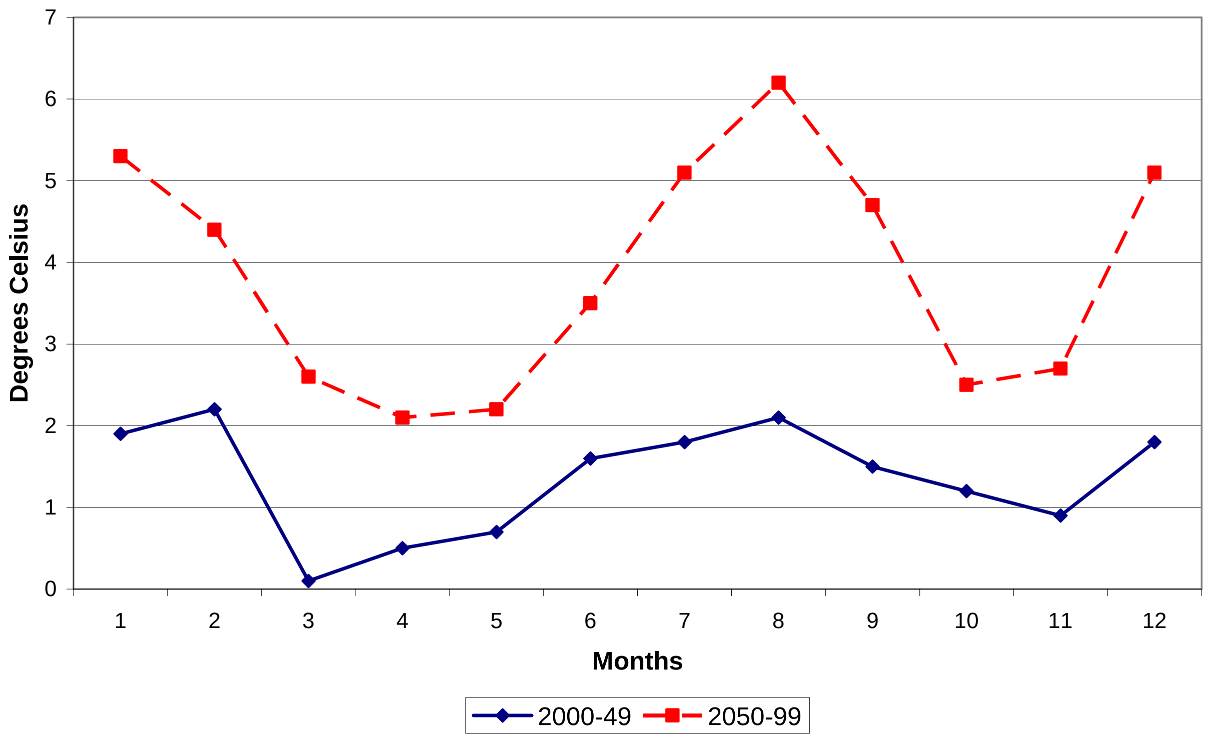
**Summary**

The broad outlines of the likely climate of Minnesota over the remainder the 21st century as projected by a particular GCM (GFDL CM2.1) seem relatively clear. The temperature will be warmer especially in the second half of the century and the late summer and winter. Precipitation will increase marginally except in the late summer. The combined temperature and precipitation changes likely will lead to decreases in available soil moisture and a general drying of the climate. The magnitude of maximum temperature extremes will increase while the coldest days are likely to be warmer. Precipitation in extreme events such as the 100 year storm will be larger.


Temperature Change SE Division
Celsius
8
7
6
5
4
3
2
1
0
-1
1
2
3
4
5
6
7
8
9
10
11
12
Month
2000-49
2050-99


Temperature Change SW Division
Celsius
8
7
6
5
4
3
2
1
0
-1
1
2
3
4
5
6
7
8
9
10
11
12
Months
2000-49
2050-99

