THE EFFECTS OF CLIMATE VARIABILITY AND "GREENHOUSE EFFECT"-- SCENARIOS ON MINNESOTA'S WATER RESOURCES

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Abstract

We examined the sensitivity of Minnesota's water resources to predicted climate changes due to global warming. Statistical models, for the current climate, of the relationship between seasonal moisture surplus (Thornthwaite water budget method) and seasonal river discharge were built for nine watersheds in Minnesota. Global Climate Model predicted temperature changes and precipitation ratios were used to adjust the observed climatic record. The moisture surplus values were recalculated for this doubled CO_2 world and became the predictor variables in the statistical models.

The results indicate a general and substantial decrease in river discharge. However, there is great spatial variation in the magnitude of the decrease. Mean annual discharge decreases ranged from 0.3% for the St. Louis River to 18% for the Blue Earth River. The individual annual discharges were about evenly split between increases and decreases for the St. Louis River while there were only four years (out of 47) with increased discharge for the Blue Earth River. All nine basins showed increased discharge during the first season (three months) of the year largely because increased temperatures shifted the snow melt period to an earlier month. The second season (April through June) had most extensive and largest decreases. In the third season (July through September) decreases were large (13% to 31%) for the southern and central river basins but were modest (2% to 7%) for the northern basins. During the last three months of the year, five basins had increased discharge and four basins, especially the Mississippi at both Anoka and St. Paul, had decreases. Thus, the southern and central portions of Minnesota would experience substantial decreases in discharge but the northern third of the state would see only modest decreases.

Introduction

Human induced climate change is a topic of national and international concern at the present time. Predictions of global warming because of increases in carbon dioxide and other "greenhouse" gases have substantial implications for water resources. It is essential that the sensitivity of the water supply to climate fluctuations be assessed so that proper preparations can be made. The transportation industry, the recreation industry, agriculturalists, and those responsible for our municipal water supply and waste disposal systems need such information.

This project provides information on evapotranspiration, water surplus, and soil moisture under conditions of global warming. From these parameters, estimates of the changes in river flow, lake levels, and well levels to be expected with global warming will be made.

Historical data on the water supply variables of stream flow, well level, and lake levels were collected. We identified nine river/watersheds completely within Minnesota suitable for establishing statistical relationships between climate variables such as temperature, precipitation, or water balance surplus and river flow. These watersheds were chosen based upon several critical factors which include the length and quality of the record, the absence of dams or other flow controls, the spatial distribution of the watersheds within the state, and the size of the watersheds.

Observation well data were collected for every well in the state with a period of record longer than 20 years. A sample of four wells were chosen for analysis. The selection of these wells was based upon another set of requirements since water level fluctuations can be the result of many natural or man-made hydrologic phenomena. In addition to length of record, proximity to highly populated areas (to reduce or avoid the effects of seasonal pumping for irrigation and cooling), aquifer type, depth of the well, and geographic distribution were all examined.

Lake level was the last water supply variable used. The majority of the lakes in Minnesota have very short periods of record or have man-made outlet controls. A short period of record is particularly important since it becomes impossible to build a reliable statistical model of the response of lake level to climatic fluctuations (change in water surplus) since many of the important climatic events (droughts, excessive wet periods, temperature extremes) have occurred prior to the level measurements on the lakes. Additionally, the presence of man-made controls can confound any detectable natural response in lake level due to the influence of climate. For these reasons only two lakes were analyzed: Lake Minnetonka, located in east central Minnesota, and Vermilion Lake which lies in the northeastern part of the state. Lake Minnetonka was formed by a number of ice blocks which created a series of interconnected basins within a terminal moraine. Vermilion Lake is a bedrock basin formed by glacial erosion and was partially dammed by glacial drift along the southern edge of the basin. These lakes are similar in that they have relatively flat basins with swamp and marshland surrounding them. Additionally, both lakes have a dam at their outlet. At the time of acquisition, the available data for Vermilion Lake was November 1950 through November 1990, while for Lake Minnetonka, the data began in June 1906 and ended in February 1991.

From the observed temperature and precipitation data, the Thornthwaite water balance was calibrated and computed from 1900 through 1989. The water surplus term in the Thornthwaite water balance was used as an independent variable in building statistical models of stream flow, lake level, and well level. Background information on Thornthwaite's method can be found in Appendix A.

The global climate model predictions of temperature and precipitation for an atmosphere with doubled carbon dioxide ($2xCO_2$) for grid points near the location of Minnesota provided an estimate of the likely increase in mean monthly temperature and change in total monthly precipitation. These changes were added to the observed climate record and the Thornthwaite water balance recalculated. These results were then used in the previously developed statistical models to estimate the effect of global warming on water resources in Minnesota.

Data Analysis and Statistical Models

Initially, we statistically modeled the relationship between both mean monthly and mean annual river flow and moisture surplus using climatological divisional weather data for several of the watersheds. Results from six cases indicated that a very good relationship exists between mean flow and the moisture surplus of the same month for watersheds ranging in size from about 140 to 19,000 square miles. Due to the problems of statistically modeling data with serial correlation, the monthly analyses were deemed inappropriate. The advantage of the annual models was the lack of temporal dependence. Comparing the two sets of models, those using annual data generally fit better than those using the monthly data. Unfortunately, the annual models did not provide enough resolution to allow any analysis for time periods less than one year, such as interannual variability on a seasonal basis.

Even though these were not the final models, they did yield some interesting observations. We found that watersheds having small areal extent, in relation to the climatological division in which they lie, have mean flows that are not representative of the moisture surplus conditions calculated for the division as a whole. This was especially true for the annual model on the Baptism River, which has the smallest area, covering only 140 square miles. When using monthly data, the highest correlations occurred in the watersheds of smallest areal coverage. We believe that this result comes from the greater likelihood that flows in a smaller watershed respond mostly to the concurrent monthly surpluses. In the larger watersheds, moisture surpluses from earlier months, lag effects, which were later investigated thoroughly, would influence the mean monthly flow to a greater degree.

These results indicated that for the smaller watersheds, the use of divisional data may not be appropriate for statistical modeling. In spite of this, it was clear that both mean monthly and mean annual flows were very closely related to the computed water surplus. These fitted statistical models were sufficiently accurate and robust to serve as an additional verification of the validity of the modeling technique as well as to allow a first approximation of the effects of doubled carbon dioxide on river flow.

The initial analyses under conditions of $2xCO_2$ were made for divisions 3 and 7 (northeast and southwest Minnesota). The northeast and southwest divisions represent the extremes in climatic variables within the state. The temperature change estimates were taken from global climate model (GCM) predictions (Jenne, 1988), while the precipitation values used were those for the current climate.

The results under these conditions showed a marked decrease in soil moisture and moisture surplus. For example, in the northeast, the average decrease in soil moisture was about 25% with a peak in August of about 55%. At the extreme, in division 7 (southwest), the annual mean reduction in soil moisture was between 40-45%, with nearly a 60% decrease during the three month period from August through October.

The $2xCO_2$ surplus values were then used as predictor variables in the previous models that showed the relationship between both mean monthly and mean annual river flow and moisture surplus. Again, it was clear that under this new climate, the predicted impact on river flow is profound. For the Cottonwood River, the predicted mean decrease is approximately 48% with a maximum estimated drop of nearly 90%. While in the St. Louis River system, the estimated mean decrease in river flow was about 44% with a maximum decline estimated around 85%.

To avoid the problems in using the averages computed over the area of a climatological division, we tried to reduce the area that was represented by the average by gathering data for individual observation sites in and around the selected watersheds. However, weather stations are irregularly spaced and often quite sparse or nonexistent within a particular watershed. In addition, missing data were common in some of the records. Because of these difficulties, we decided to grid the entire state for temperature and precipitation on a monthly basis for the period 1890 through the present. The gridding procedure was accomplished using the SURFER program from Golden Software (1987). This process created a regularly spaced grid of temperatures and precipitation from the irregularly spaced data. The interpolation method used was based on kriging using a quadrant search method. This search method specifies that the original data points used to estimate a particular grid element be found by dividing the area around that grid element into four quadrants. The nearest *n* points (specified by user) are found within each quadrant around the point being estimated. This is constrained by the user specified 'search radius' and the 'number of nearest points'. If there are fewer than *n* points in a quadrant, the program will use the points that are available.

The grid spacing for these data sets is approximately nine miles by nine miles for the entire state. The development of such a detailed gridded precipitation and temperature data set for such an extended period of time should be of substantial value. When averaged over the area of the watershed, the estimated means for the gridded data will be more representative and precise than we could achieve trying to take a weighted average of the few stations available per watershed.

Enhancements were added to the gridding procedure to take advantage of Minnesota's high density data set that began in the 1950s (includes networks such as the Metropolitan Mosquito Control District, Soil Water Conservation District, DNR Forestry Offices and Future Farmers of America) which extends well beyond the coverage of the National Weather Service network. For the temperature data, adjustments were made for "time of observation" differences each month before gridding. An example of a gridded precipitation map is shown for July 1987 (Figure 1).

At the conclusion of the earlier modeling attempts, we were able to acquire flow data for three more watersheds which expanded our coverage into the southeastern, south central, and western parts of the state (Fig. 2). With all nine models built with concurrent data, we then began to investigate the importance of surplus lag effects on the fit of the models. In all cases, moisture surplus at one or more lags proved to be significant. While the models using monthly data indicated that a very good relationship existed between moisture surplus and river flow for all nine river/watersheds, we again encountered significant violations of the underlying assumptions of regression. As before, the most important of which was temporal autocorrelation in the residuals. Thus, it was concluded that using monthly data was again not appropriate and that seasonal data should be examined. The seasonal data would have less temporal dependence than the monthly data and would still provide useful information that could not be found using the annual models (such as seasonal variability).

The monthly data were grouped into season categories (or periods) based on the water year (October - September). These seasons or periods that are defined here are not meant to be taken in the traditional sense of the word. The two terms (season and period) can be used interchangeably. They simply show that the data have been clustered into groups for the express purpose of facilitating statistical analysis and in no way implies the creation of "new seasons", which could be confusing especially when dealing with the predicted conditions in a doubled CO_2 world. The first season consists of the months of January, February, and March; season 2 uses April, May, and June; season 3 uses July, August, and September; and season 4 is composed of October, November, and December. The models were recomputed using total seasonal surplus and mean seasonal river flow. In all cases they showed a strong

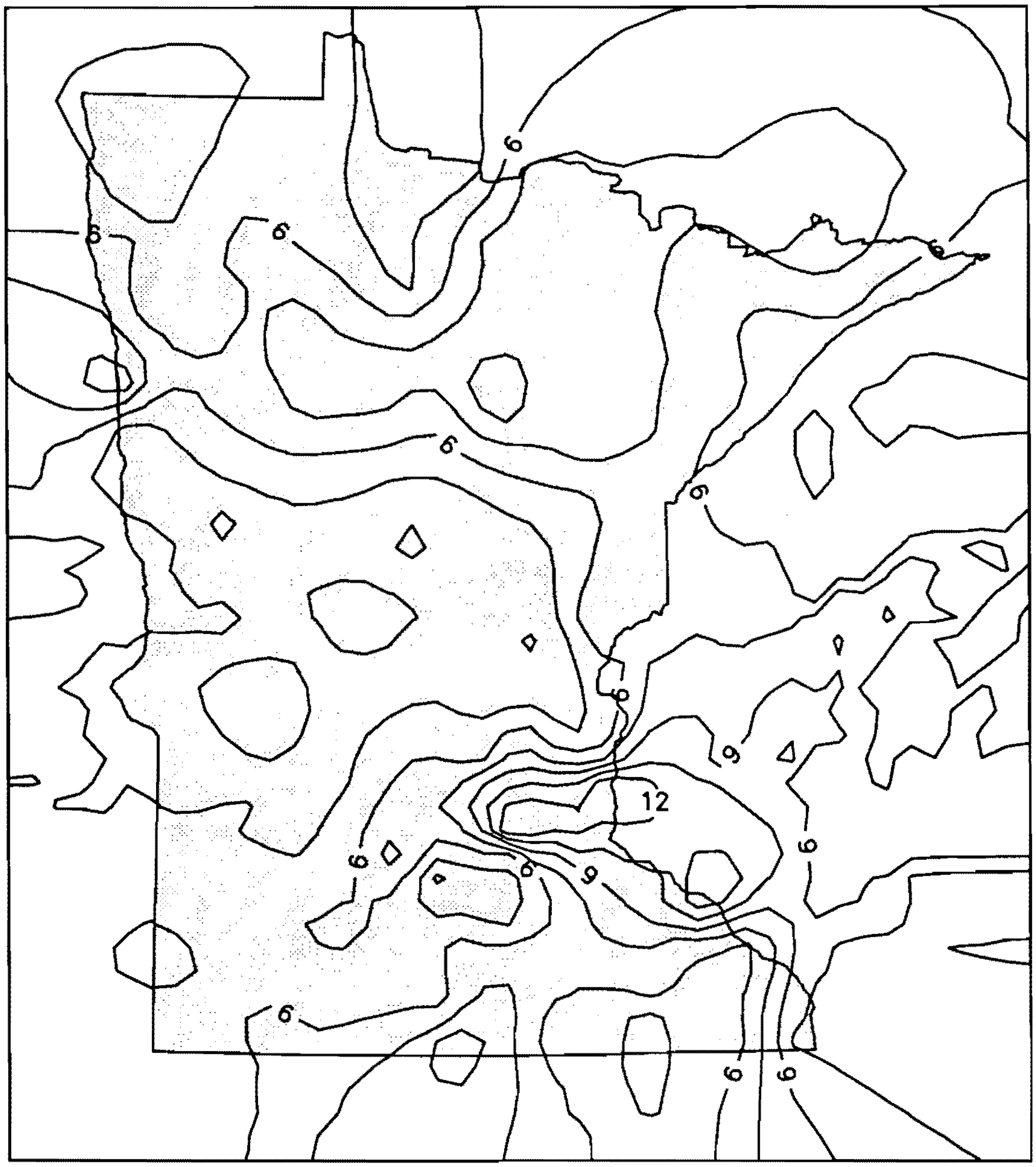


Figure 1. Gridded precipitation data, July 1987.

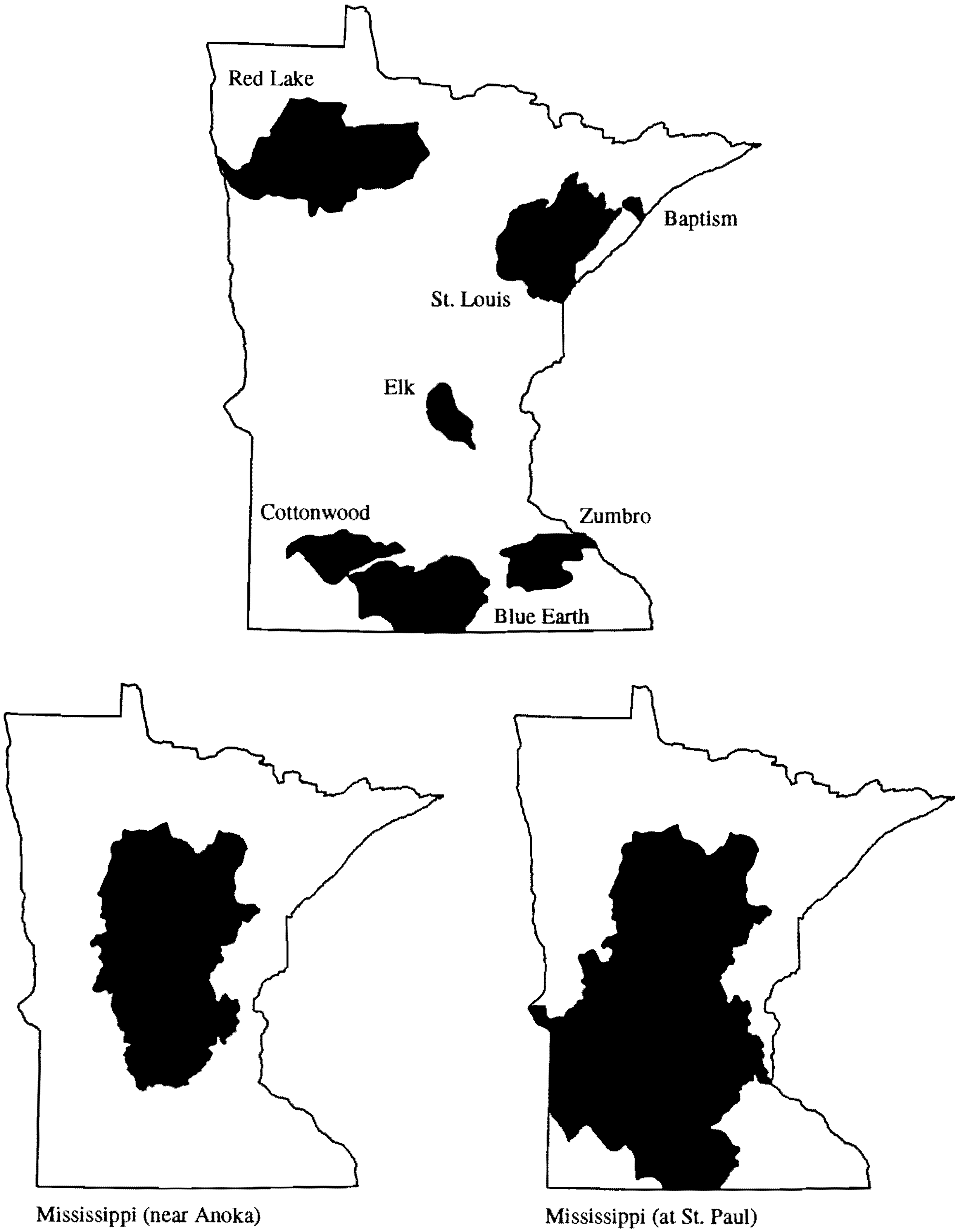


Figure 2. Nine selected model watersheds.

relationship. The assumptions were reexamined and showed marked improvement; no significant violations were found. We, therefore, concluded that the seasonal level of analysis was most viable for the entire river flow portion of the study.

The above models were built using surpluses based on a climatological division, i.e., monthly values of average temperature and total precipitation for each division were used to compute the surplus values. This meant that the surplus values were used as predictor(s) in the models even if the watershed(s) covered only a portion of that division. In other words, areas that did not lie within the drainage basin of the watershed could be of potential influence. During the initial analyses we saw that this appeared to be an important consideration. Conceptually, it seems better to compute surpluses based on the climatological variables measured within the area that the gaging station is measuring. Therefore, we proceeded to build the models on a watershed level.

We used the set of gridded monthly temperature and precipitation data and accessed it by using the CLIMON program that was developed by the State Climatology Office. Using a newly added feature of the program, we were able to specify a watershed or combination of watersheds and have the mean temperature and precipitation values computed over that area alone on a monthly basis for the entire period of record (1890-1988). The original grid spacing was approximately nine miles, but for the averaging procedure a finer mesh of three miles was selected to facilitate in the interpolation to the watershed boundary. In most cases, the watershed desired could be easily specified within the CLIMON program. However, watersheds like the Baptism and the Elk River are actually sub-watersheds of the major watershed units upon which the program was designed. Therefore, obtaining estimates over these small areas would have been extremely difficult to acquire. The Elk River Watershed basin is the eastern half of the Mississippi River (St. Cloud) Watershed and is divided by the Mississippi River itself. The Baptism River Watershed is situated near the border between the Lake Superior (north) and the Lake Superior (south) Watersheds. A random sample of precipitation gridded values were taken for each of the Lake Superior watersheds and compared to an average estimated roughly over the Baptism River basin by using the closest weather stations. The mean deviation of the gridded values from the observed average were -0.04 inches for the northern basin and -0.01 for the southern basin. Due to the small estimation errors, it was decided that the Lake Superior (south) Watershed basin could be substituted for the Baptism River Watershed basin for the temperature and precipitation averaging procedure. Similar results were found for the Mississippi River (St. Cloud) and the Elk River basins and the substitution was made.

The two Mississippi watersheds each cover a large portion of the state and cover regions with different climatic characteristics. To help isolate any geographical/climatic influence within the statistical models, each of these watersheds was divided into groups. The Mississippi River near Anoka was divided into Mississippi Upper and Lower. To these divisions were added the Minnesota West and Central for the Mississippi River at St. Paul. For each of these separate groups, grid averaged temperature and precipitation were computed which were then used to calculate the water budgets. In a later part of this report, the analysis of the computed soil moisture and water surplus are examined using these groups.

To assess the accuracy and value of the gridded data, we examined the difference between the average computed over the watershed through gridding with that produced by averaging the irregularly spaced observation stations from the National Weather Service network that lie within the boundaries of the watersheds. Unfortunately, many smaller watersheds have few, if any, stations within the drainage basin, so nearby ones had to be used. This lack of climatological data within many of the study areas was the primary reason for taking the time to grid these data sets at the outset of this project.

The results of this analysis showed that the gridded average was a superior estimate of the climatic conditions existing over the watershed as a whole. This was especially apparent in the case of precipitation, since rainfall can be a highly localized phenomenon, particularly during the convective precipitation season. An example of this is shown in Figure 3 from the Le Sueur Watershed Basin in south central Minnesota for the April - October period of 1935. The large variability in precipitation can be clearly seen between Waseca and Mankato, the two stations that lie within this watershed (Fig. 3b). In August of that year 4.26 inches fell at Mankato while less than 30 miles southeast, 10.11 inches were recorded at Waseca. This total at Waseca was 6.41 inches above normal and more than three inches greater than the next wettest station in all of south central and southeastern Minnesota. Extreme values such as this will exert a large influence when they are used in the computation of the mean. This effect is illustrated in Figures 4a and b. Figure 4a shows the difference between the three-station mean (two inside the watershed and one outside) and the grid mean. The influence of Waseca is seen as a peak in the monthly deviation of the grid mean from the station mean as seen in Figure 4b. In this case, with so few stations actually inside the drainage basin, a watershed precipitation average based on existing stations alone would likely be an overestimation. Similar results were found for other watersheds.

Accepting the temperature and precipitation series produced through gridding, the water budgets were recomputed using the Thornthwaite method (as used in the initial divisional water budgets) and the statistical models rebuilt. Table 1 shows the regression correlation coefficients as well as the selected model variables (seasonal models using watershed data).

The comparison of the seasonal models using divisional data versus the seasonal models using watershed data (not shown) revealed that within five of the nine cases, the watershed based model showed improved fit and within six of the nine, the degree of autocorrelation decreased. For example, the autocorrelation decreased by 76% for the Mississippi River (measured as St. Paul), by 41% for the Mississippi River (measured near Anoka), and by 73% for the Zumbro River. As noted before, it was the violation of the autocorrelation assumption that primarily necessitated the move from monthly to seasonal models. We decided that the best models were those using the watershed-based surpluses. These models will be used later in this study to determine the estimated changes in river flow under conditions of doubled CO_2 ($2xCO_2$).

Table 1: Regression correlation coefficients and model variables for each basin. The independent variables are seasonal moisture surplus (S) and the numbers represent the lag; e.g., S3 means surplus three seasons earlier. The Mississippi River basin was divided into four regional groups; upper and lower halves (U and L) for the portions above Anoka, and west and central halves (W and C) for the Minnesota River which contributes to the Mississippi measured at St. Paul. Correlations between these variables appear in Appendix B.

River/Watershed	Correlation Coefficient	Model Variables
Baptism	0.909	S0, S3
Blue Earth	0.877	S0, S1
Cottonwood	0.806	S0, S1
Elk	0.858	S0, S1
Mississippi (Anoka)	0.874	SU0, SL1, SL2, SL3, SU4
Mississippi (St. Paul)	0.846	SC0, SL1, SL2, SU4
Red Lake	0.841	S0, S1, S2, S3, S4
St. Louis	0.918	S0, S1, S2
Zumbro	0.785	S0, S1, S3

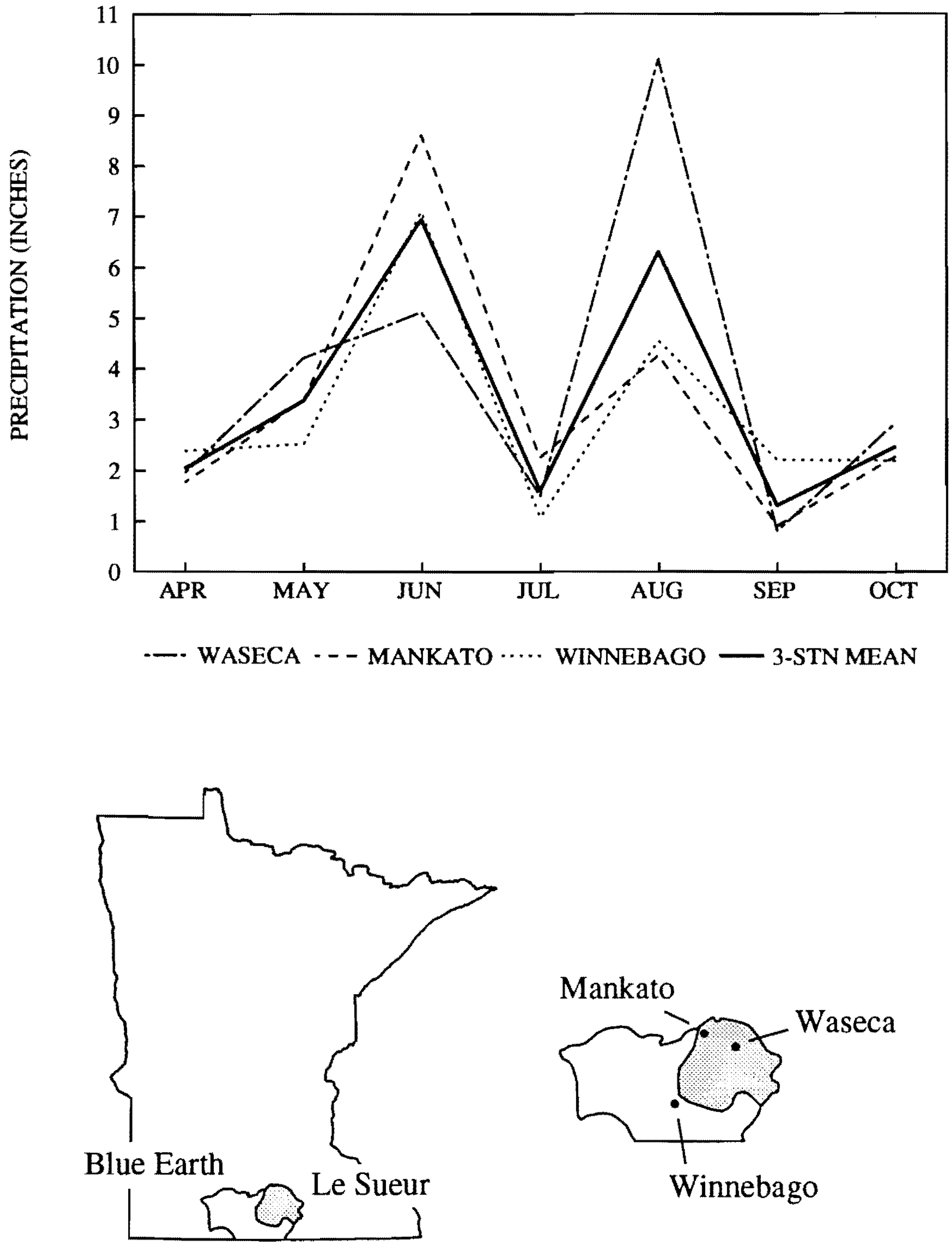


Figure 3. (a) Monthly precipitation totals for the Le Sueur watershed basin (April-October, 1935); and (b) locational map of the individual climatological stations. The Le Sueur Watershed basin (sub-watershed of the Blue Earth basin) is shaded.

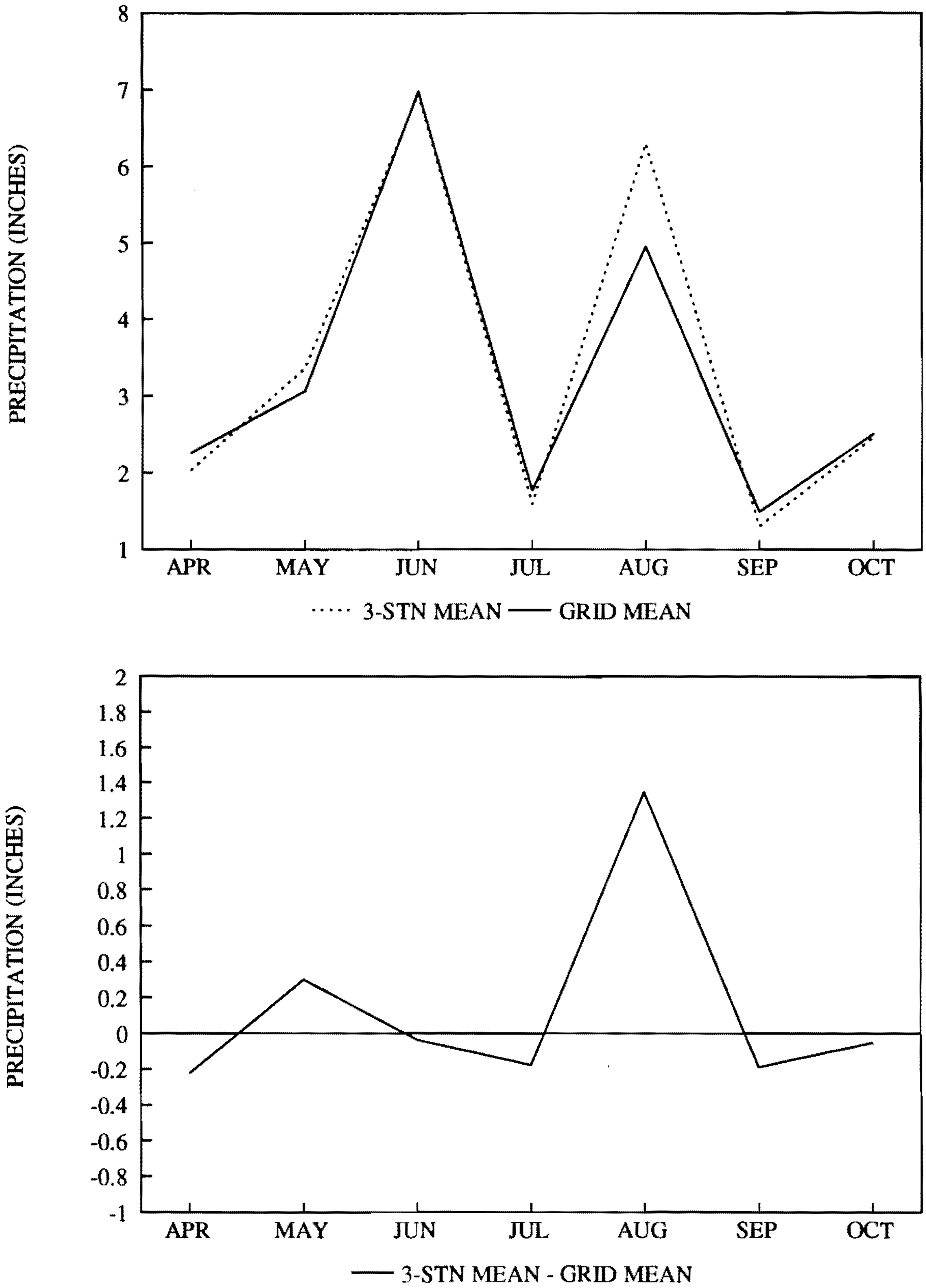


Figure 4. (a) Total monthly precipitation for the Le Sueur watershed basin using a 3-station mean and the grid mean (April-October, 1935), and (b) monthly deviation of grid-estimated mean from the 3-station mean.

We examined the output from three climate models that estimate the likely temperature and precipitation changes in a doubled carbon dioxide world. The three models used were prepared by the following groups:

GISS: Goddard Institute for Space Studies, New York
GFDL: Geophysical Fluid Dynamics Laboratory of NOAA, at Princeton
UK: United Kingdom model

For each model, 9-12 grid points (depending on the model resolution) were selected that covered the full latitudinal and longitudinal extent of Minnesota (selected domains and their resolutions are shown in Figure 5). The temperature and precipitation difference values were gridded and contoured for analysis and comparative purposes. The three models proved to be divergent in their predictions, varying in the magnitude and the direction of the estimated changes. The model chosen was the GISS model.

The UK model could be eliminated because a newer version of the model recently has been run with a cloud parameterization scheme that shows that the predicted temperature changes are half of the original estimates (Mitchell et al., 1989). This newer run of the model was unavailable to us when we acquired the output of the three models from the National Center for Atmospheric Research (NCAR).

Comparisons of the GCM computed temperature change and precipitation ratios on a monthly and a seasonal basis are shown in Figures 6 and 7. The striking difference between the UK model temperature estimates as compared to the GFDL and the GISS models are clearly evident in Figure 6. The UK model can be eliminated based on temperature alone. It can be seen from these two figures that the GISS model estimates for both parameters are generally the most conservative and internally stable, particularly with respect to the estimated precipitation changes. While the GFDL and GISS models have very similar predicted temperature changes as well as realistic patterns of precipitation change, the magnitude of the precipitation changes for the GFDL appear too large.

After settling on the GISS model, two possible methods of estimating the changes in temperature and precipitation over the state were tested. The first method consisted of a simple average of the four grid points immediately surrounding Minnesota, and the second was to take an estimate of the value at the state centroid. We felt that it was inappropriate to use the points in the gridding of temperature and precipitation to estimate a value over a watershed since this would be placing too much confidence on unmeasured points.

Figure 8 shows the difference between monthly estimates of temperature change and precipitation ratio for the GISS model using the two methods. The two methods provide values that are at times virtually identical. The maximum difference in the temperature change estimate was approximately 0.5°C and the maximum percent change in precipitation ratio was about 6.5%. Since these two methods gave estimates that are so similar, we decided that it would be most appropriate to use the actual model grid points values and compute the average.

The temperature change and precipitation ratio estimates based on this method were computed for each month and these values were used to adjust the observed temperature and precipitation records computed for each watershed. The water budgets were recalculated using these adjusted values. The new surplus values were used as predictor variables in the previous models that showed the relationship between total seasonal moisture surplus and mean seasonal river flow.

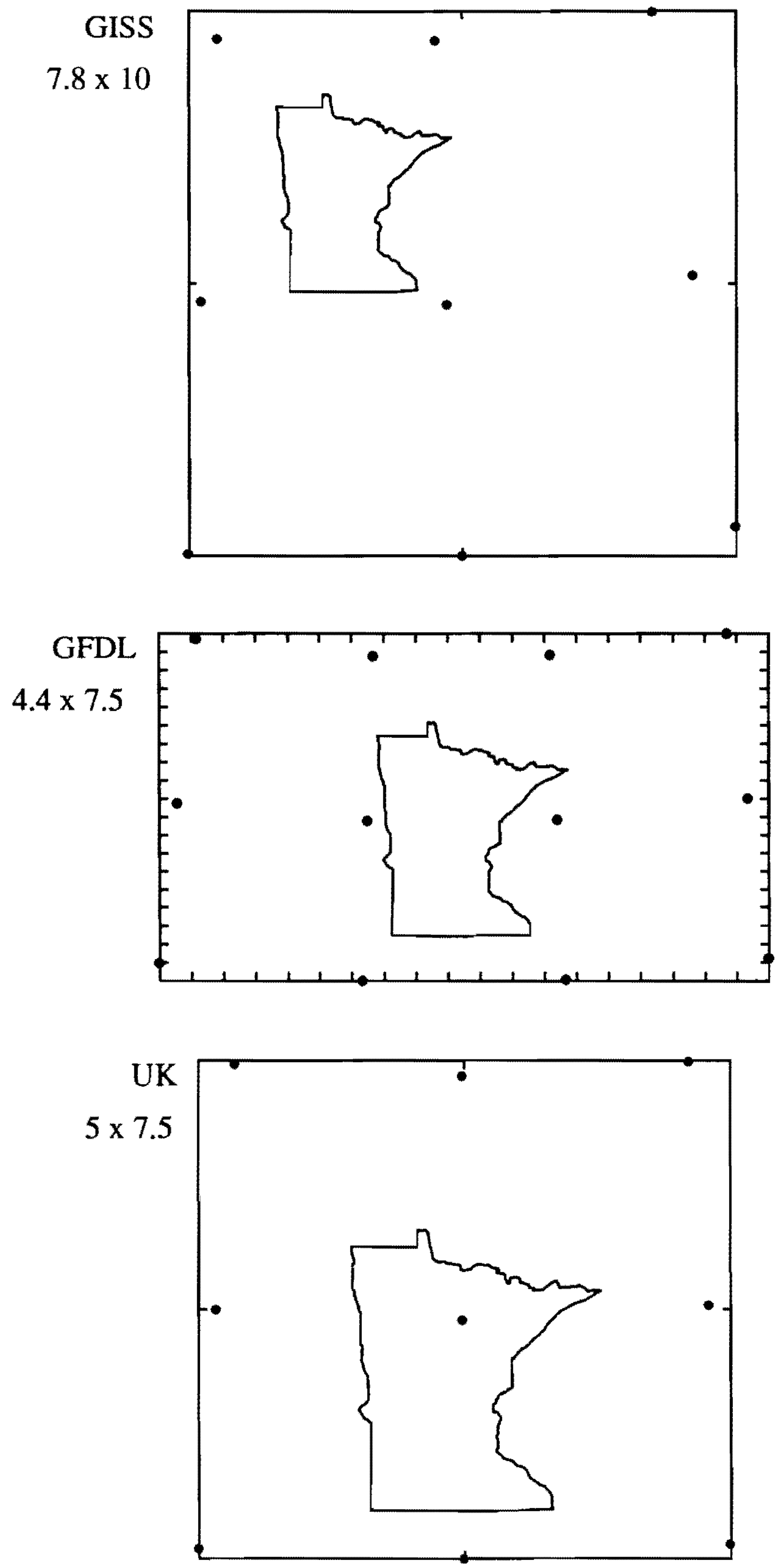
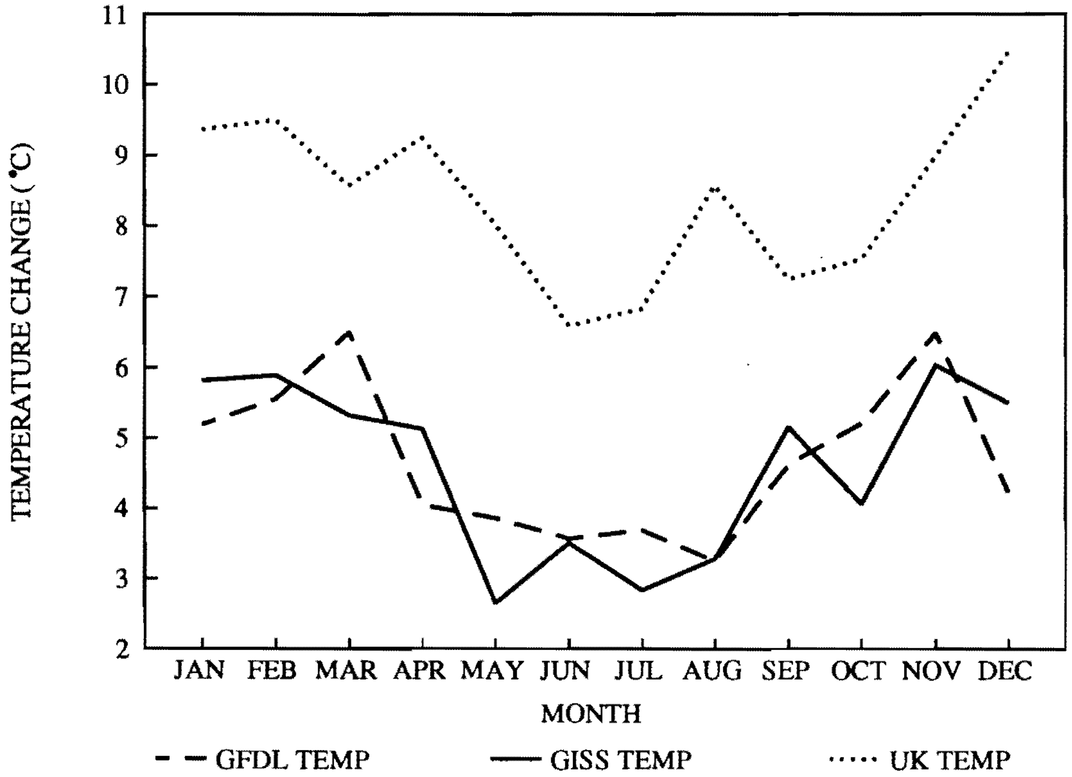


Figure 5. Selected GCM model domains: (a) GISS; (b) GDFL; and (c) UK. Grid resolution for each domain is shown in degrees latitude by degrees longitude.