**Temperature Change NW Division**

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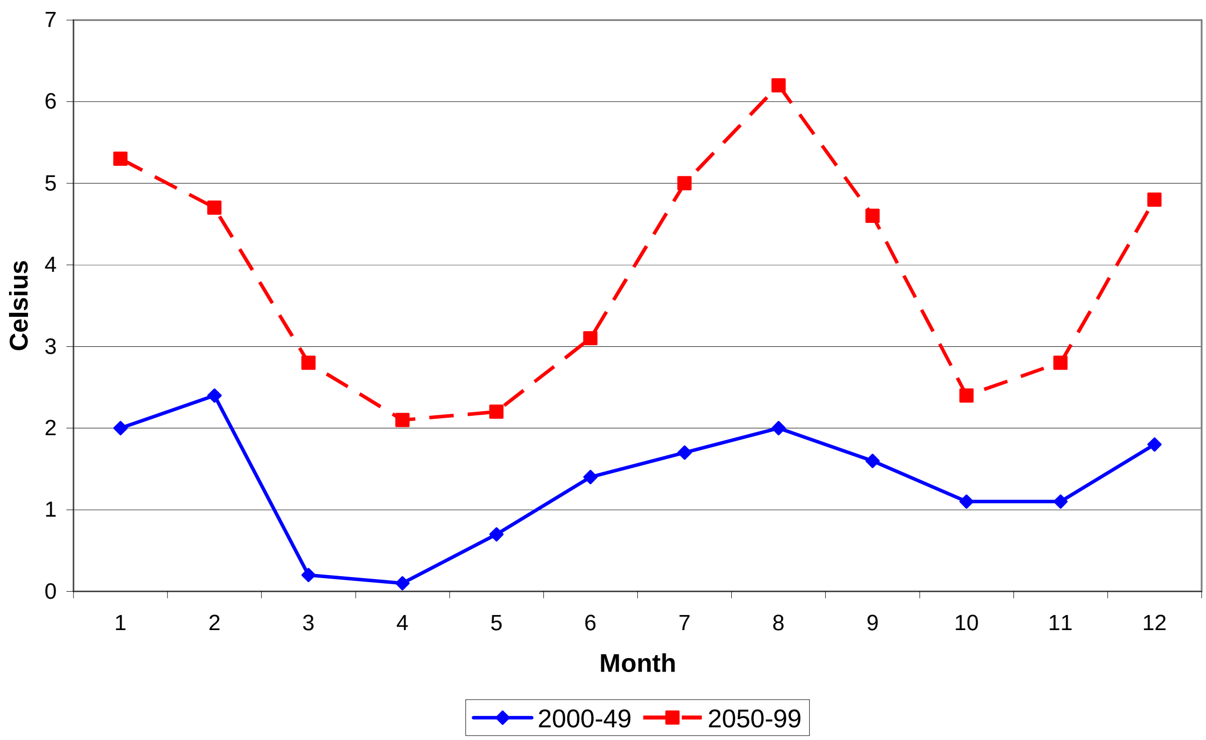