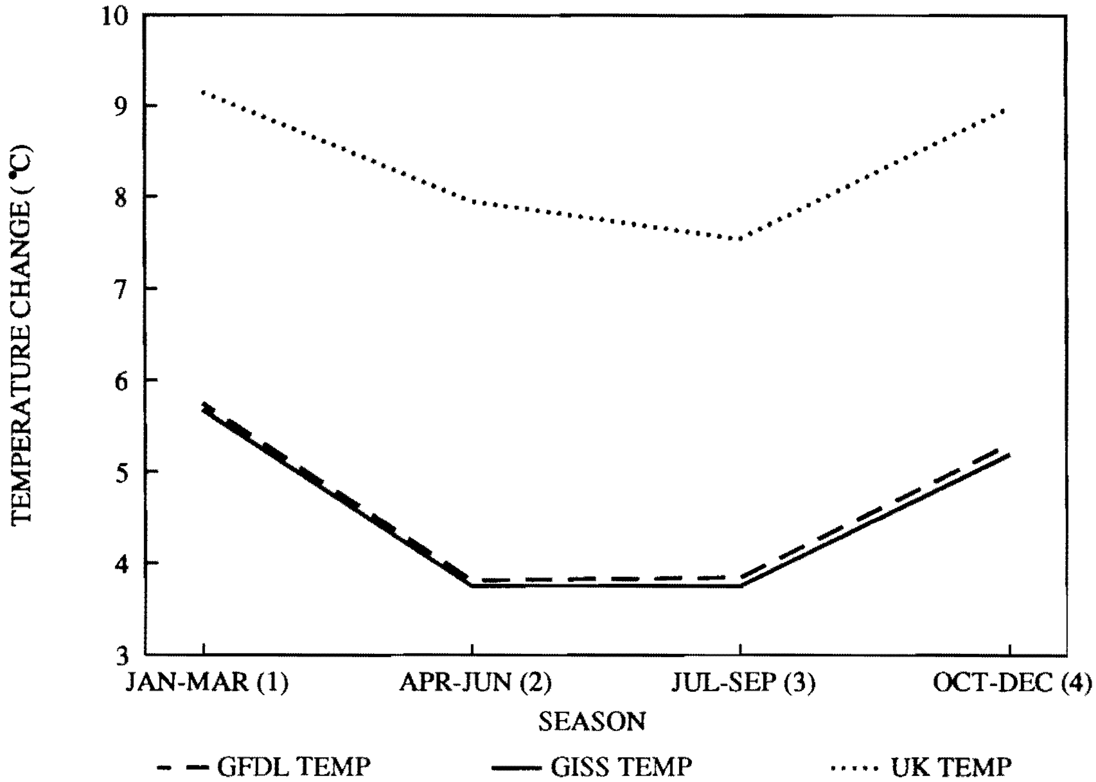
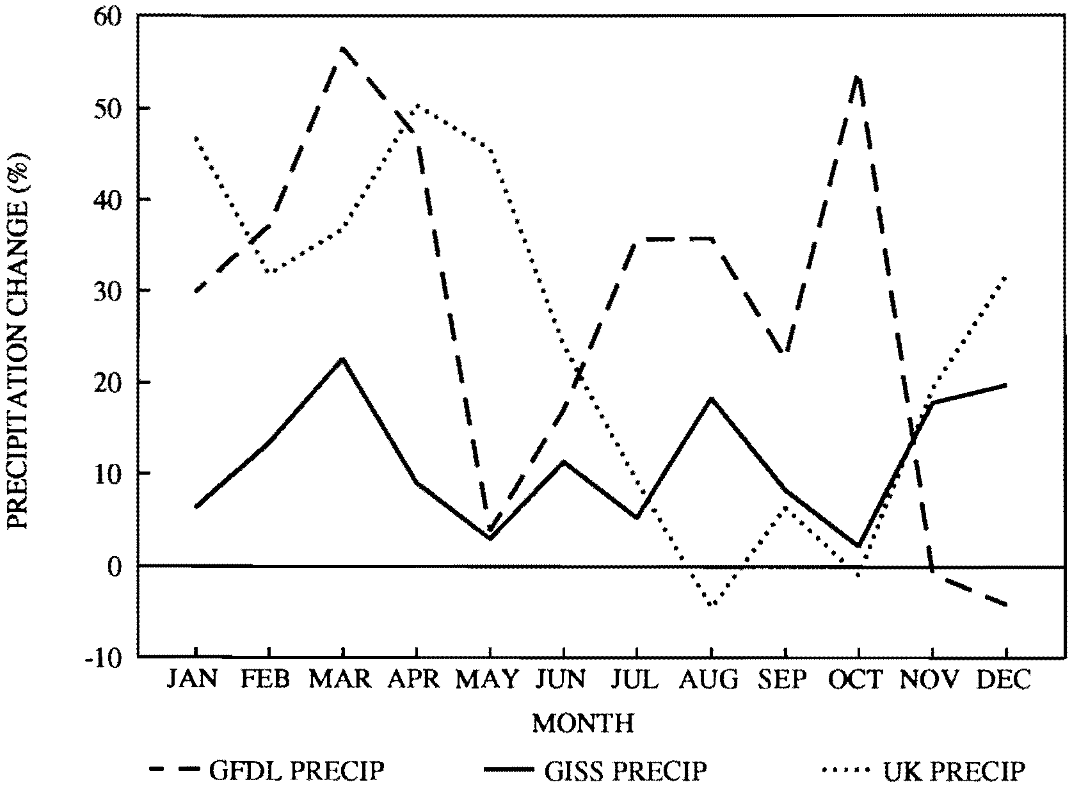


Figure 6. GCM computed temperature change ($2xCO_2$- $1xCO_2$) by month (a); and by season (b).



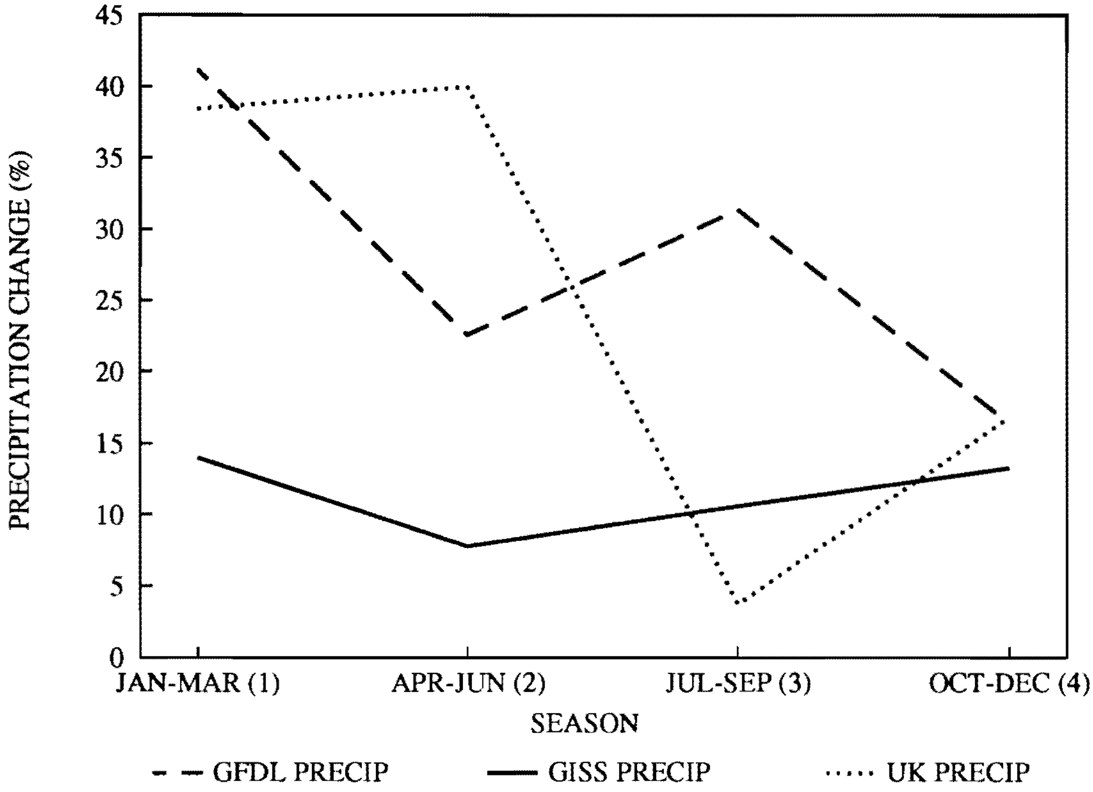


Figure 7. GCM computed precipitation ratio ($2xCO_2/1xCO_2$ percent change) by month (a); and by season (b).

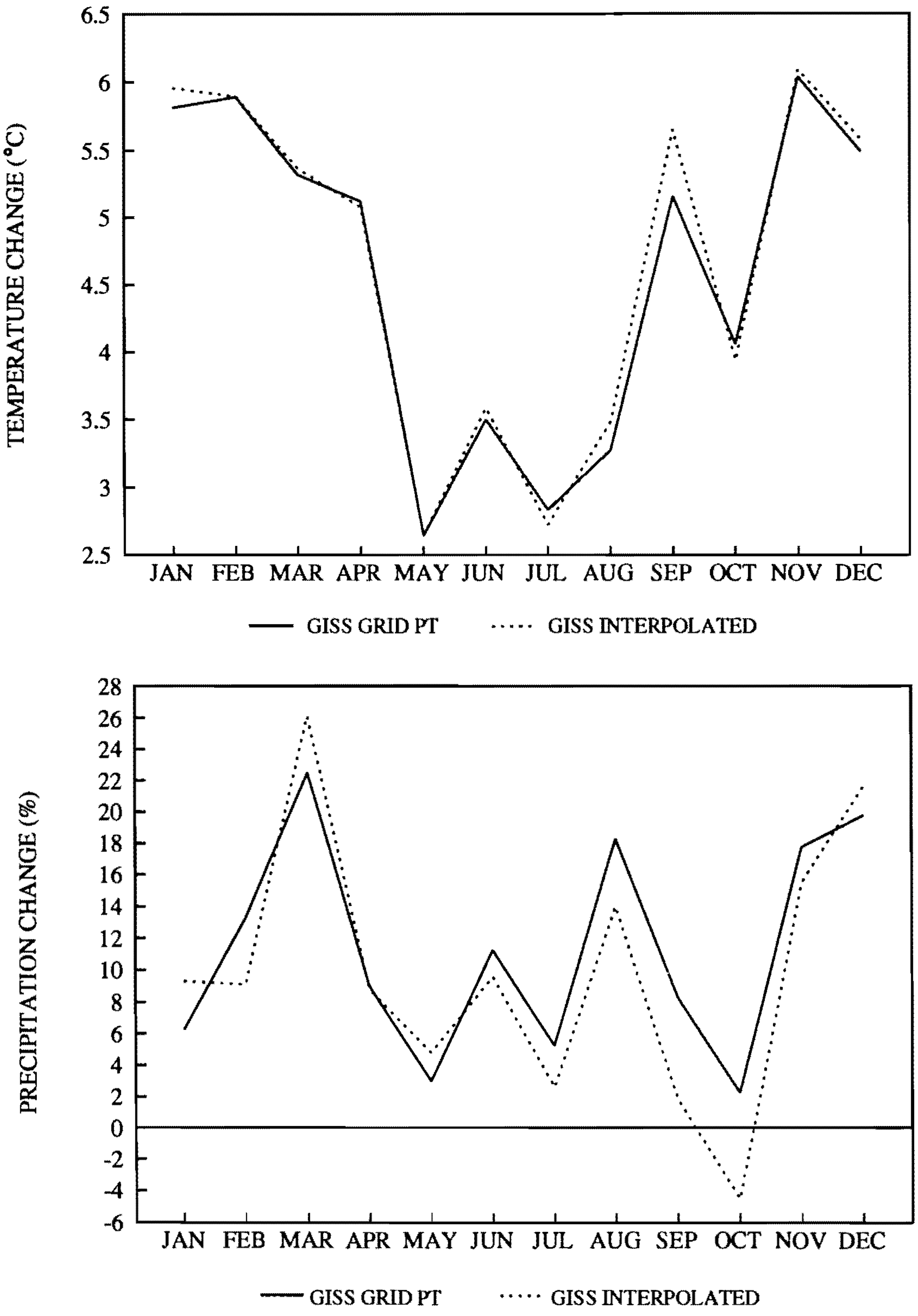


Figure 8. (a) GISS predicted temperature change ($2xCO_2$-$1xCO_2$) estimated by state centroid (interpolated) and by average of original GISS grid point values. (b) GISS predicted precipitation ratio ($2xCO_2/1xCO_2$ percent change) estimated by the above methods.

The following results describe predicted changes in mean seasonal and annual river flow as well as mean monthly temperatures, soil moisture, and water surplus under conditions of doubled CO_2. Through the examination of these various parameters it became apparent that there was an obvious latitudinal variation in the magnitude and direction of changes. If Minnesota were to be divided into relatively homogeneous groups, the southern two-thirds would form the first and the northern third the second. This holds for all of the above parameters except for annual river flow where the southern one-third is distinctly different from the northern two-thirds. For all of the discussions below, the variations across the state will be viewed in terms of three latitudinal sections: south, central and north.

Results

Seasonal and Annual River Flow

The differences (in percent) in the mean seasonal discharge volume estimates from the current climate to conditions of $2xCO_2$ are shown in Figures 9 through 12. It is obvious that under the new climatic conditions the predicted river discharges are significantly influenced. Both the seasonal and annual graphs have been sorted so that the watersheds are arranged according to their general latitude (south to north). Season 1 (Jan-Mar) shows that all of the watersheds exhibit a general increase in river discharge. These changes range between 10-50%, with the Baptism River having more than a 300% increase in discharge volume during these months. The differences observed during Season 1 are the result of the warmer temperatures which shift the spring flood from April (Season 2) to March (Season 1). The smallest increases, those for the southern watershed basins, are due to the fact that there are occurrences of runoff during this season under the current climate. In the case of the Baptism River, the huge increase in flow is a likely result of the extremely small size of the basin. At 140 square miles (sq.mi.), the spring flood is a tremendous proportion of the seasonal flow for this river.

In Season 2 (Apr-Jun), the exact opposite pattern occurs with every basin showing a decrease in flow as the snow melt has been shifted out of this season. The largest decreases in discharge volume occur for the Baptism River followed closely by the southern and western watershed basins. The sizable values for these watersheds correspond to the increases seen in Season 1. These observed decreases are to be expected as a result of the shift in the time of the spring flood.

Season 3 (Jul-Sep) reveals a significant pattern of flow change as well as the influence of latitude on that change. The percent change in discharge volume decreases as latitude increases. It appears that unlike soil moisture and moisture surplus, the southern one-third of the state is now different from the northern two-thirds. This is quite apparent when viewing the changes in mean annual discharge volume (Fig. 13). During this season, discharge volumes decrease for all of the watersheds within the state. The mean decrease within the northern region is approximately 4%, with a 13% decrease in the middle third of the state, and about a -23% change in the southern third.

In Season 4 (Oct-Dec), we again see increases in mean discharge volume for the northern watersheds. This is due to the warmer temperatures during this period which results in precipitation falling as rain rather than as snow which is stored at the surface. Additionally, as long as the soils remain unfrozen, heat would be transferred to melt any snow that fell thus allowing infiltration and/or runoff.

The mean annual discharge volume changes are shown in Figure 13. As noted before, there is a dramatic difference in flow change between the northern and southern parts of the

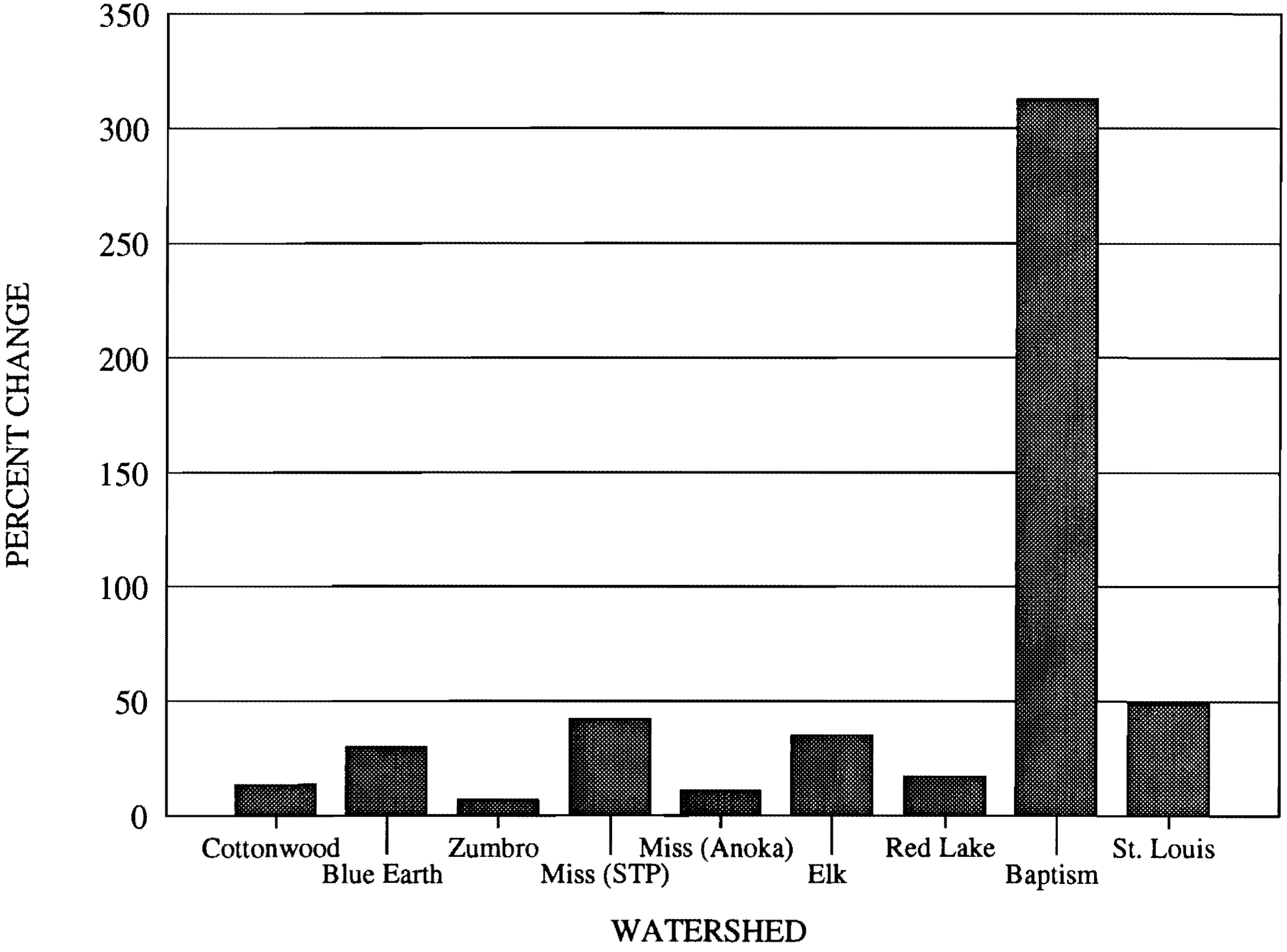


Figure 9. Season 1 (Jan-Mar) mean change in discharge volume from the current climate ($1xCO_2$) to conditions of doubled CO_2 ($2xCO_2$).

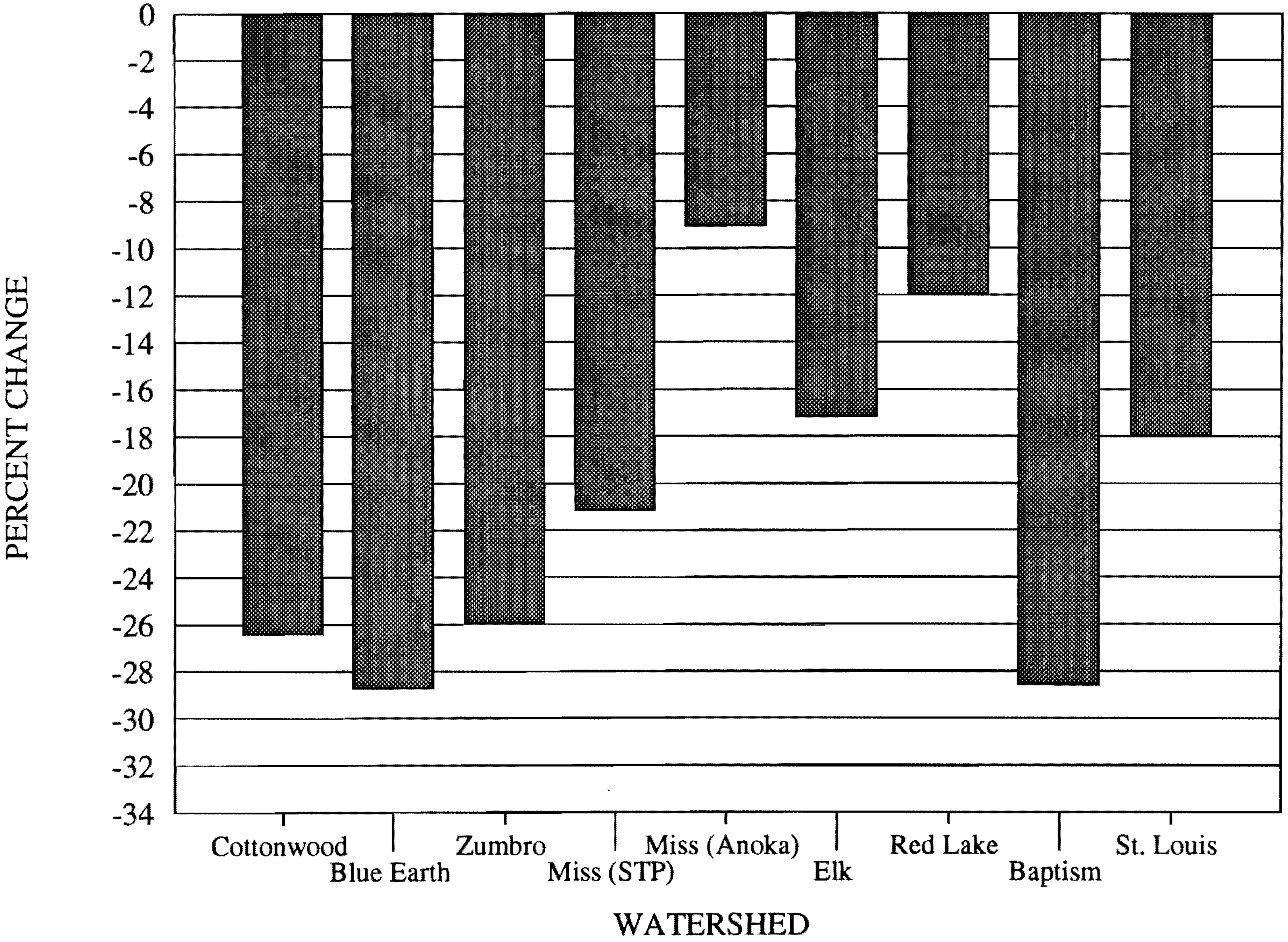


Figure 10. Season 2 (Apr-Jun) mean change in discharge volume from the current climate ($1xCO_2$) to conditions of doubled CO_2 ($2xCO_2$).

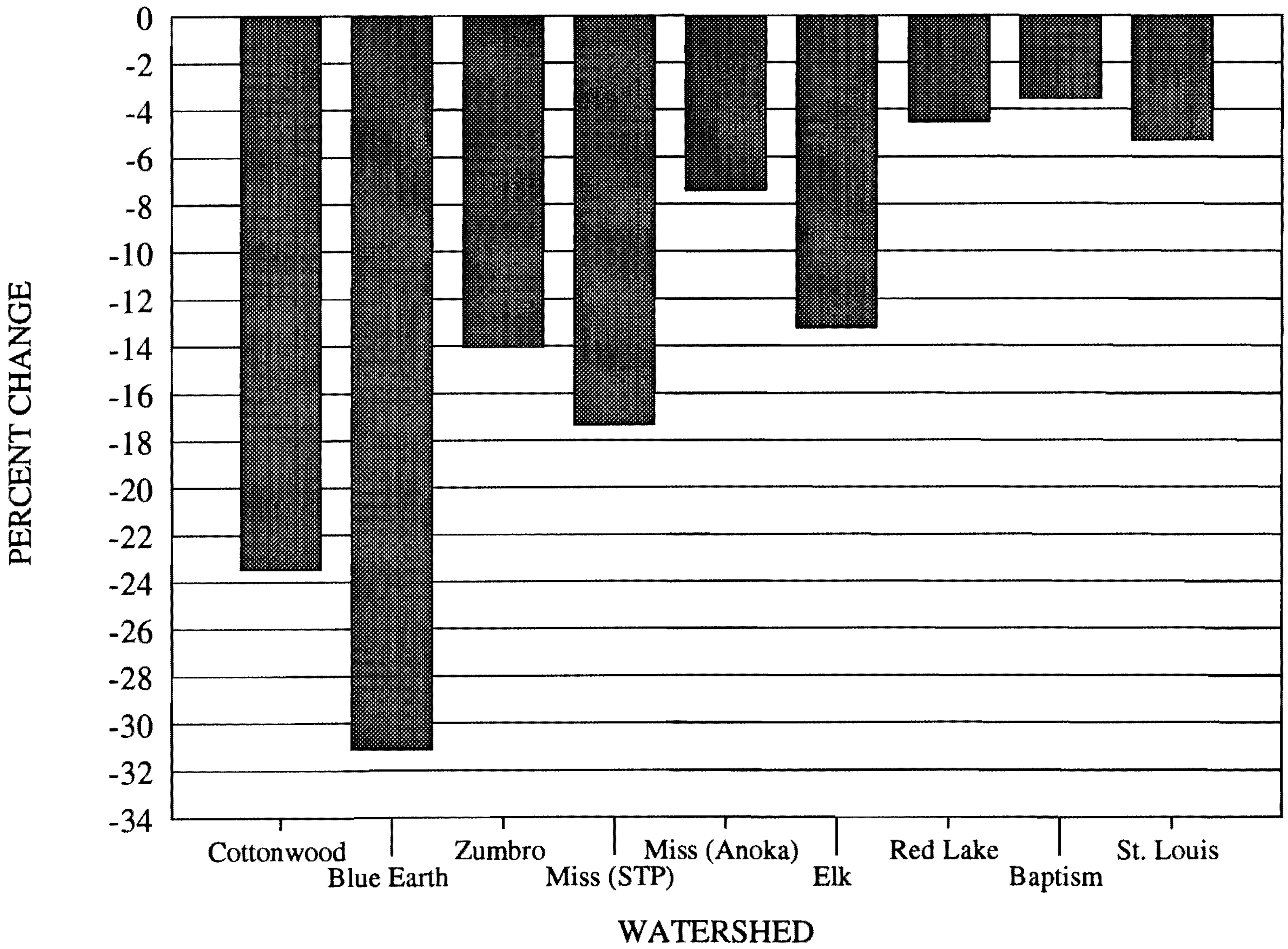


Figure 11. Season 3 (Jul-Sep) mean change in discharge volume from the current climate ($1xCO_2$) to conditions of doubled CO_2 ($2xCO_2$).

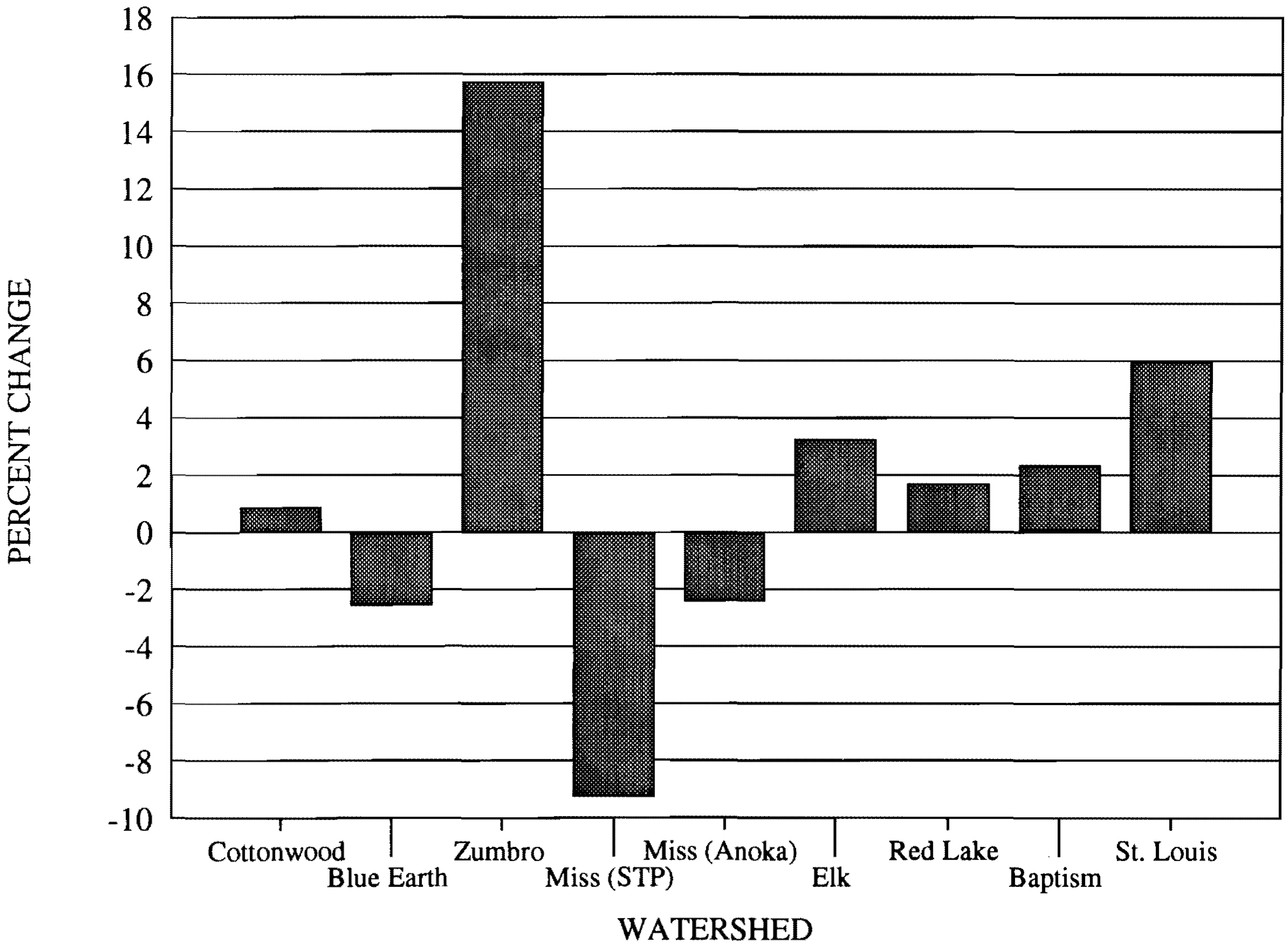


Figure 12. Season 4 (Oct-Dec) mean change in discharge volume from the current climate ($1xCO_2$) to conditions of doubled CO_2 ($2xCO_2$).

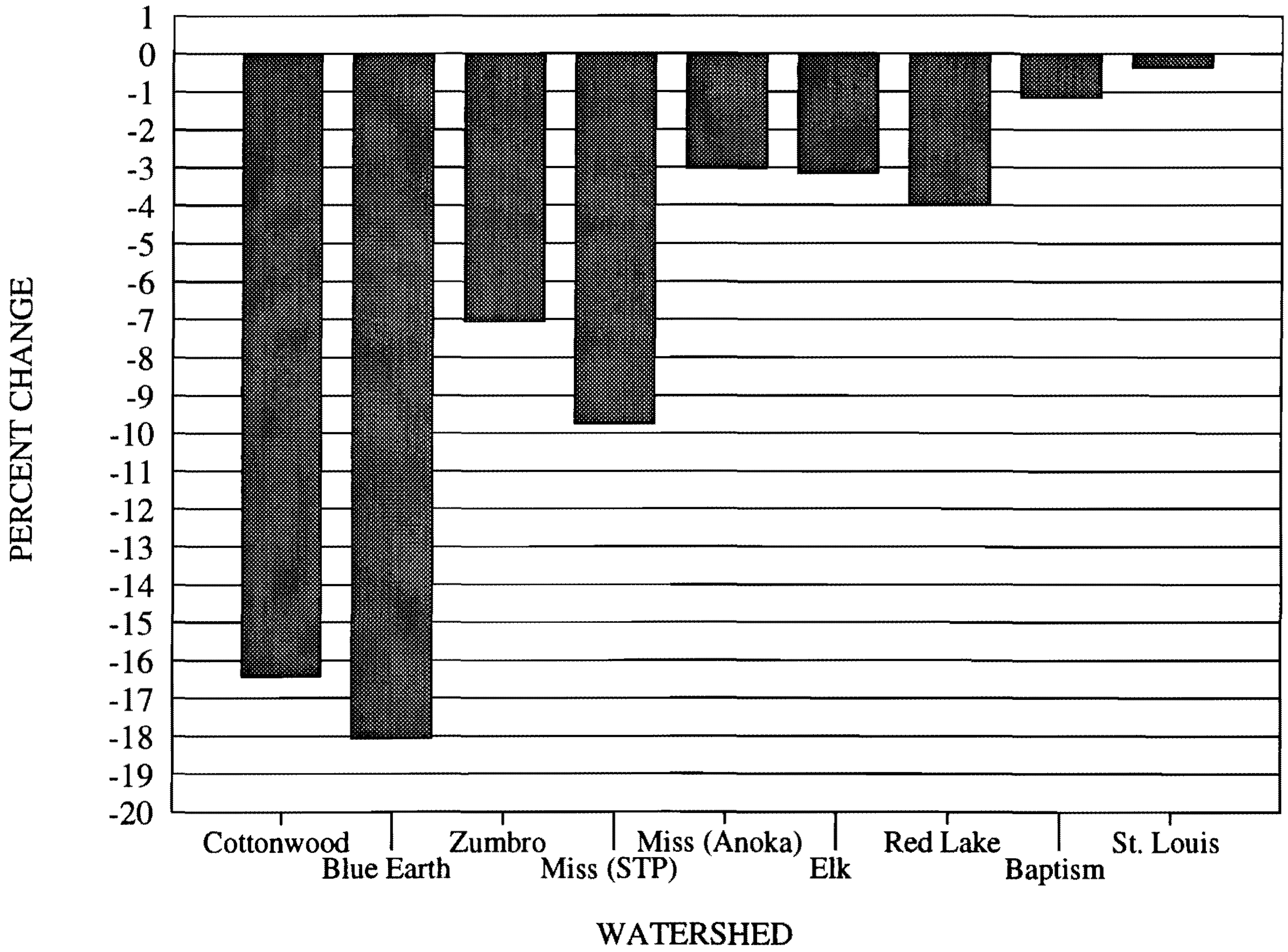


Figure 13. Mean annual change in discharge volume from the current climate ($1xCO_2$) to conditions of doubled $CO_2(2xCO_2)$.

state. Annually, the decreases are two times as great in the south. The largest estimated changes are found in the watersheds located in the southeastern, south central and western portions of the state where decreases are found to range between 10 and 18%.

The next several graphs illustrate the predicted changes in yearly mean discharge volume for a sample of watersheds. Figure 14, for the Blue Earth (south central) and the St. Louis (northeast) River basins, demonstrates the spatial variation and magnitude of the decrease in discharge volume. The mean annual decrease for the Blue Earth River is approximately 18% while on the St. Louis River it is only 0.3%. Examining the pattern of individual yearly discharges, the Blue Earth River shows only four years in which there is an increase in discharge volume. This is compared to the St. Louis River where the number of years with positive and negative changes is nearly evenly split. The years in which there appears to be no change in the discharge in the Blue Earth River system are the result of missing data.

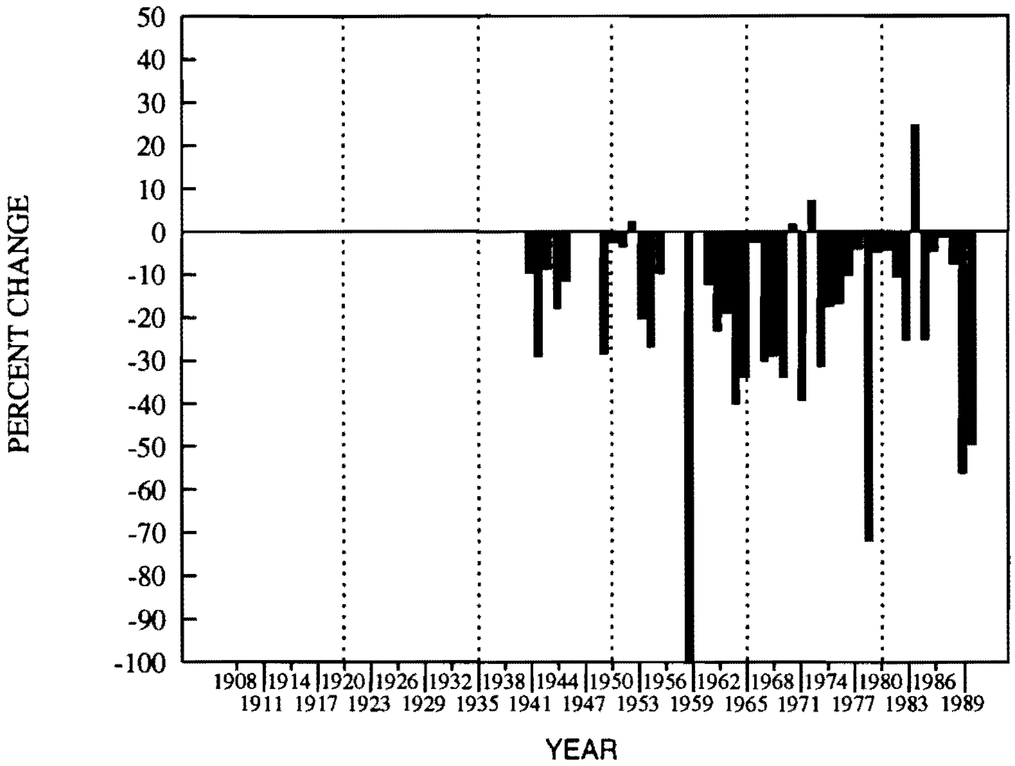
Figure 15 represents two data sets measured for the Mississippi River. The differences seen between them are the result of the location of the gaging station. The gaging station "near Anoka" measures the flow on the Mississippi River only. The station "at St. Paul" includes the flow from the Minnesota River as well. The observed difference between these figures represents the influence that the western and south central parts of the state have on the change in predicted flow. Under current ($1xCO_2$) climatic conditions, these are the regions within the state in which evapotranspiration is at a maximum and precipitation and runoff are at a minimum. In comparing the two figures, it can be seen that the southern one-third and the west central regions have a significant impact upon the magnitude of the decrease. The average percent change over the period of record for the Mississippi measured near Anoka is -3.03% with the largest decrease of -21.43%. The mean percent change for the Mississippi at St. Paul is -9.75% with a maximum decrease of -37.78%. Over the period 1932 through 1988, there are approximately half as many occurrences of increased discharge volume for the Mississippi at St. Paul as for the Mississippi near Anoka.

Mean Monthly Temperatures

The impact of doubled CO_2 on mean monthly air temperatures is important to examine because of the influence temperature has in the computation of the water balance and the time at which snow melt (reflected as runoff/surplus after soil moisture is at field capacity) will occur. This can be analyzed in terms of the change in the frequency of months over the period of record in which the mean temperature is greater than 0°C.

The most dramatic and significant changes occur in the months of March and November for all watersheds. These are the transition months around where the mean monthly temperatures rise above or fall below 0°C. Figures 16 through 18 (a) show the percent of months over the period of record with mean monthly temperatures below freezing and (b) the percent change in the number of months below freezing between the $1xCO_2$ and $2xCO_2$ climates for a sample of the watersheds.

The Zumbro river in southeastern Minnesota (Fig. 16) shows nearly a 50% decrease in the number of months in which the March mean monthly air temperature is below freezing. The 40% decrease in November results in only 2% of the Novembers in the southeast having a mean below freezing. Additionally, for the $1xCO_2$ climate, 100% of the months in December and January had sub-zero means, whereas, under the $2xCO_2$ conditions 13% of Decembers and 3% of Januaries went above freezing. Similar behavior was seen for the Blue Earth and Cottonwood River watershed basins, also in southern Minnesota.



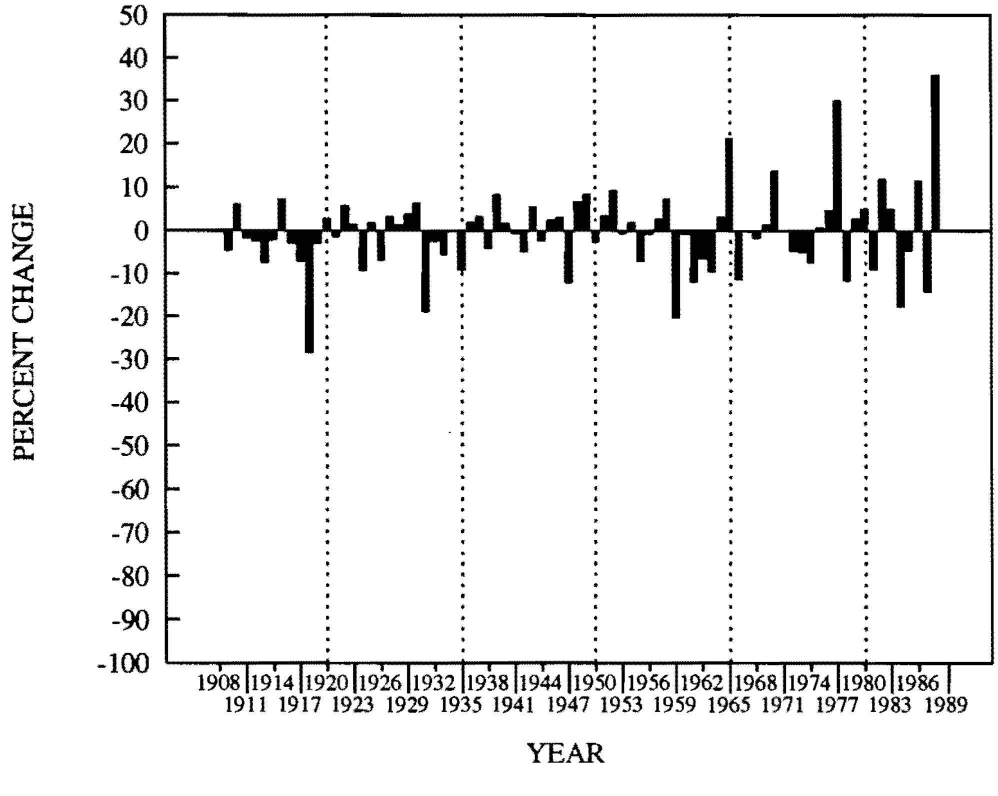
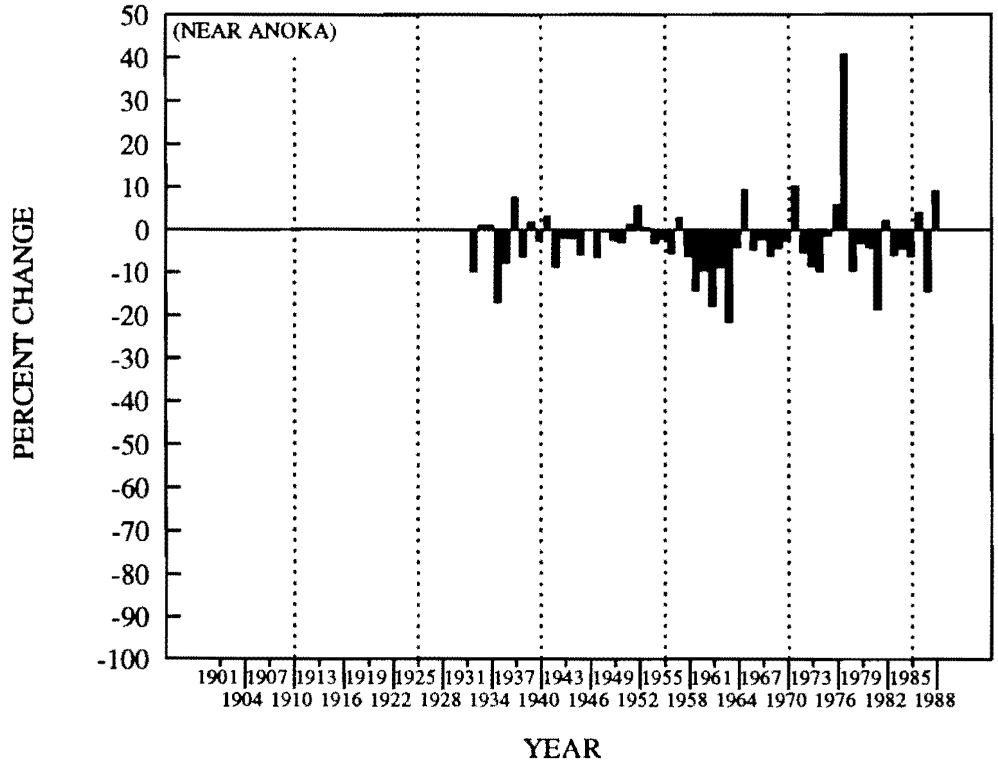


Figure 14. Estimated yearly mean change in discharge volume: (a) Blue Earth River watershed basin (south central); (b) St. Louis River watershed basin (northeast). It should be noted that river flow data was not available until 1940 on the Blue Earth River. Years with no apparent percent change are the result of missing data.