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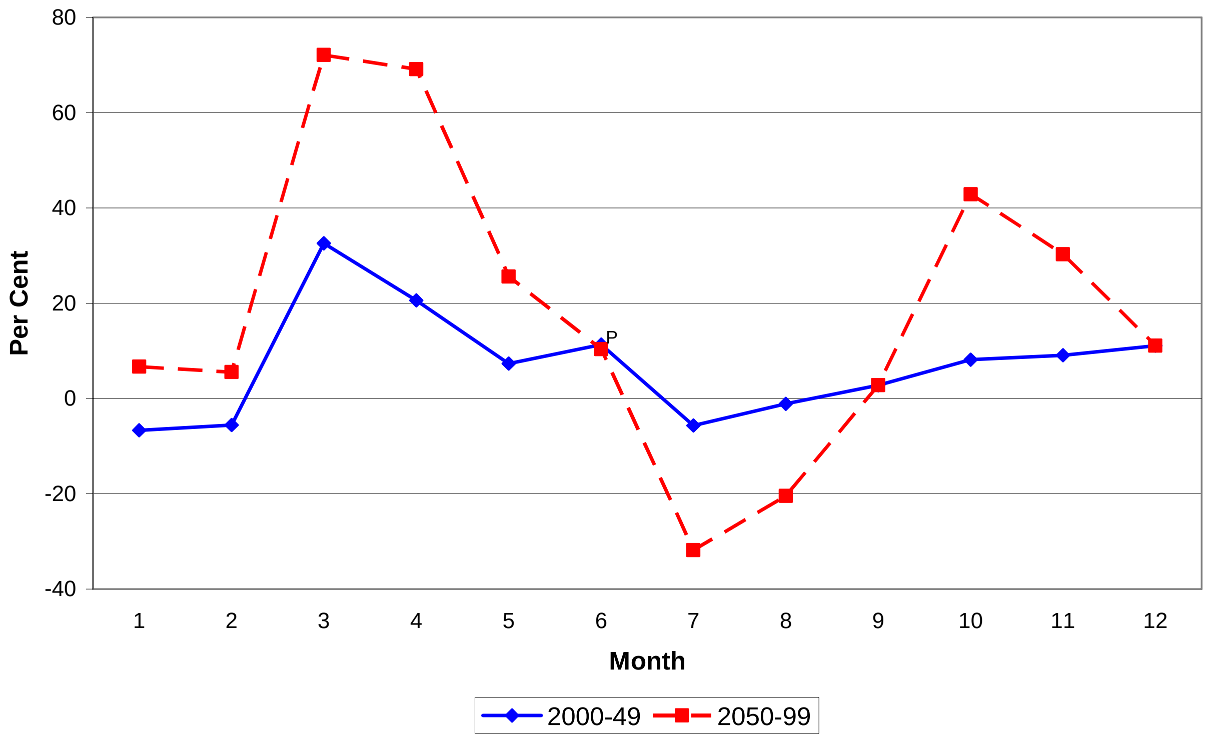