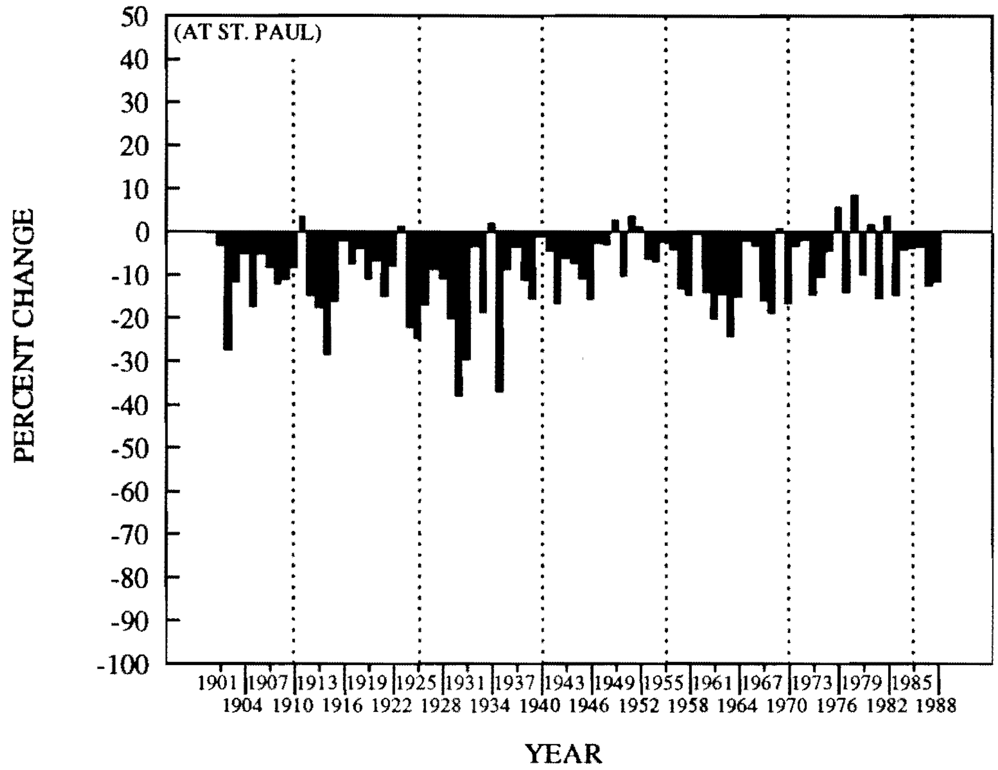


Figure 15. Estimated yearly mean change in discharge volume: (a) Mississippi River watershed basin (near Anoka); (b) Mississippi River watershed basin (at St. Paul). It should be noted that river flow data was not available until June 1931 on the Mississippi River (near Anoka).

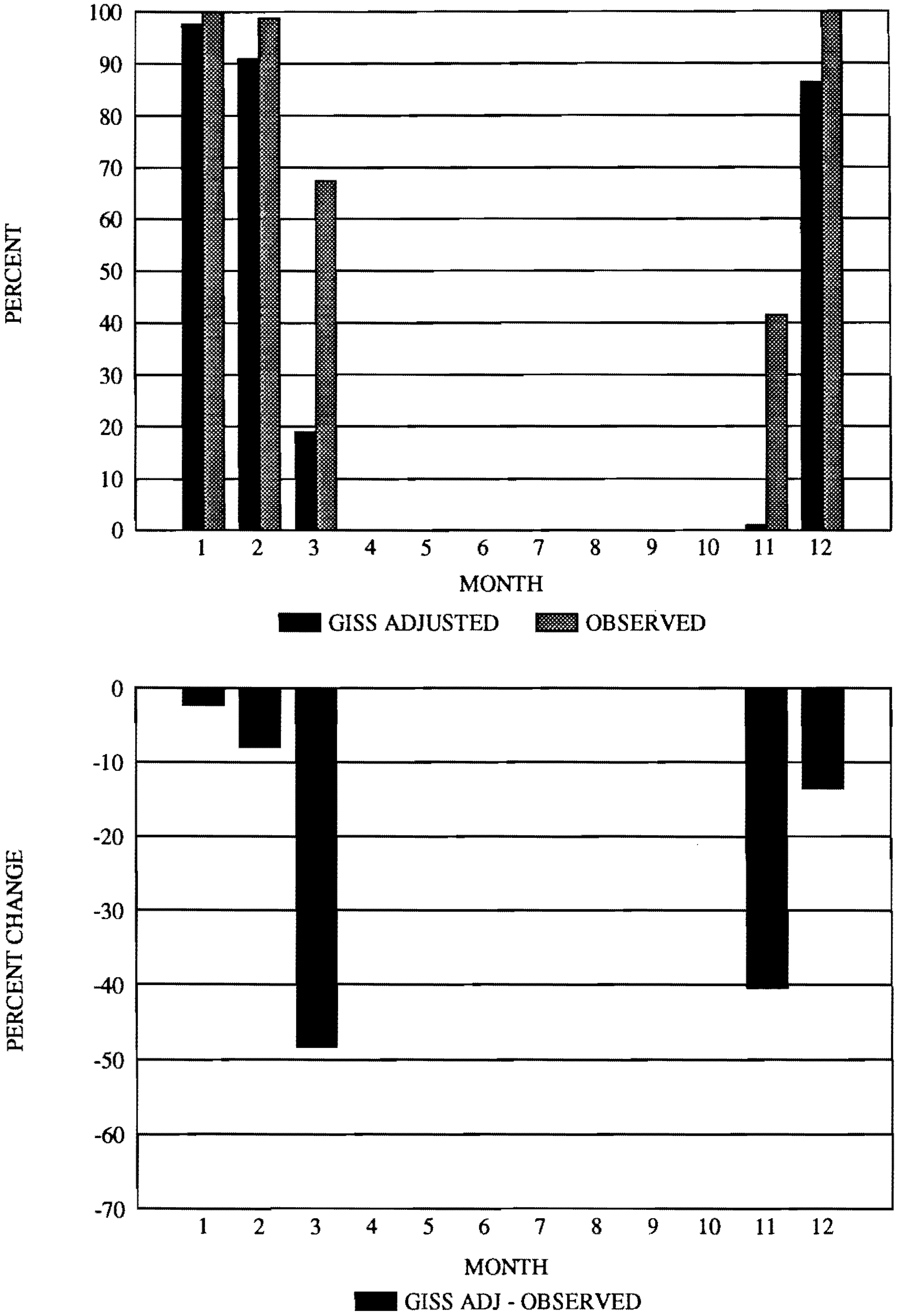


Figure 16. Percent of months in the Zumbro River watershed basin with mean monthly temperatures below freezing: (a) GISS adjusted and observed temperature series; (b) percent change between the observed and GISS adjusted series.

The central third of the state was also characterized by the patterns found in the southern portion with the exception of more significant changes in November where 40-60% of the observations now had means above 0°C. An example of this is seen in Figure 17 showing the western half of the Minnesota River watershed basin. Finally, in the northern third, the spring pattern shifts slightly, showing less change in March than what was seen in the southern two-thirds of the state. This is due to the colder temperatures that persist into April. This can be seen in Figure 18 which shows the graphs for the St. Louis River watershed basin. Under the current climate, about 6% of the Aprils in the north have a mean monthly temperature below freezing and for the $2xCO_2$ climate, these no longer occur. Dramatic changes of 50-60% occur in November but no change is seen in either December or January.

A simple illustration to visualize the shift in the time of year where the mean monthly temperatures are below freezing is shown in Figure 19 for the Zumbro River watershed basin. In the spring the mean monthly temperature crosses the 0°C line in very early March and moves to mid-February under the new climate; a shift of a little over two weeks. Similarly, in the autumn, the shift is from the beginning of November to mid-November. The same type of response was seen for all watershed basins.

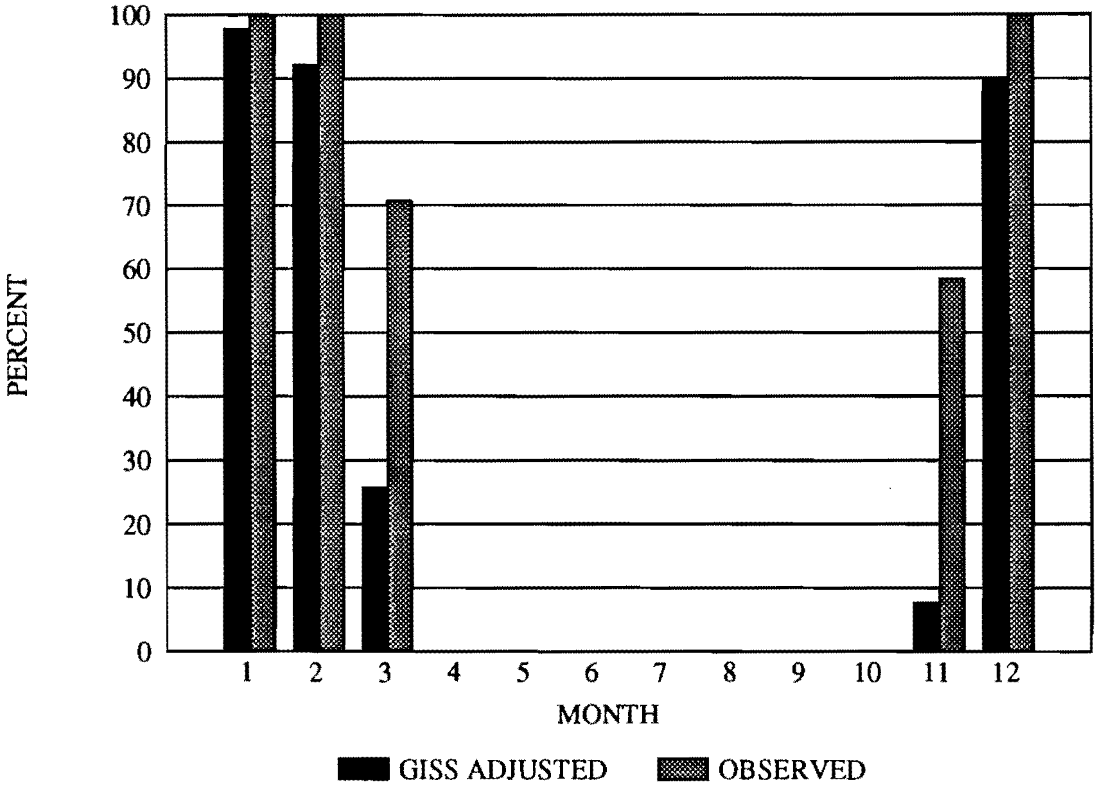
Soil Moisture and Water Surplus

Soil Moisture

The results of a doubled CO_2 world on soil moisture and water surplus is significant. As noted previously in our earlier examination, there is an overall marked decrease in both parameters. Figures 20 through 22 show monthly computed soil moisture change for each watershed stratified by latitude (southern, central and northern Minnesota). For every watershed, there is a large increase in soil moisture during March which is a result of the shift in the spring snow melt and the subsequent recharge period. These increases range from 5-10% in the southern part of the state, up to 15-20% in the central and northern regions. For the southern watersheds, this is the only month in which an increase is observed.

Within the central and northern parts of the state, there are a greater number of months with increased soil moisture, specifically the winter months. Both the Elk River basin and the Mississippi Lower basin, which encompasses the Elk River basin, show a very slight increase in soil moisture in February, about 1%. The northernmost watersheds display the greatest winter month differences. Increases of between 5-10% appear for the months of November through February for the Baptism, Mississippi Upper, Red Lake and St. Louis watersheds. Warmer temperatures under the conditions of $2xCO_2$ would result in soils remaining unfrozen for a longer period of time as well as a decrease in the storage of water as snow. These observed increases are the result of the infiltration of water during these months in which little occurs under current climatic conditions.

Beginning in April, there is a steady decrease in soil moisture through the growing season reaching a minimum in October followed by a recharge. Interestingly, in August, there is a small break in the decline of soil moisture. While the soil moisture change is still negative, it does not follow the continuous declining pattern that one typically sees during the growing season. Usually, August would still be part of the "grand consumption" period during which plants are continuing to draw water from the soil. This occurrence is found in every watershed and is the most dramatic in the northern one-third of the state. This feature also coincides with the increases in computed moisture surplus that are also seen in August for several of the watersheds. The computed moisture surplus change is positive in every



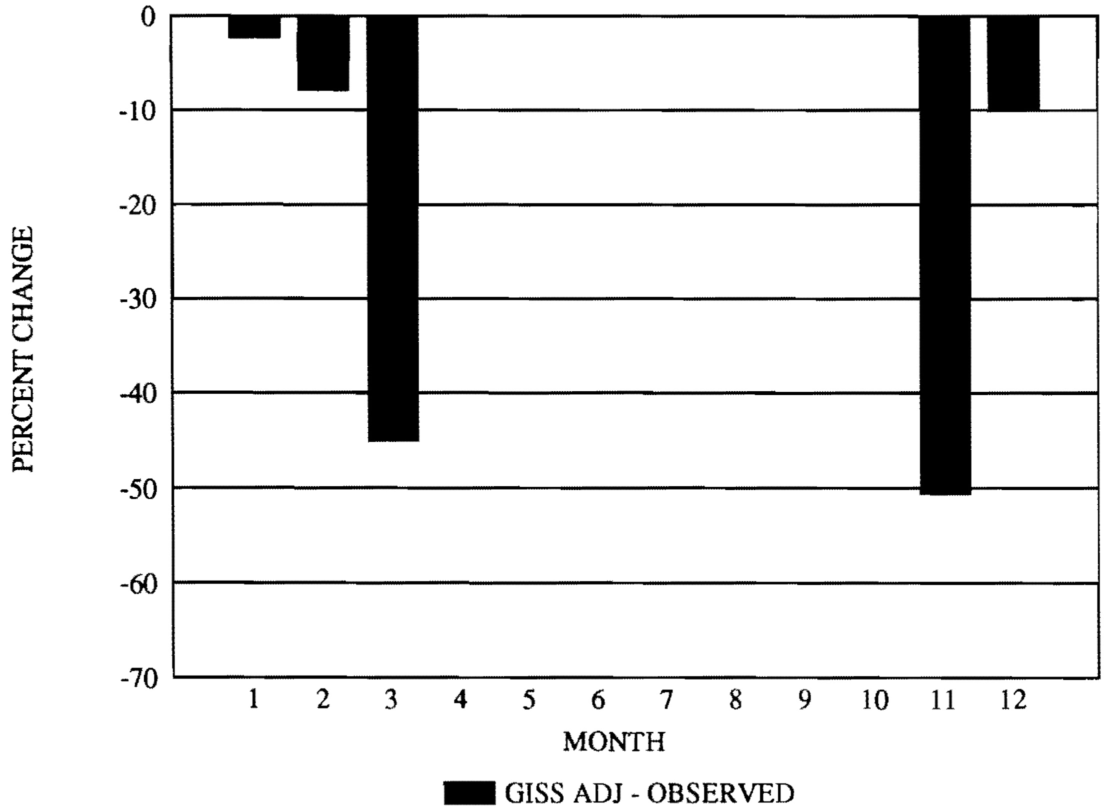


Figure 17. Percent of months in the Minnesota West watershed basin with mean monthly temperatures below freezing: (a) GISS adjusted and observed temperature series; (b) percent change between the observed and GISS adjusted series.

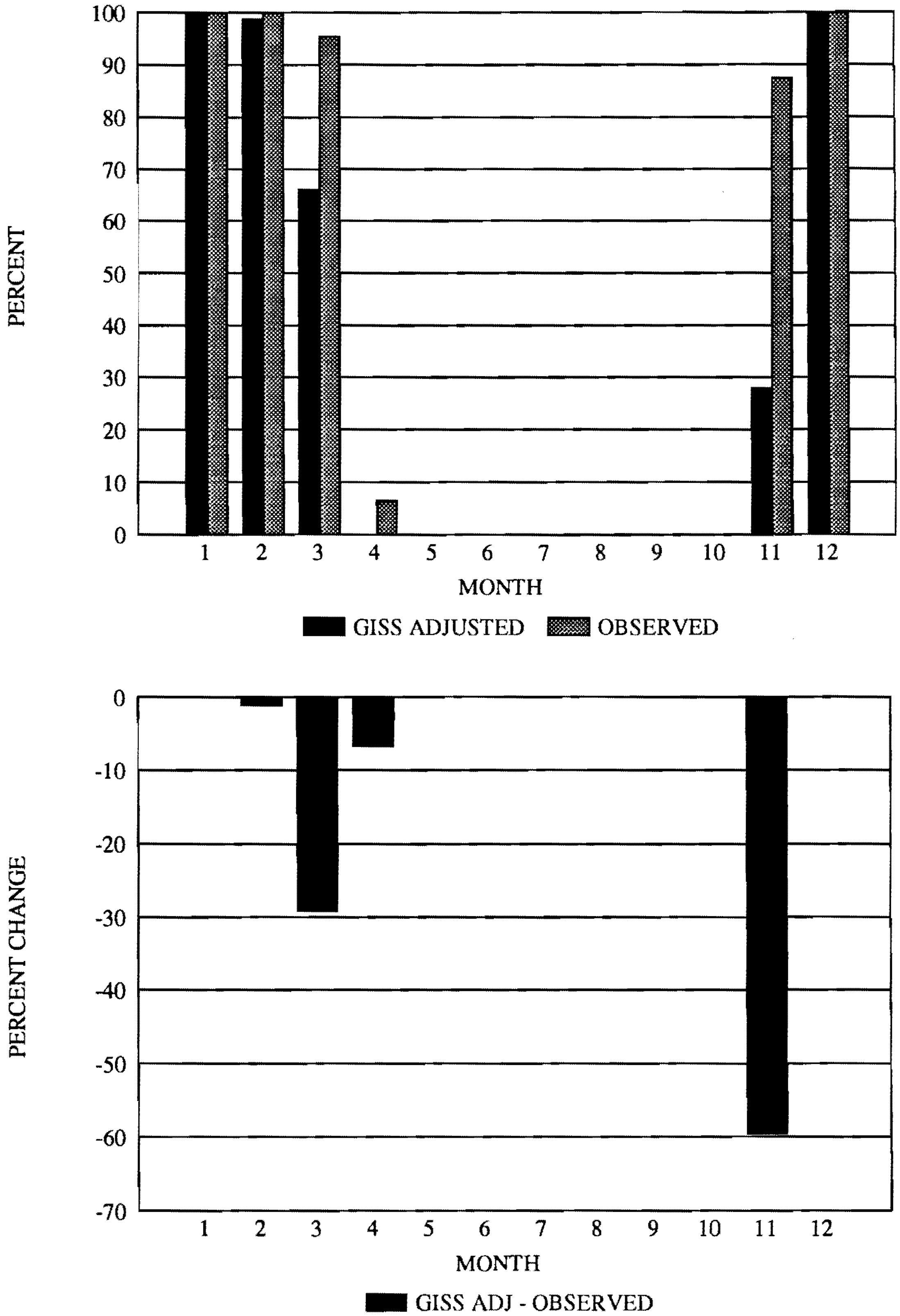


Figure 18. Percent of months in the St. Louis River watershed basin with mean monthly temperatures below freezing: (a) GISS adjusted and observed temperature series; (b) percent change between the observed and GISS adjusted series.

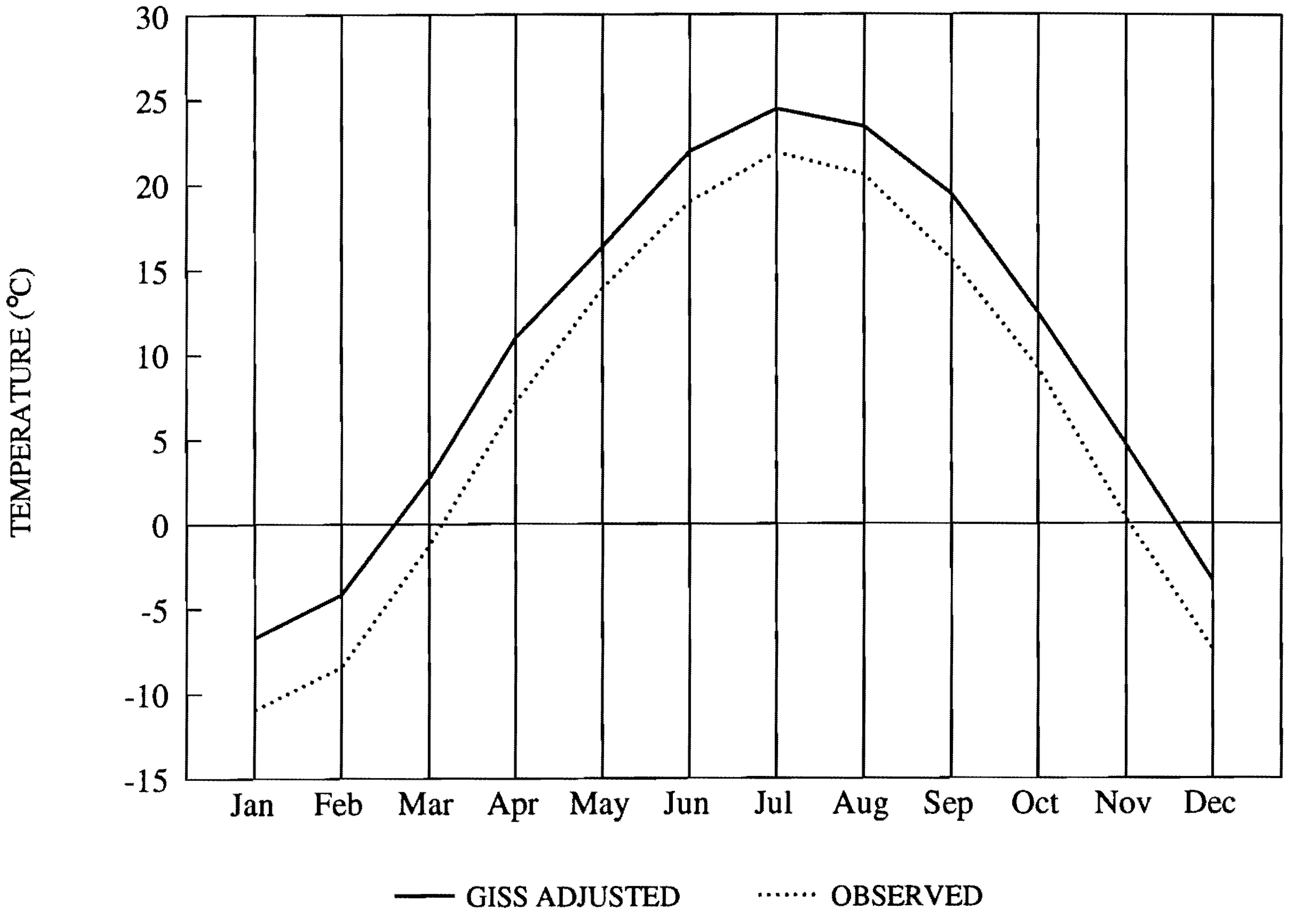


Figure 19. Zumbro River watershed basin mean monthly temperatures for the observed and GISS adjusted series.