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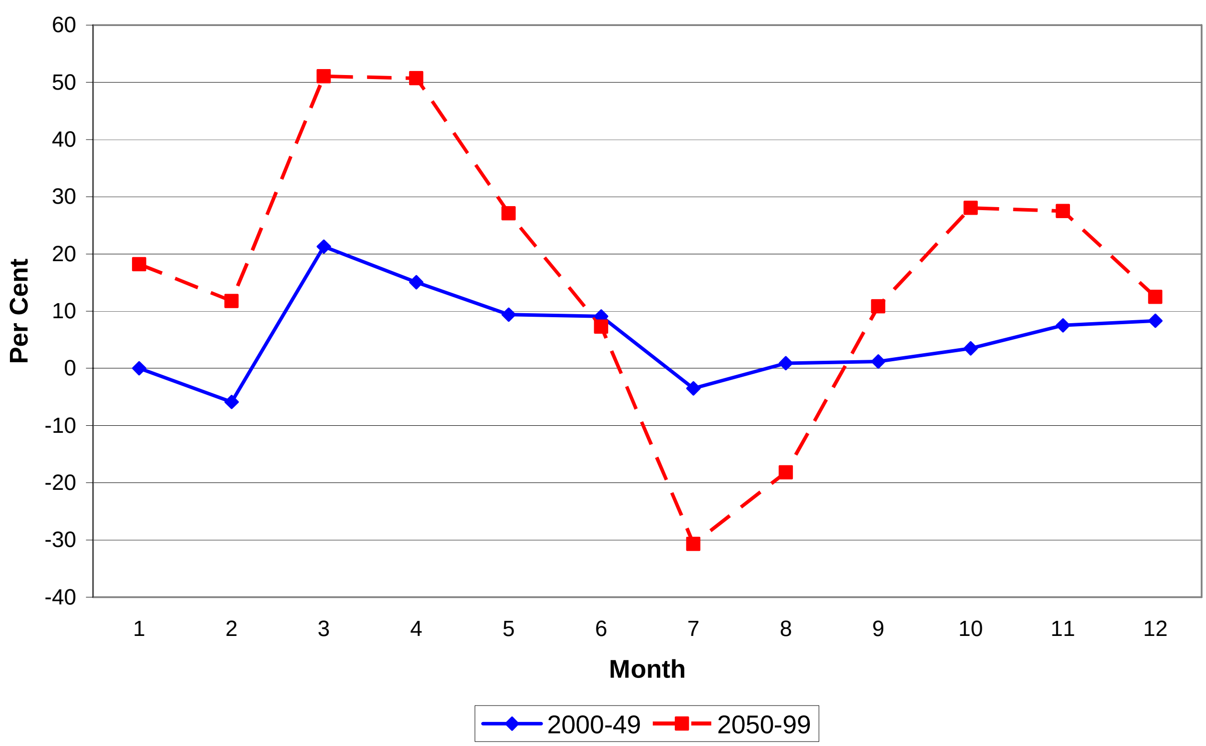
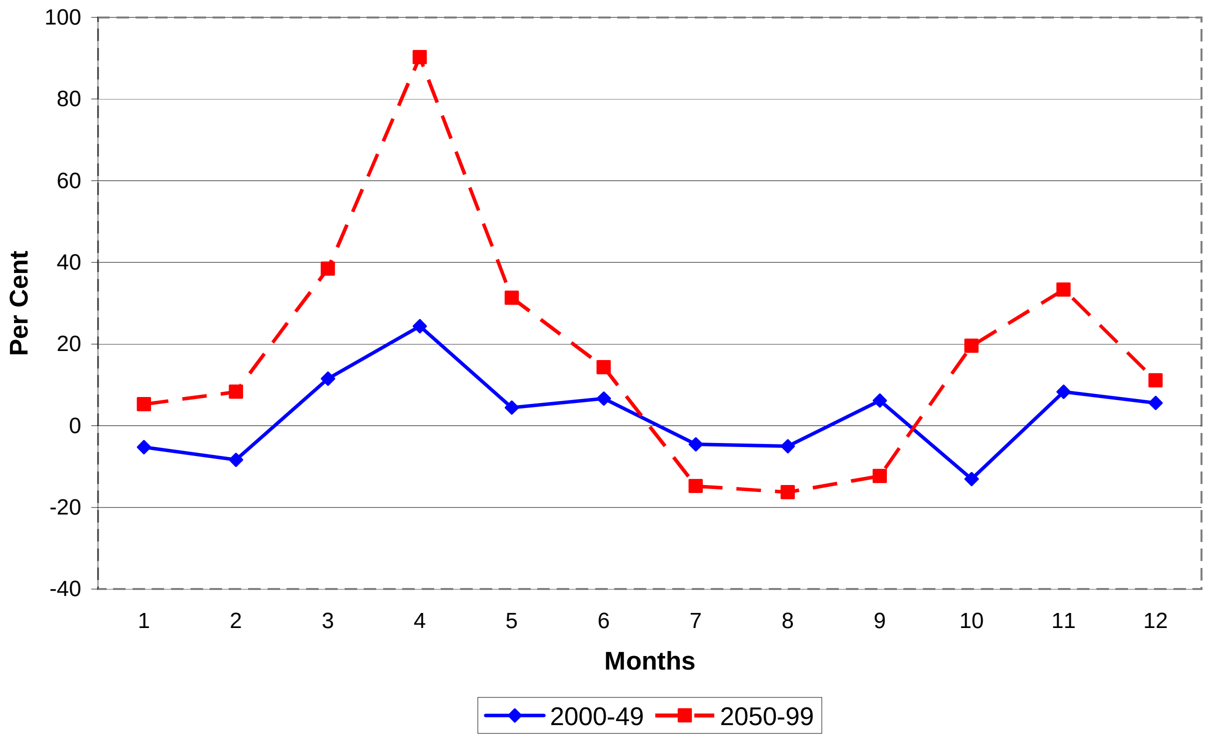