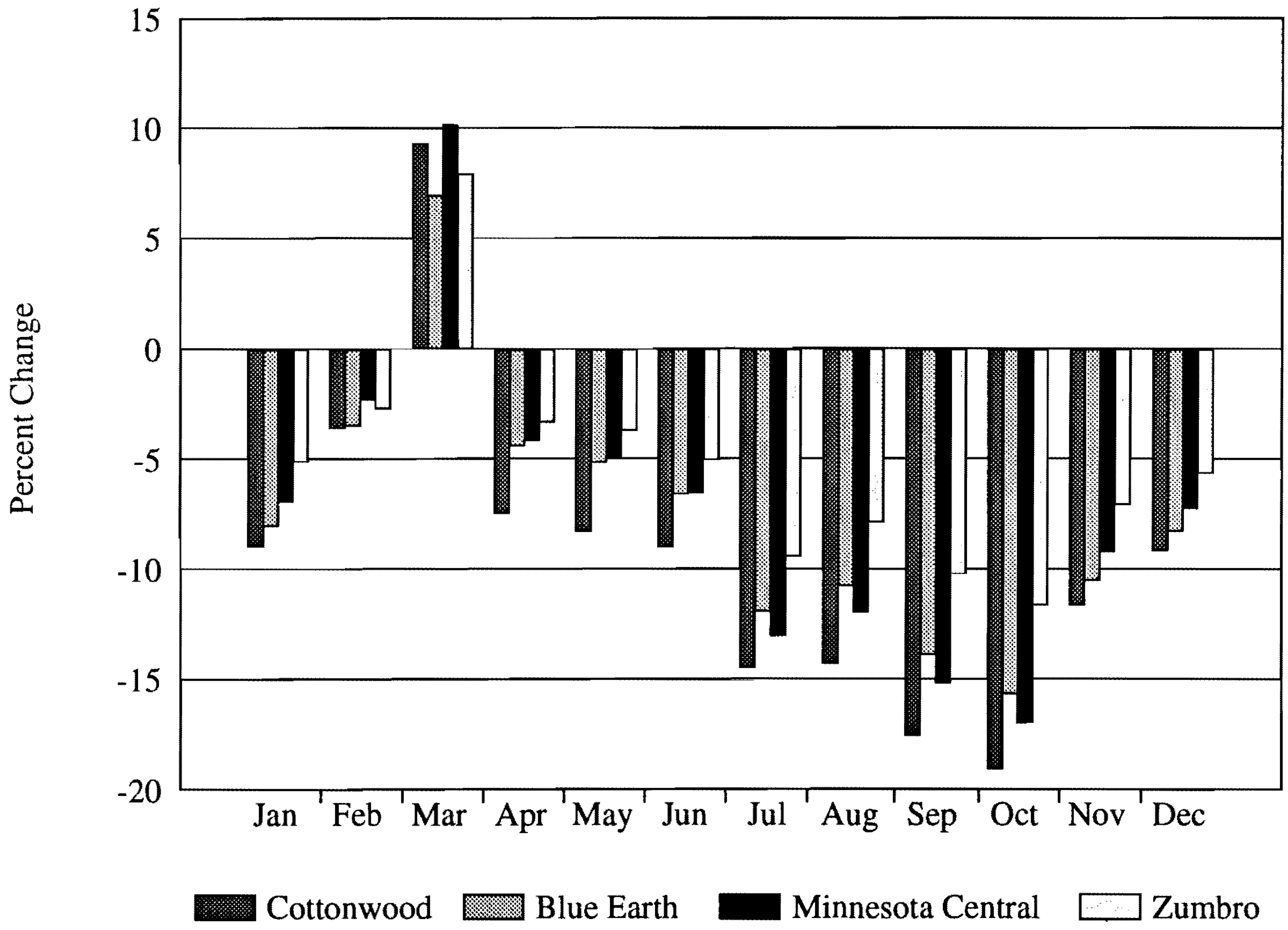


Figure 20. Southern Minnesota percent change in computed monthly soil moisture.

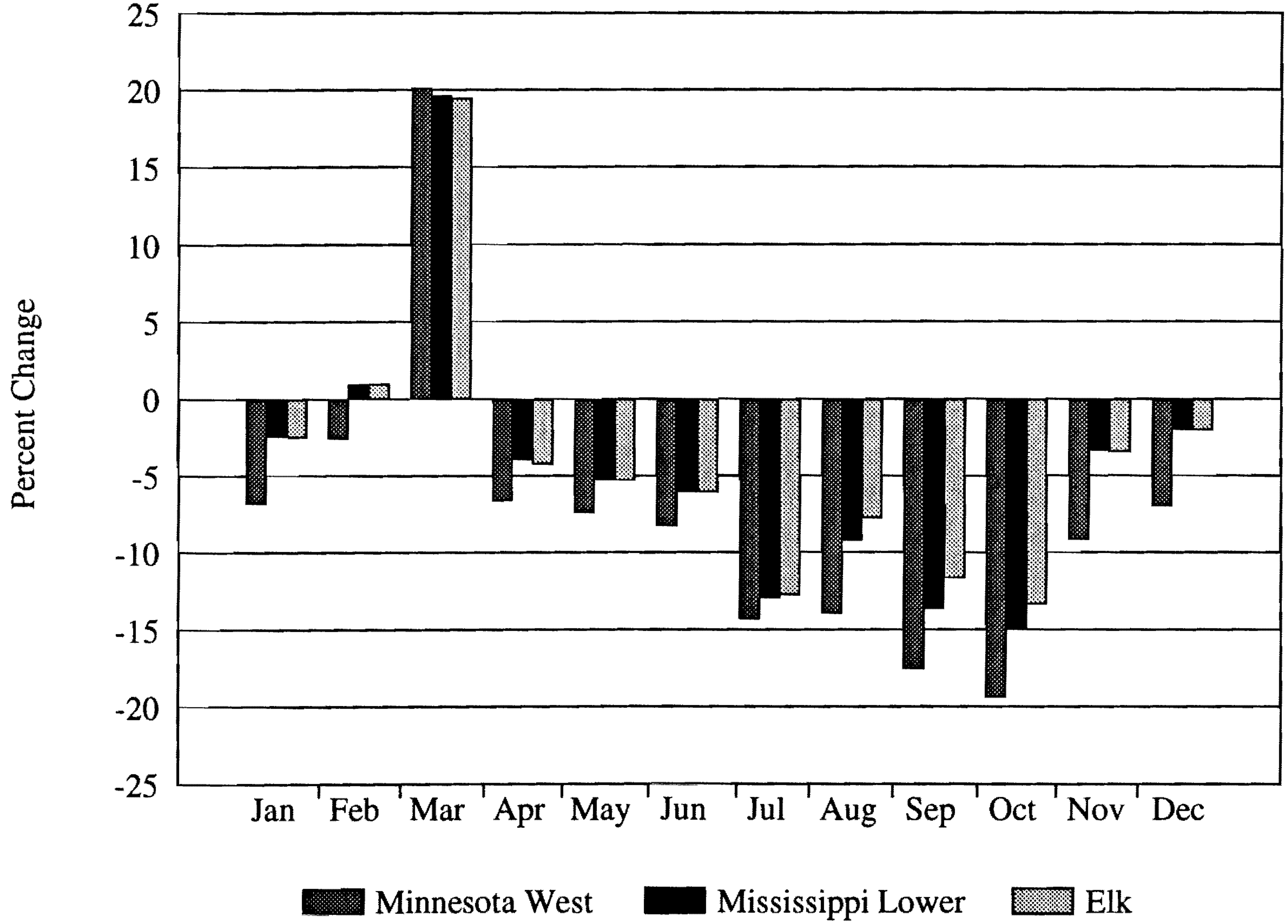


Figure 21. Central Minnesota percent change in computed monthly soil moisture.

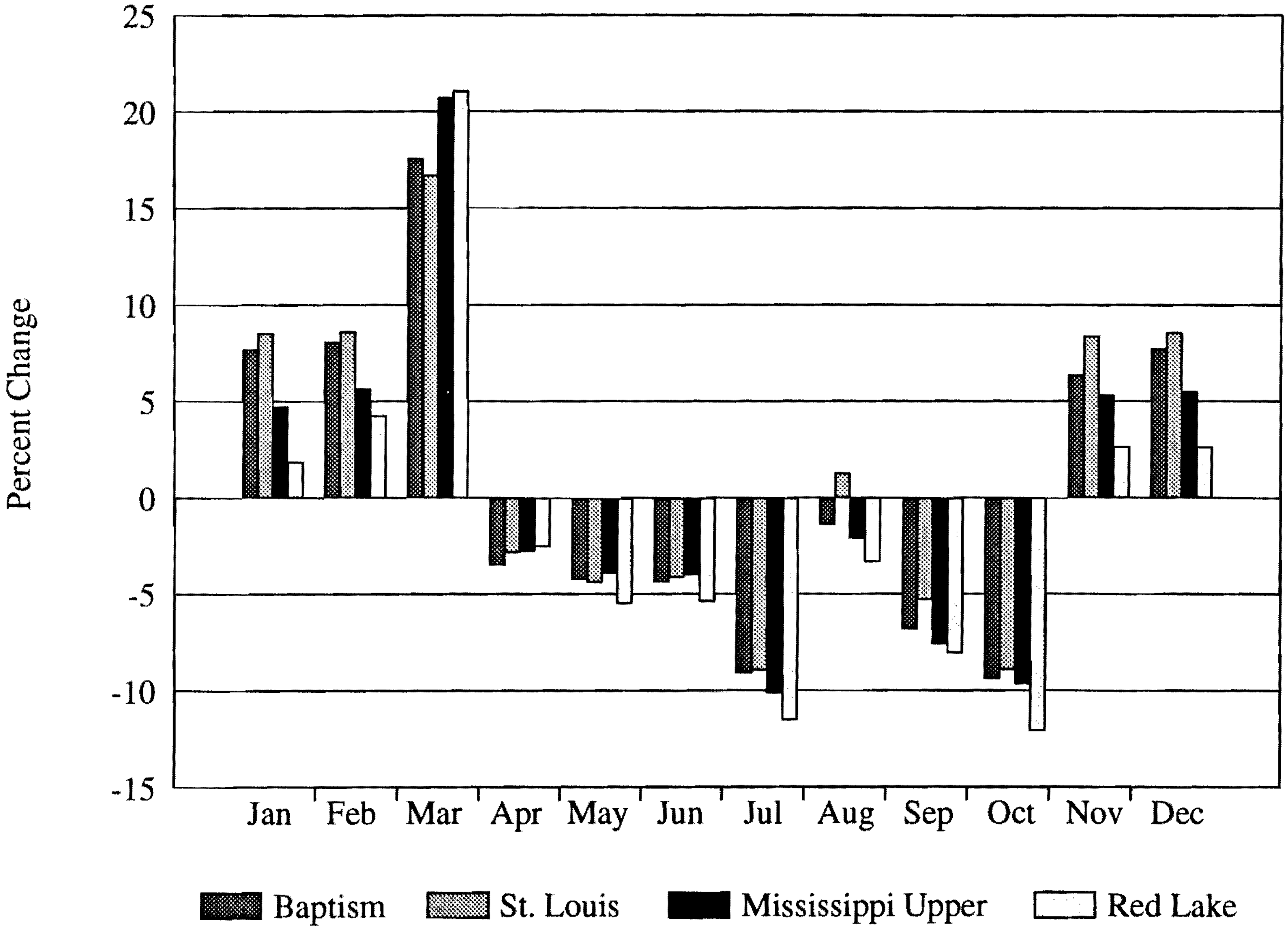


Figure 22. Northern Minnesota percent change in computed monthly soil moisture.

watershed except for those found in the south central and west central parts of the state, namely the Blue Earth, Minnesota West, and Minnesota Central basins.

The explanation for this behavior can be found by examining the GISS predicted precipitation ratios. Through the summer and fall, the GISS model predicts percent changes varying from +2% (October) to +11% (June). The exception is August, which has a predicted precipitation increase of 18%. This increase is significant enough to temporarily increase the soil moisture in every watershed basin. In the case of the St. Louis watershed basin, there is actually a positive percent change in soil moisture so that under the new climate there is more moisture in the soil than under current conditions during the month of August.

The above findings reveal the sensitivity of the Thornthwaite method to the input precipitation series. Accurate precipitation (and temperature) values are crucial components in the water balance calculations, therefore errors in either measurement may result in significant errors in the water budget results. It is for this reason that so much effort went into gridding these data sets and then taking the averages computed over the watershed areas rather than the entire climatological divisions for input into the water balance program.

Water Surplus

For the majority of the watersheds, there is a dramatic decrease in moisture surplus for the period from March through October (Figures 23 through 25). This is most obvious for the southern watersheds where decreases range from approximately -25% to -100%. The values near or at -100% occur in the south central part of the state, within the Blue Earth and the Minnesota Central watershed basins during the month of July. The minimum decreases (or increases) for this period occur for the month of August, as discussed previously, and for the month of June, which has the second highest GISS predicted precipitation change of +11%. June shows smaller decreases generally extending from around 0 to -30%. In the central third of Minnesota, decreases generally range from 0 to -70% while in the north, values are between 0 and -60%. Again, all of these watersheds show an increase in August.

For the period November through March, there is an increase in surplus during February, March and December over all watersheds except for the Red Lake River basin. This watershed is located in northwestern Minnesota which has the lowest mean annual precipitation values. The largest December increases ranging from +50 to +300% are found for those watersheds which lie in the south central part of the state.

For the month of November, the southern third of the state differs greatly from the northern two-thirds. The southern and western watersheds show decreased surplus values ranging from -10% to -60%, while the central and northern basins show dramatic increases in surplus with values between +50% up to +950%. The values over +100% occur in the northernmost watersheds, specifically: Red Lake, St. Louis, and Mississippi Upper. The change for the Baptism River is around +180% which is less than half of the size of the increases seen on the other three watersheds. However, while the December surplus values for the northern basins only reflect a 0 - 12% increase, the Baptism River shows a change of +42%. This is likely due to the fact that the entire Baptism River basin lies within 10 - 15 miles of Lake Superior and would be subjected to its climatic influence. Additionally, there is a 1200 foot elevation rise from the lake level (about 602 mean sea level) up to the source of the river. With a moist, easterly lake breeze forced to ascend the north shore ridge, significant locally heavy snowfalls can occur. This area can be particularly narrow if the ascending air meets with prevailing northwesterly winds. The lake also exerts a moderating effect on the temperature in that the higher temperatures observed at stations close to the shore are the result of the lake being ice-free during December and early January (Baker et al., 1985). The

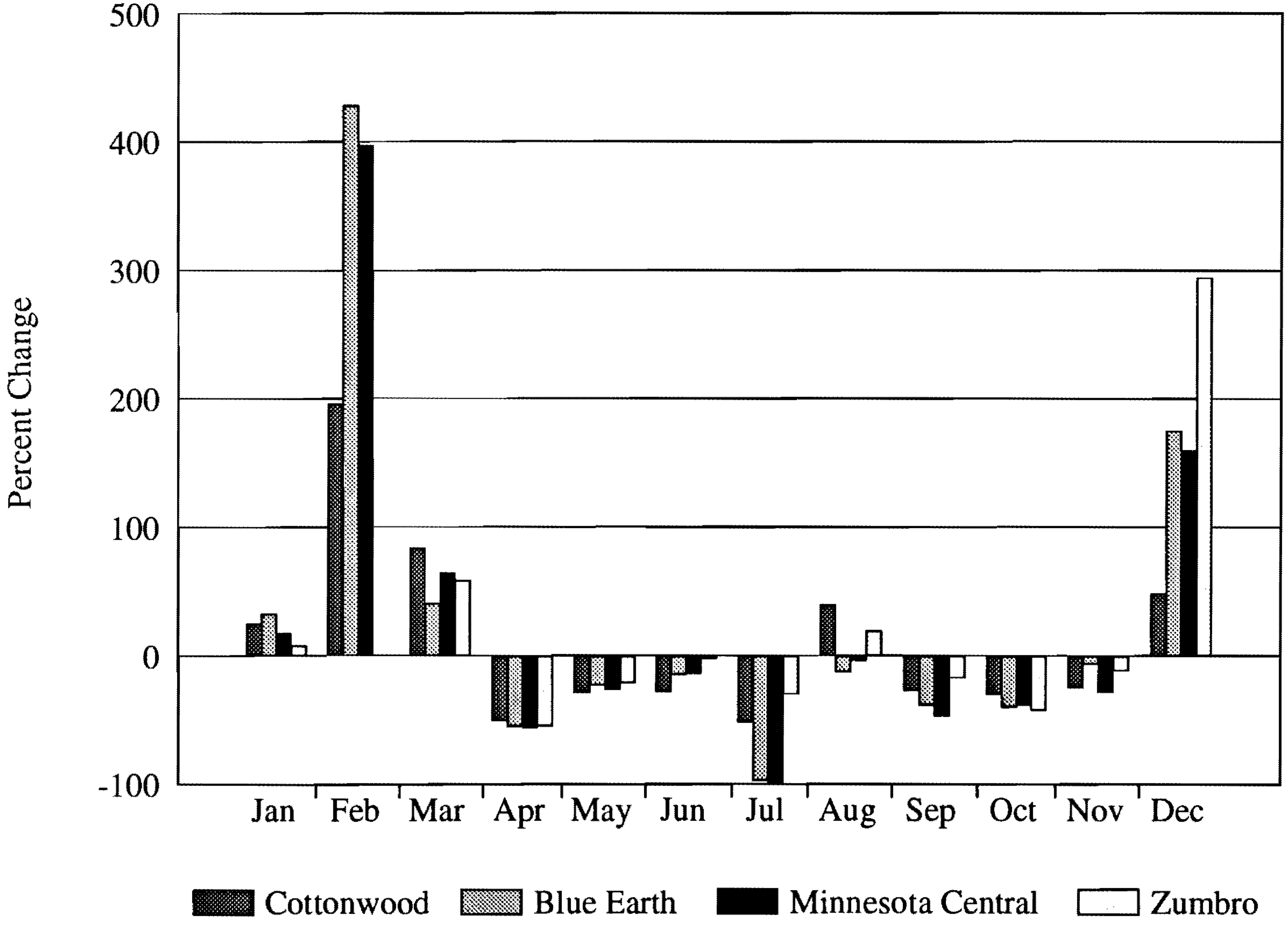


Figure 23. Southern Minnesota percent change in computed monthly moisture surplus.

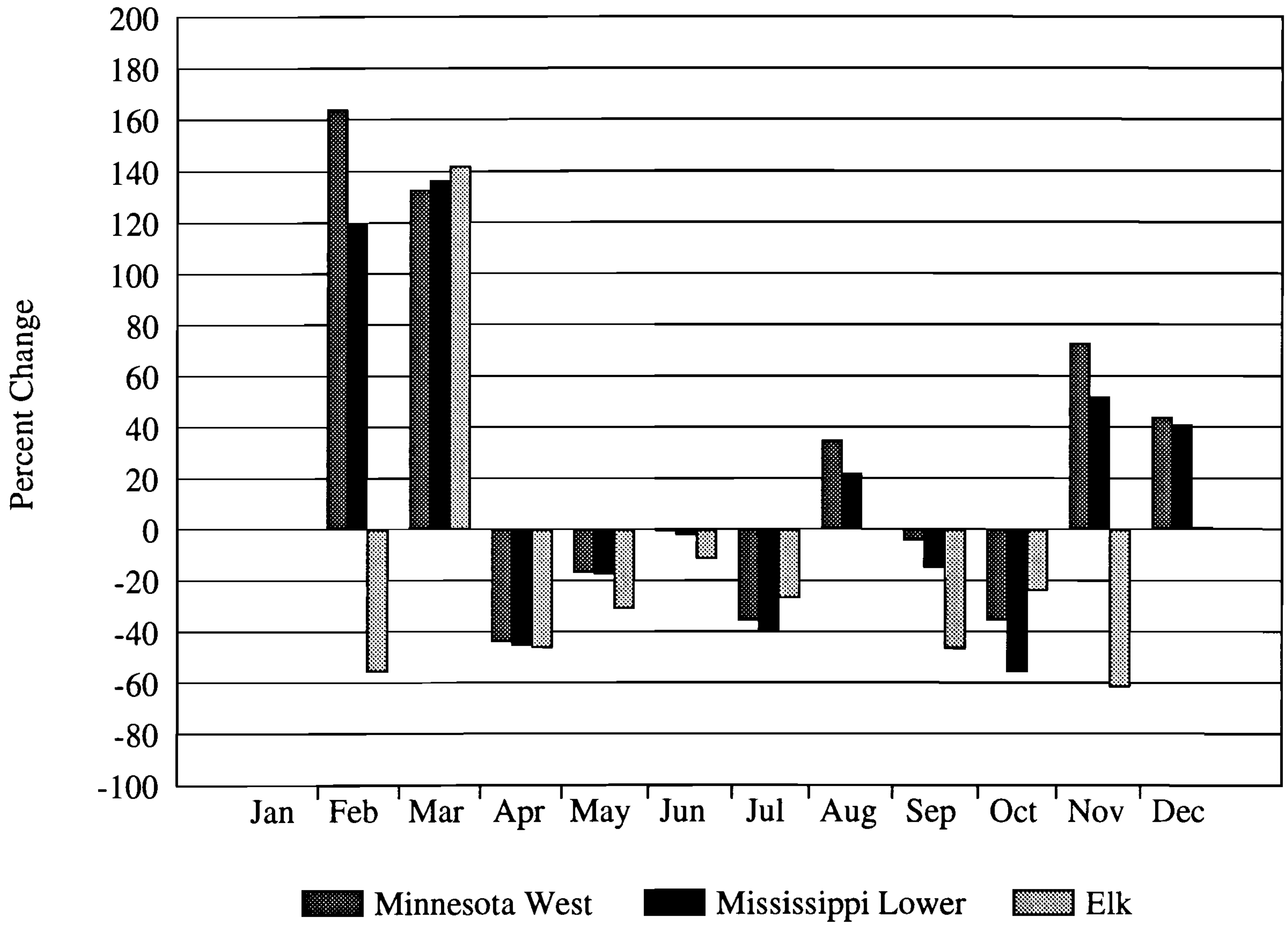


Figure 24. Central Minnesota percent change in computed monthly moisture surplus.

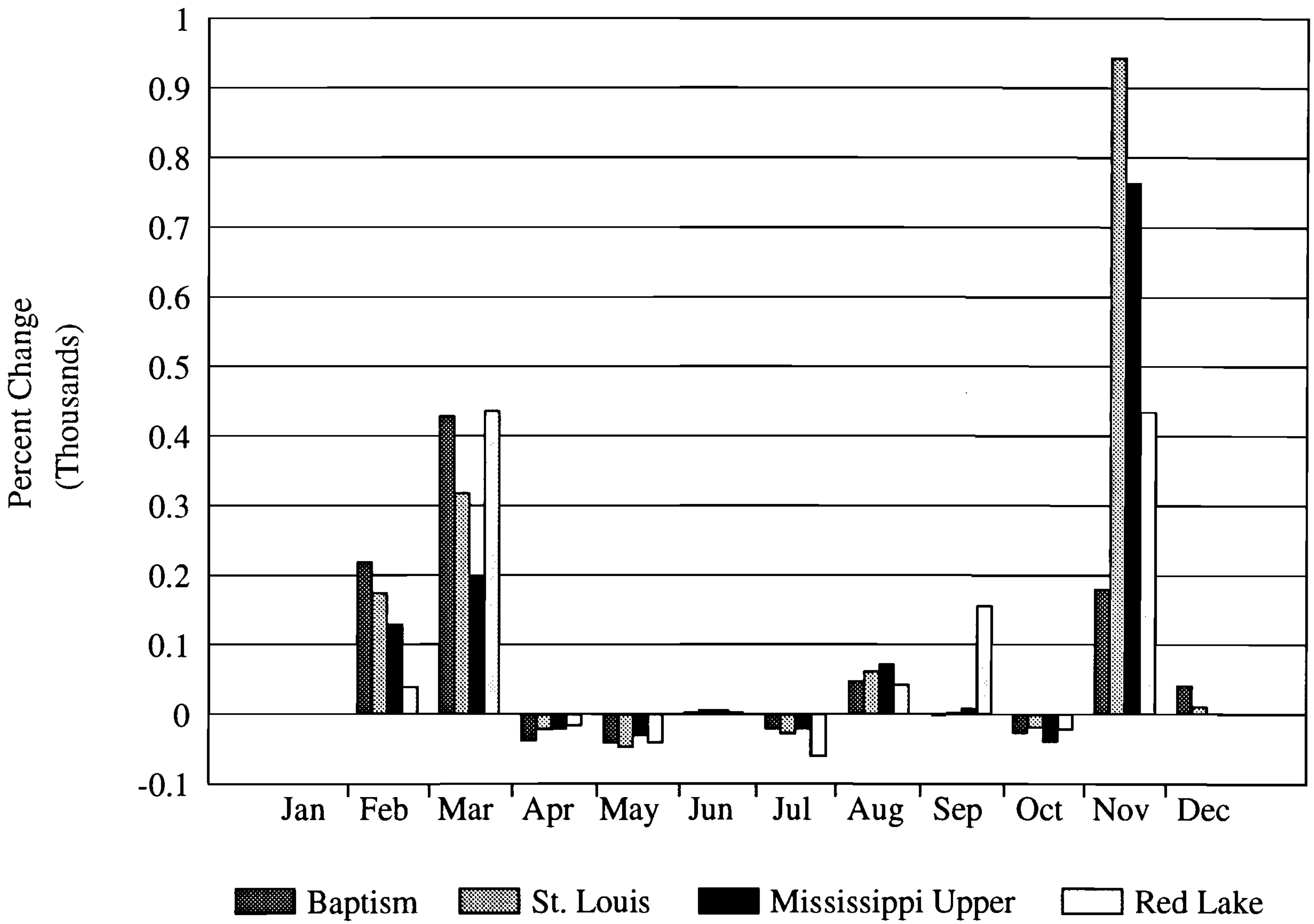


Figure 25. Northern Minnesota percent change in computed monthly moisture surplus.

nearby land surfaces are usually snow covered and are significantly colder. Therefore, over an area covering most of the Baptism River watershed, not only is there a potential supply of additional moisture, but warmer temperatures could allow the release of water through the melting of snow which would be reflected in increased surplus.

Well Levels

Figure 26 shows the approximate positions of the four selected wells within their respective counties. The specifications for each well are detailed below in Table 2 (Groundwater Unit, Division of Waters, 1989).

Table 2. Observation Well Specifications

County	Depth (ft)*	Record (yrs)	Region	Aquifer Type
Clay #14001	131	42	Northwest	QWTA
Morrison #49014	59	40	Central	QWTA
St. Louis #69001	40	35	Northeast	QBAA
Brown #08000	32	46	South Central	QWTA

* Depth in feet below land surface datum
QWTA = Quaternary Water Table Aquifer
QBAA = Quaternary Buried Artesian Aquifer

Well level data for these wells were plotted graphically (hydrographs) to see the patterns of fluctuation over the period of record. Two smoothing methods were applied to the data--a running median method (called 4253H in Velleman and Hoaglin, 1981) and Cleveland's LOWESS method (Cleveland, 1981). The running median procedure did not smooth the data adequately; therefore, Cleveland's method was used. The chosen value of F (the approximate fraction of points that are used in the calculation of each fitted value) was 0.2. This value is close to zero which indicates that more of the local details in the data will be picked up. The smoothed data show the general trends in the well levels and are plotted along with the observed well levels in Figures 27 and 28.

The observation well data were then analyzed by examining the relationship between divisional moisture surplus and the well level over various temporal lags. Water surplus values for the appropriate climatological division were used as the independent variable(s). Cross-correlation analysis (CCA) was performed to investigate the lag relationships. This examination of lags is important since it provides a way to test for relationships at later time periods thereby permitting the display of well level changes due to any precipitation that may infiltrate into and recharge the aquifer.

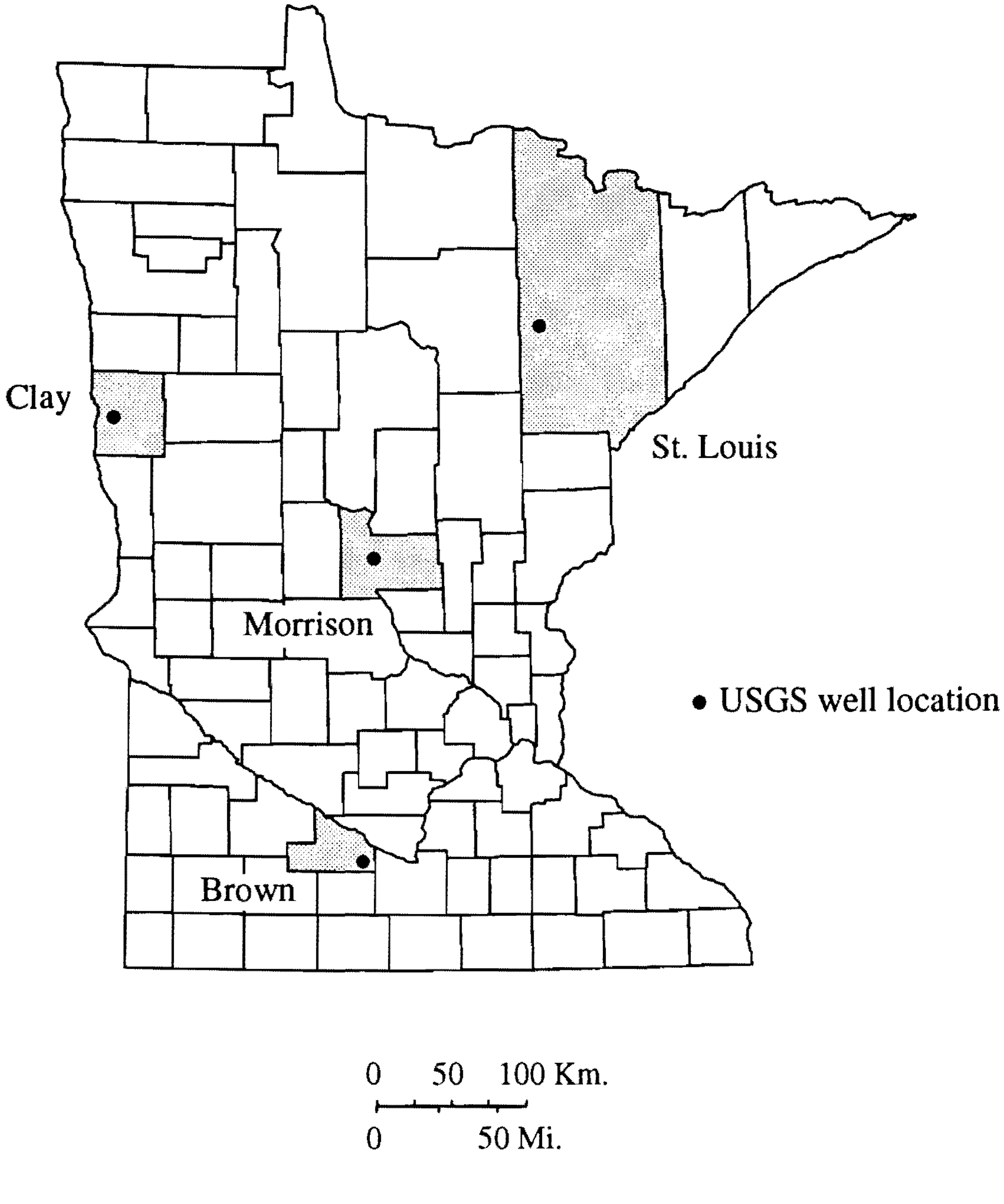


Figure 26. Selected observation well locations.

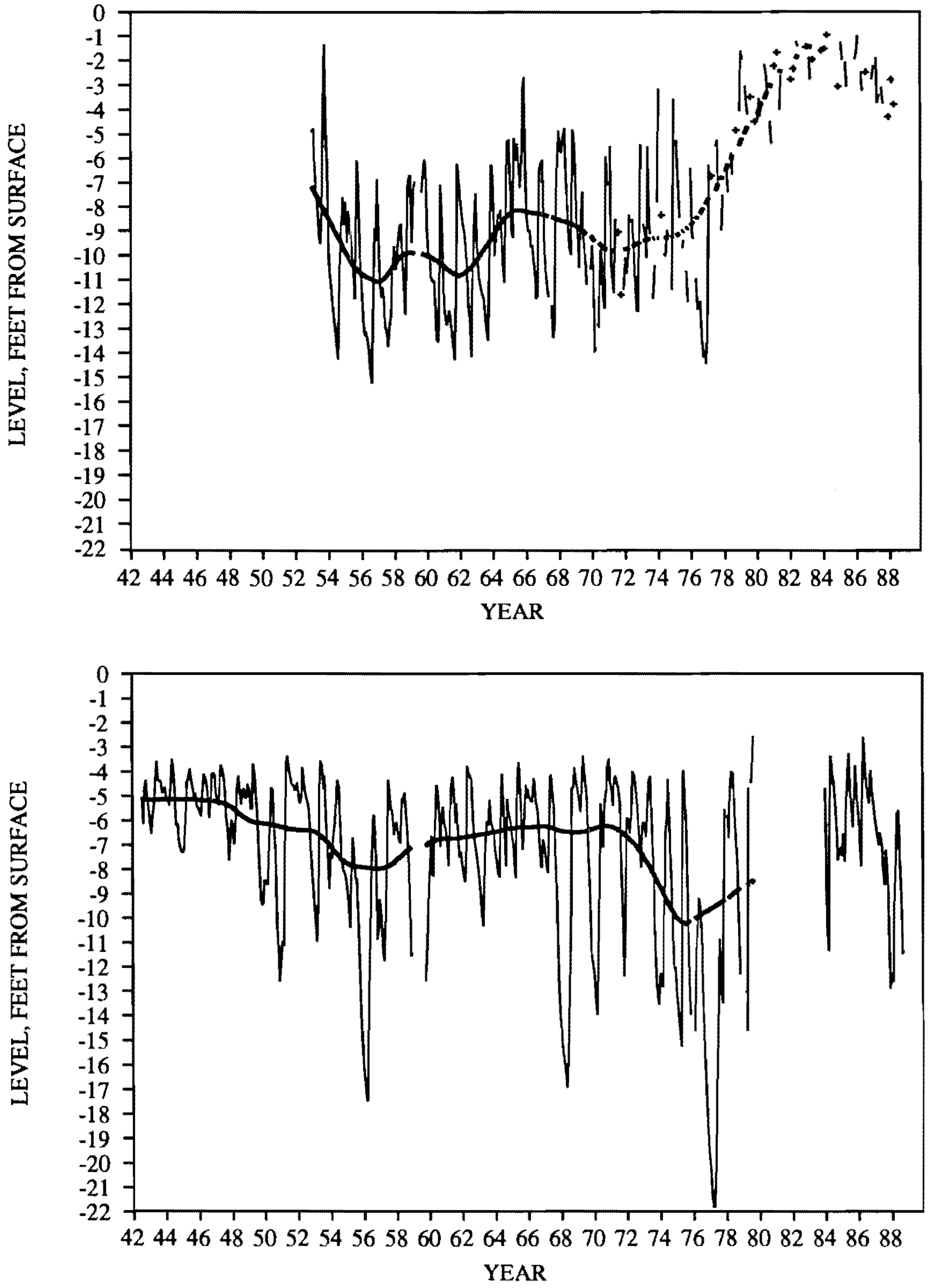


Figure 27. Observation well hydrographs showing observed level (——) and smoothed curve (▬▬) obtained by Cleveland's LOWESS method with f=0.2: (a) Well 69001 - St. Louis County, located in the northeast; and (b) Well 08000 - Brown County, located in south central Minnesota. Plus (+) marks indicate isolated level measurements during periods of infrequent observations.

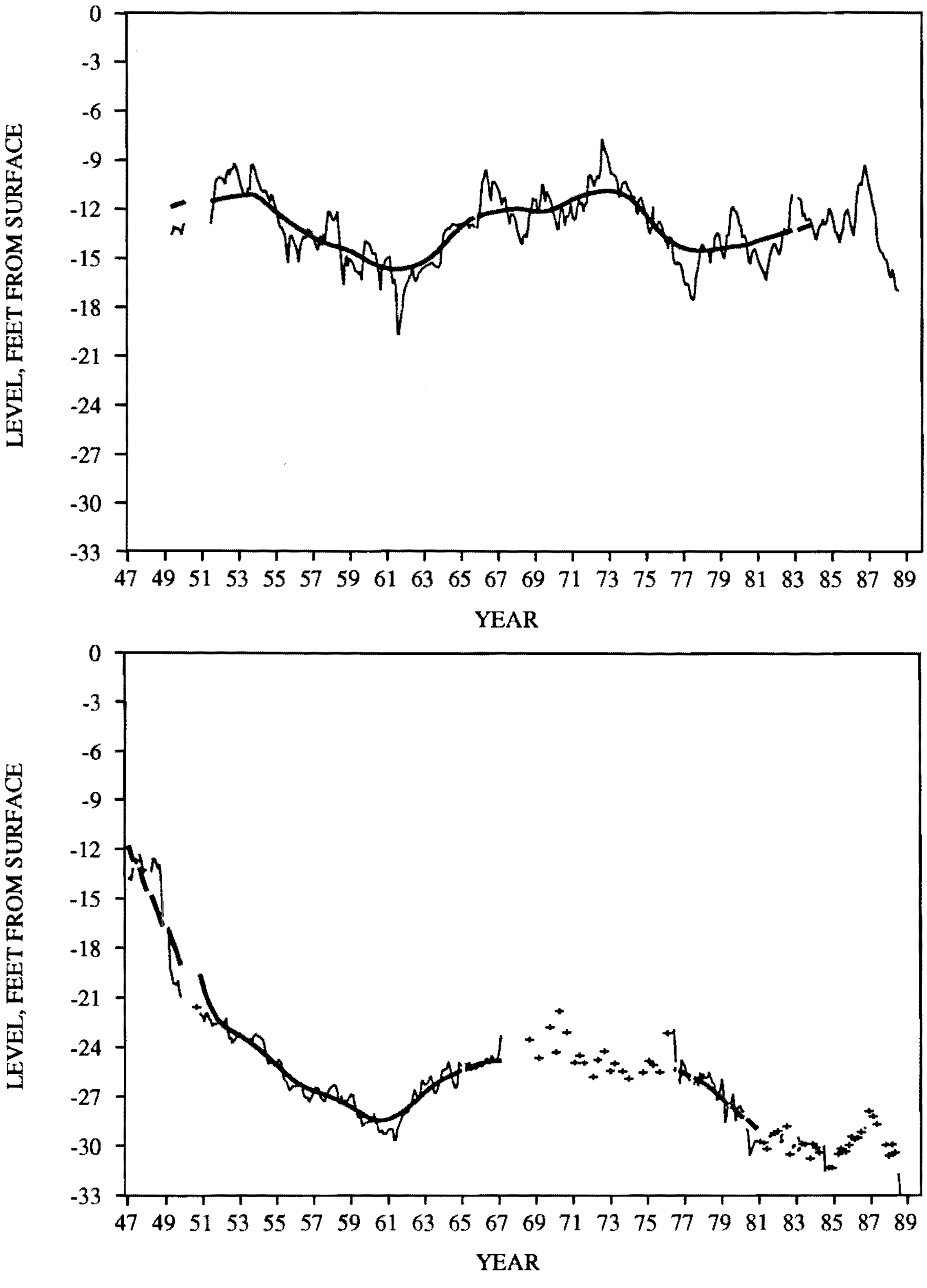


Figure 28. Observation well hydrographs showing observed level (——) and smoothed curve (——) obtained by Cleveland's LOWESS method with f=0.2: (a) Well 49014 - Morrison County, located in central Minnesota and (b) Well 14001 - Clay County, in the west central part of the state. Plus (+) marks indicate isolated level measurements during periods of infrequent observations.

Regression analyses were performed using divisional mean annual well level and moisture surplus summed over the calendar year. The models created using monthly data had first-order autocorrelations that were extremely large, ranging from 0.834 to 0.971. Within the annual models, a significant amount of autocorrelation remained which required that a first difference transformation of the dependent variable by taken. This differencing (replacing the yearly well level by the differences between that particular level and the previous level) removes the trend as well as the dependence from one year to the next.

Of the four wells that were examined, three were water table aquifers and one was a buried artesian aquifer. Only one of the water table aquifers showed any kind of significant relationship between moisture surplus and mean annual well level difference. Figure 29 shows the output of the regression analysis for Morrison County (#49014) and Clay County (#14001). The model for Morrison Co. fit rather well having a correlation coefficient of 0.704 and residual autocorrelation of -0.117. This model included surplus for the concurrent time period (lag 0) as well as for lag +2 years. On the other hand, the well in Clay Co. showed a very weak relationship where only 15% of the variance was explained by the model. The correlation coefficient was 0.385 and the serial autocorrelation value of 0.347 was still quite large. Well 08000, in Brown Co. showed no relationship between the variables at any time lag.

The last well, 69001 (a buried artesian aquifer), located in St. Louis Co., showed an interesting statistical relationship. Using mean annual well level (not the year to year difference), a CCA showed that the significant lags were at +13, +14, and +15 years. The fitted model had a surprisingly high correlation coefficient of 0.957, explaining approximately 92% of the variance. The serial autocorrelation coefficient was 0.219. Unfortunately, with long lags such as these and a relatively short period of record, there simply isn't enough data to ensure that this relationship would remain stable. This result is very interesting but clearly more data is required before anything definitive can be said about the relationship between moisture surplus and well level in this (type of) well.

Based on these analyses, it appears that the fluctuations in well levels do not behave in a similar fashion. Since a significant relationship could not be consistently found for all of the tested wells, it was concluded that the application of well data to facilitate modeling the impact of global warming on water resources in Minnesota is not feasible at this time. In the future, when well records have increased in length, this type of analysis should again be performed.