## Precipitation Change NW Division

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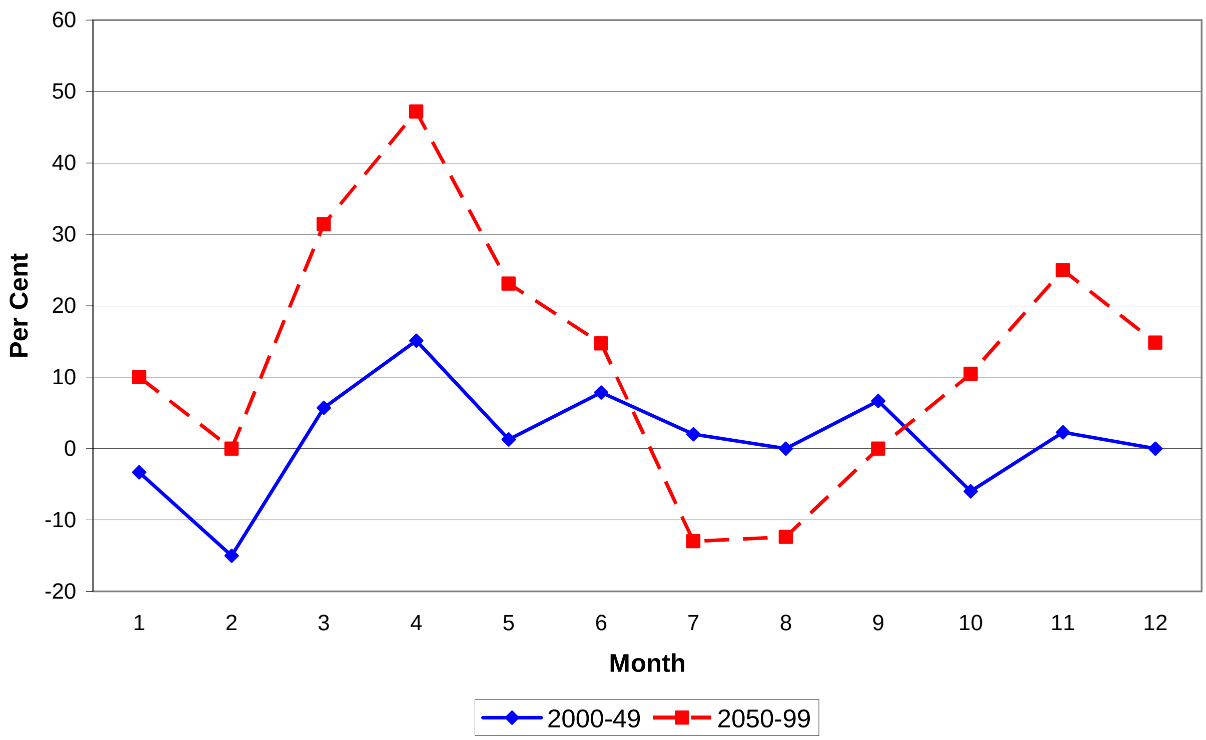
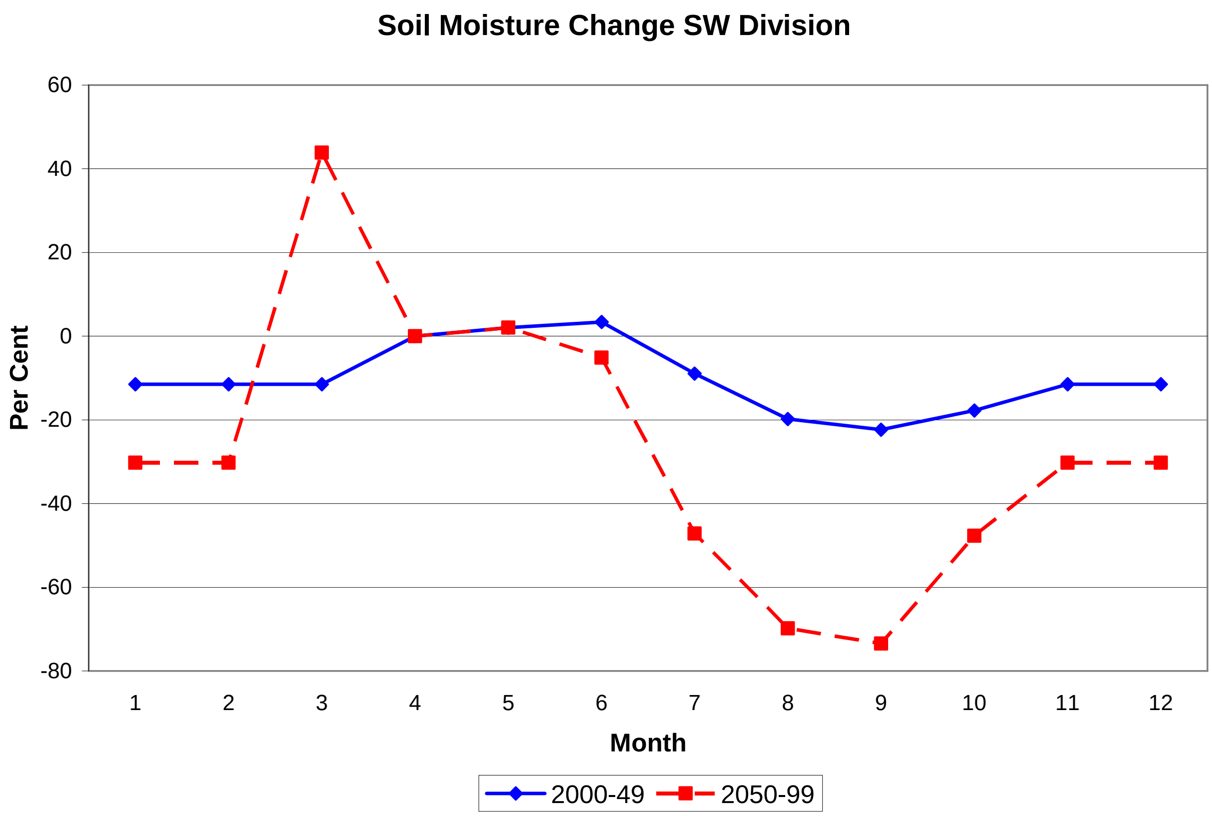
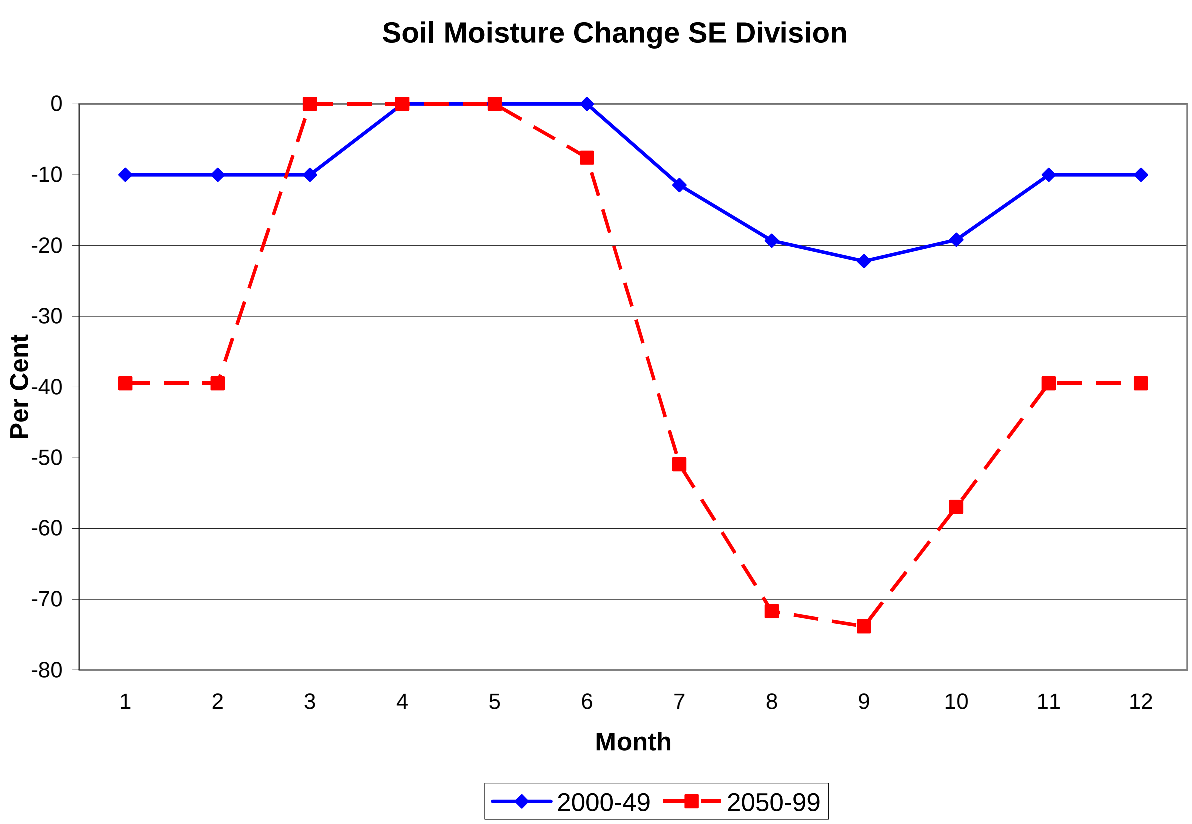
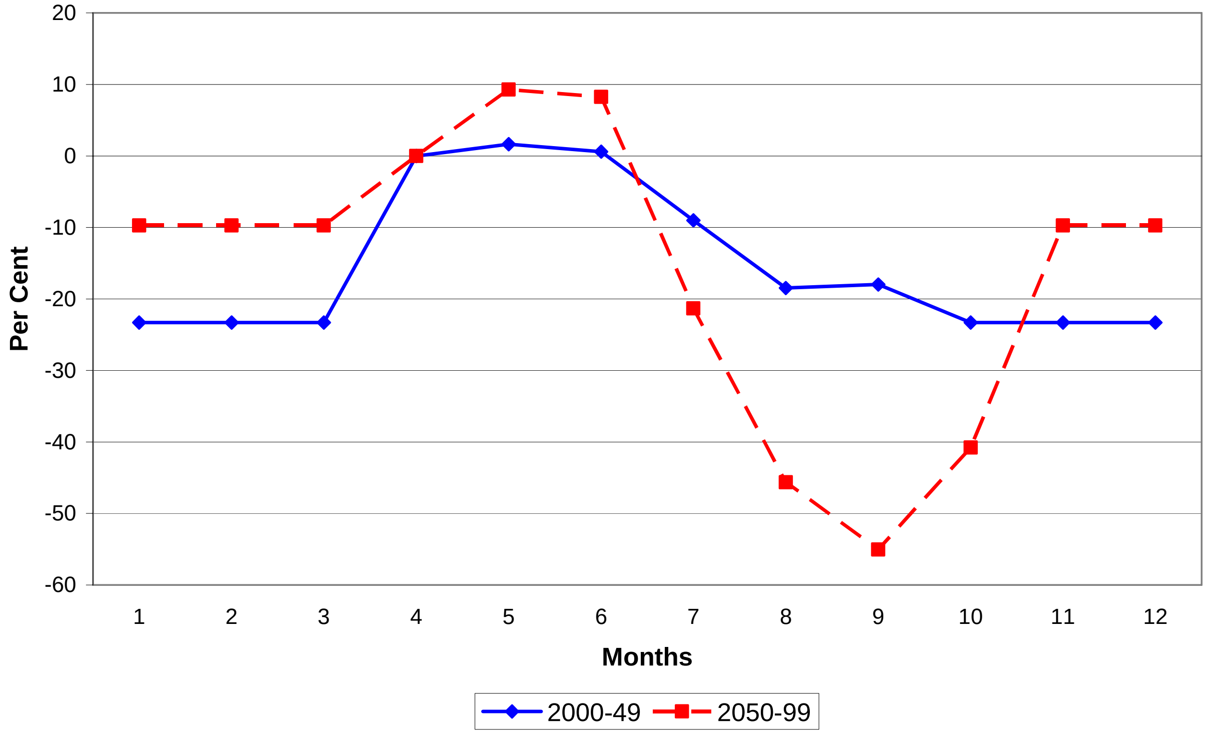



Soil Moisture Change SW Division
60
40
20
0
-20
-40
-60
-80
Per Cent
1
2
3
4
5
6
7
8
9
10
11
12
Month
2000-49
2050-99


Soil Moisture Change SE Division
0
-10
-20
-30
-40
-50
-60
-70
-80
Per Cent
1
2
3
4
5
6
7
8
9
10
11
12
Month
2000-49
2050-99

Soil Moisture Change NW Division




Soil Moisture Change NE Division