Lake Levels

The lake level data were obtained from the Department of Natural Resources (DNR) and contained stage readings which varied anywhere from none to several times per month. In recent years, the number of observations ranged between 15 - 20 with a maximum of 24 times per month. From these level values, the mean monthly and annual lake levels were calculated. The analysis was performed on an annual time scale because of the difficulties encountered when statistically modeling data having serial correlation. The first difference of the annual mean lake level was taken to remove some of the remaining autocorrelation. These first difference values were then used as the dependent variable in the statistical model.

For the independent variable(s), the water surplus values used were those calculated for the appropriate climatological divisions; division 3 for Vermilion Lake and division 6 for Lake Minnetonka (Figure 30). The computed surplus values were summed over the year (Jan-Dec).

Well 49014 - Morrison County

4 CASES DELETED DUE TO MISSING DATA.

DEP VAR: 1STDIFF N: 38 MULTIPLE R: 0.704 SQUARED MULTIPLE R: 0.495
ADJUSTED SQUARED MULTIPLE R: .467 STANDARD ERROR OF ESTIMATE: 0.332

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	-0.030	0.126	0.000	.	-0.238	0.813
SURPSUM	0.002	0.001	0.465	0.9600518	3.797	0.001
LAG2	-0.002	0.001	-0.443	0.9600518	-3.617	0.001

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
REGRESSION	3.777	2	1.889	17.178	0.000
RESIDUAL	3.848	35	0.110		

DURBIN-WATSON D STATISTIC 2.193
FIRST ORDER AUTOCORRELATION -.117

Well 14001 - Clay County

1 CASES DELETED DUE TO MISSING DATA.

DEP VAR: 1STDIFF N: 41 MULTIPLE R: 0.385 SQUARED MULTIPLE R: 0.148
ADJUSTED SQUARED MULTIPLE R: .126 STANDARD ERROR OF ESTIMATE: 0.371

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	-0.263	0.076	0.000	.	-3.476	0.001
SURPSUM	0.003	0.001	0.385	.100E+01	2.605	0.013

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
REGRESSION	0.932	1	0.932	6.785	0.013
RESIDUAL	5.356	39	0.137		

DURBIN-WATSON D STATISTIC 1.277
FIRST ORDER AUTOCORRELATION .347

Figure 29. Regression output for Morrison County (#49014) and Clay County (#14001).

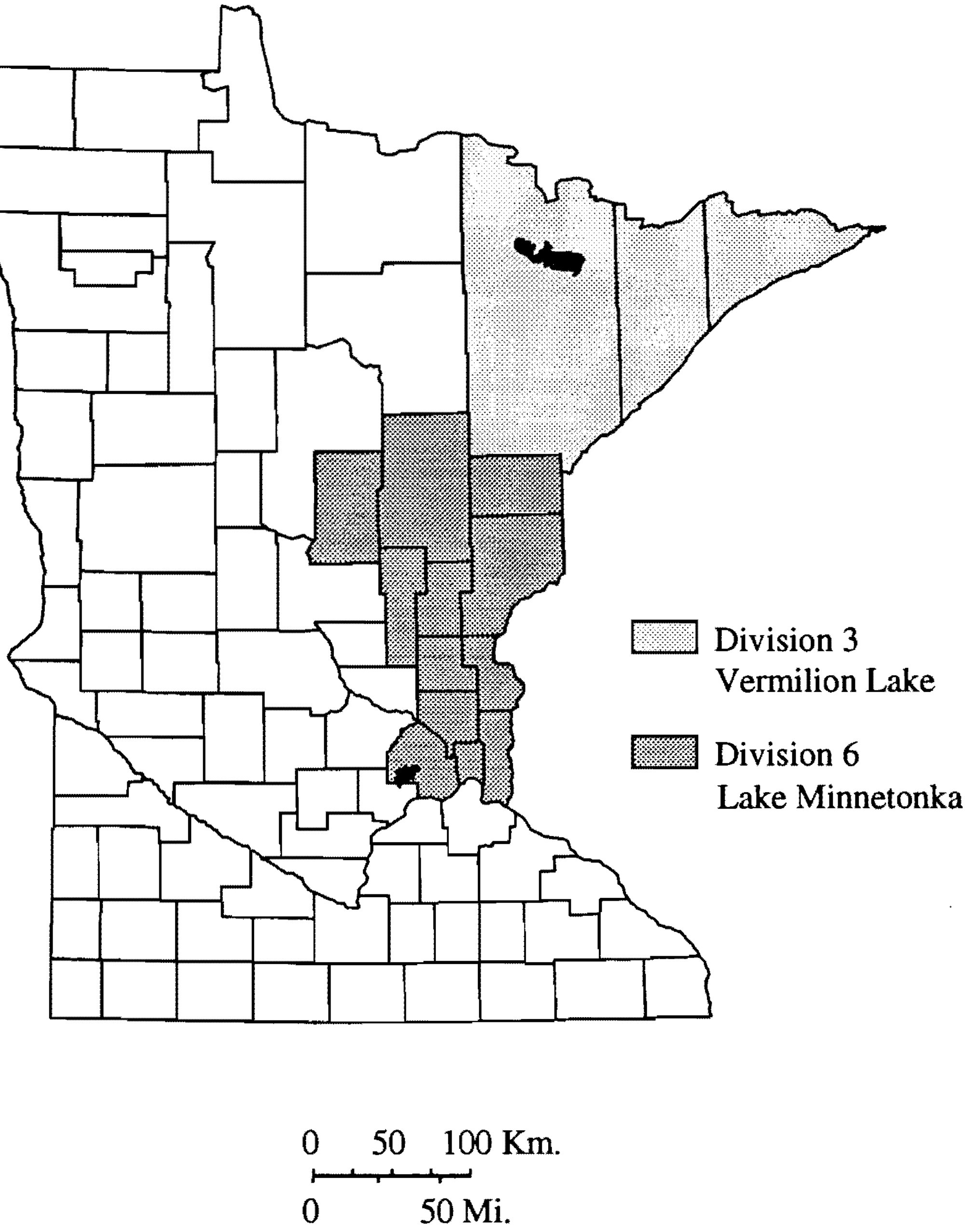


Figure 30. Selected Minnesota lakes.

CCA was performed to investigate any lag relationships. For Vermilion Lake, significant correlations occurred for the concurrent time period (lag 0) and for lag +1. Since the dependent variable is a difference, an example of the interpretation of these lags would be:

Lag 0 = 1989 surplus sum correlated with the 1989-1988 annual level difference;
Lag +1 = 1989 surplus sum correlated with the 1990-1989 annual level difference (1 year into the future).

This model fit reasonably well having a correlation coefficient of 0.764 and residual autocorrelation of -0.178.

The same approach was taken to model Lake Minnetonka, however, there were several significant problems. In the early years of the Lake Minnetonka record (1906 - 1936), there was an absence of lake level measurements during the winter months, generally November through March. These winter month measurements have a statistically significant impact upon the annual mean lake level. Therefore, simply using the mean annual level computed with the available months for the entire period of record (1906 - 1991) was inappropriate. To avoid this problem, the model was fitted using the annual mean lake level for the period 1937 - 1991 only. Unfortunately, this model excluded valuable data from the early part of the century and was complicated by the strong autocorrelation within the dependent variable (lake level difference). The next approach to modeling was to use the September lake level (end of the water year) and the surplus sum over the water year. Once again the first difference was used for the lake level (Sept-Sept).

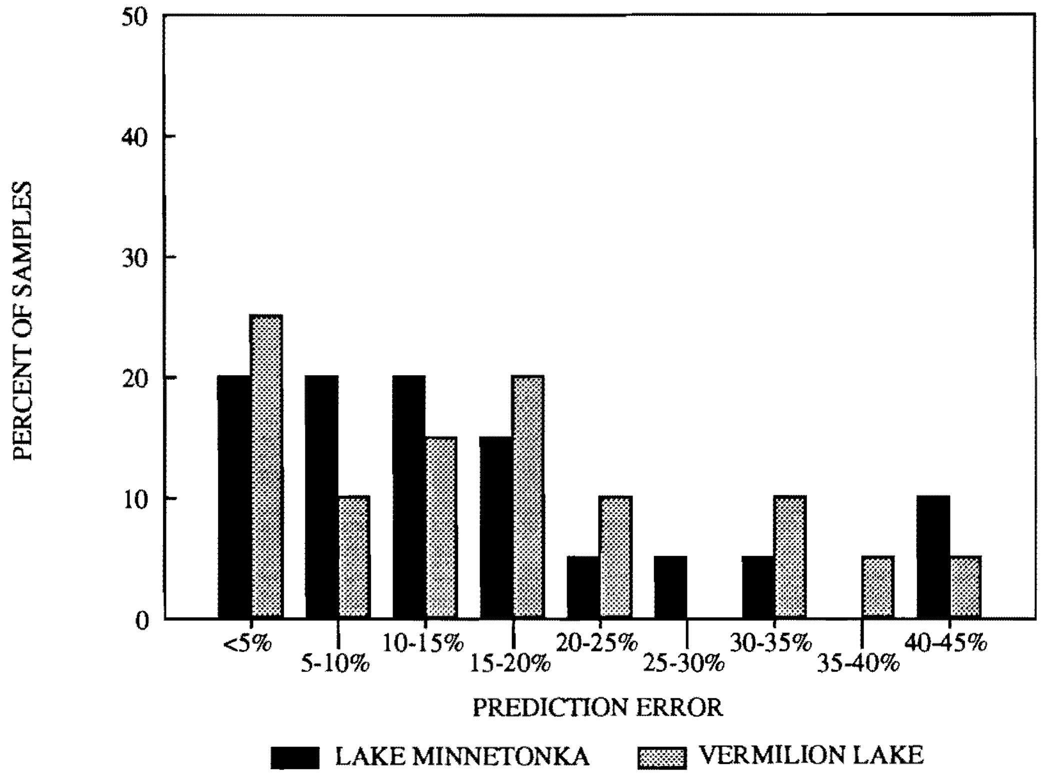
CCA was again used to search for any lag relationships. For Lake Minnetonka, the significant correlations occurred for the concurrent time period (lag 0) and for lag +2. An example of the interpretation of these lags would be:

Lag 0 = 1989 water year surplus sum correlated with the 1989-1988 September level difference;
Lag +2 = 1989 water year surplus sum correlated with the 1991-1990 September level difference (2 years into the future).

This model, which was the best model that could be used for this data set, fit rather poorly having a correlation coefficient of 0.504, but now had a satisfactorily small residual autocorrelation of -0.143.

Validation of both models was performed using the technique of cross-validation. Prediction errors were found by defining a column of weights for weighted least squares where values with a weight of one were used to construct the model and values with zero weight were used for the verification. Estimated values, residuals, and other related statistics were computed for the zero weight cases which were initially ignored in building the model. For each lake, 20 random samples were taken and the regression mean square for each was compared to that obtained for the model built using all of the data (Figure 31). For both lakes, 70-75% of the samples had average prediction error of 20% or less. The remaining samples had excessively high error values, specifically, 10% of the samples for Vermilion Lake had an average prediction error of between 30-35%, with another 10% of the samples with errors between 35-45%. A 45% prediction error on Vermilion Lake equates to a level difference error of about one inch. For Lake Minnetonka, 10% of the samples had error levels of 40-45%. In the case of Lake Minnetonka, this amounts to a lake level difference error of approximately 10 inches.

The temperature change and precipitation ratio estimates from the GISS GCM model were used to adjust the observed temperature and precipitation records for each of the



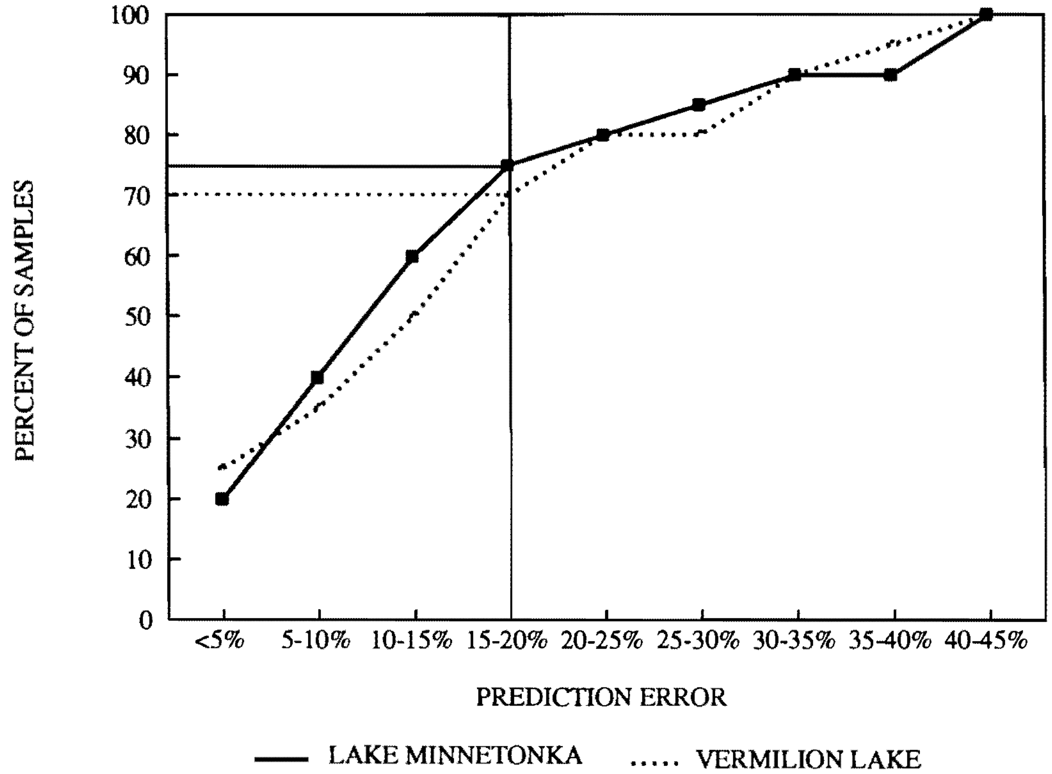


Figure 31. (a) Lake level model average prediction errors and (b) cumulative frequency of prediction error values for samples of size 20.

divisions. The water budgets were recalculated using these $2xCO_2$ values. These new surplus values were used as predictor variables in the previous models that showed the relationship between total moisture surplus and mean lake level difference (over the appropriate periods).

Lake Minnetonka

The observed mean September lake level difference averaged over the entire period of record was 4.0 mm. The model estimated ($1xCO_2$ or current climate) mean September lake level difference over the same period was found to be 5.2 mm and the model estimated difference for the $2xCO_2$ climate was 6.0 mm. A comparison of model estimates showed an increase in September to September (year-to-year) difference or variability for the $2xCO_2$ conditions but by only 0.8 mm. The maximum Sept-Sept difference between the $2xCO_2$ and the $1xCO_2$ estimates was approximately 45 mm ($2xCO_2$ model with the larger difference). Unfortunately with possible prediction errors of up to 254 mm for this lake, these estimates must be considered unreliable.

Vermilion Lake

For Vermilion Lake, the observed mean annual lake level difference averaged over the period of record was 4.13 mm which was exactly equalled by the $1xCO_2$ model estimate. The difference estimated for doubled CO_2 is 3.88 mm. For this lake, the change between $2xCO_2$ and $1xCO_2$ climates appeared to be a decrease in variability in lake level from the current climate to the new climate. This estimated decrease amounts to approximately 0.25 mm. The estimated maximum annual difference between the two climates was about 110 mm. Prediction errors approaching 26 mm (six times the mean value for the entire period), are possible for Vermilion, so again like Minnetonka, the estimates should be used with caution and only in a qualitative fashion (if at all).

Overall, the potential changes in lake level and level variability associated with a doubling of atmospheric CO_2 that are visible for both lakes are interesting albeit small. It is unfortunate that a more conclusive statement cannot be made about the impact of this new climate on lake level and that quantitative estimates of yearly changes in level and water volume cannot be reliably computed.

Summary & Conclusions

We examined the sensitivity of Minnesota's water resources to predicted climate changes due to global warming. The results indicate that a doubling of atmospheric CO_2 significantly influences the amount, as well as the spatial and temporal distribution of several water supply variables; namely, river flow, soil moisture, and moisture surplus.

The predicted increases in temperature induce a shift in the times of the year when the mean monthly temperatures are below freezing. Under the new climate, the mean monthly temperature crosses the 0°C line earlier in the spring (March) and later in autumn (November) by about two weeks. This is evident in every watershed basin and serves as a factor in the shifts observed in the temporal distributions of the water supply variables.

Overall, there is a general decrease in river flow across the entire state, however, the magnitude and direction of the change is not uniform. A definite north to south gradient is apparent, with modest decreases occurring in the northern third and substantial decreases in the south. On a temporal basis, the period of peak flow which coincides with the spring snow melt shifts into March instead of April. Additionally, in the latter parts of the year, higher flows are noted in November and December since warmer temperatures result in soils remaining unfrozen for a longer period of time allowing continued runoff.

The soil moisture and moisture surplus parameters also show a shift in the spring time due to the earlier thaw. Beginning in April, there is a general decline in soil moisture with a minimum occurring in October. This is in contrast to the typical condition of a maximum in June and a minimum reached in September under current climatic conditions. Growing season moisture surplus is generally decreased over the period with a slight increase seen in August due to a large value of GISS GCM predicted precipitation. During the winter months (November-February), substantial increases in soil moisture are found in the northern one-third of the state. Increases in moisture surplus are observed over the entire state during much of the winter. Analogous to river flow, both variables exhibit a lack of spatial homogeneity across the state as a whole. Again, there is a pronounced latitudinal gradient but with different groupings than those for river flow. Here, the southern two-thirds of the state are distinctly different from the northern one-third.

This analysis was also performed on lake and observation well levels. Unfortunately, the results are of limited use. While the lake models did show visible declines in level associated with a doubling of CO_2, they proved to be unstable and would provide unreliable quantitative estimates of level change. As for the well levels, based on the length of the records as well as the variation in the behavior of similar types of wells, it was concluded that the scenario building exercise was not justifiable at this time.

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Appendix A - Thornthwaite Water Balance

Thornthwaite's method is an empirically derived technique that was developed by using regression analysis to define potential evapotranspiration (PE) in terms of temperature alone. Thornthwaite based his work on the assumption that surface air temperature can be substituted for surface radiation fluxes within the known physical relationship between radiation and evapotranspiration (E_t), i.e., an assumption was made that temperature and radiation are correlated. The additional motivation for his methodology was the fact that there was a lack of radiation measurements available for analysis.

Following the computation of PE, his technique then uses an accounting system for the estimation of actual PE (AET), soil moisture, surplus, and deficit (PE-AET). As defined by Thornthwaite, PE is "water loss from an extensive, closed homogeneous cover of vegetation that never suffers from a lack of water." Precipitation and soil moisture are the moisture sources and evapotranspiration (E_t) changes as moisture is added to or extracted from the soil. The assumption is that all precipitation goes to PE and AET will proceed at the PE rate as long as precipitation is not limiting.

The calculation of the Thornthwaite water budget requires the following information:

1) mean monthly air temperature;
2) total monthly precipitation;
3) water holding capacity of the depth of soil for which the balance is being computed;
4) information on constants necessary for the computations such as latitude, heat index value (which can be computed by balancing), and soil moisture resistance.

Thornthwaite's method works well over longer periods of time (such as on a monthly basis) and in temperate continental regions (region where the method was developed). Several authors have pointed out the limitations of using Thornthwaite for daily computations (Jensen and Haise, 1963; Penman, 1956). They point out that since Thornthwaite's formula does not include radiation, wind and humidity directly, the PE value is not accurate on a daily basis. However, on a monthly basis, these factors, which influence E_t, do not show significant variation over such a period and PE calculations can therefore be based solely on mean monthly temperature.

Appendix B - Moisture Surplus/River Flow Correlations
Matrices of Spearman Correlation Coefficients

Baptism River

	FLOW	S0	S3
FLOW	1.000		
S0	0.841	1.000	
S3	-0.426	-0.242	1.000

Blue Earth River

	FLOW	S0	S1
FLOW	1.000		
S0	0.727	1.000	
S1	0.261	-0.022	1.000

Cottonwood River

	FLOW	S0	S1
FLOW	1.000		
S0	0.639	1.000	
S1	0.199	0.033	1.000

Elk River

	FLOW	S0	S1
FLOW	1.000		
S0	0.749	1.000	
S1	0.092	-0.124	1.000

Mississippi River (near Anoka)

	FLOW	SU0	SL1	SL2	SL3	SL4
FLOW	1.000					
SU0	0.700	1.000				
SL1	0.200	-0.143	1.000			
SL2	0.038	-0.120	-0.083	1.000		
SL3	-0.027	-0.157	-0.032	-0.083	1.000	
SU4	0.561	0.609	-0.079	-0.028	-0.171	1.000

Matrices of Spearman Correlation Coefficients (cont.)

Mississippi River (at St. Paul)

	FLOW	SC0	SL1	SL2	SU4
FLOW	1.000				
SC0	0.621	1.000			
SL1	0.257	-0.140	1.000		
SL2	0.027	-0.038	-0.070	1.000	
SU4	0.518	0.482	-0.099	-0.007	1.000

Red Lake River

	FLOW	S0	S1	S2	S3	S4
FLOW	1.000					
S0	0.553	1.000				
S1	0.153	-0.136	1.000			
S2	-0.017	-0.162	-0.136	1.000		
S3	-0.047	-0.143	-0.162	-0.136	1.000	
S4	0.417	0.503	-0.143	-0.162	-0.136	1.000

St. Louis River

	FLOW	S0	S1	S2
FLOW	1.000			
S0	0.802	1.000		
S1	0.042	-0.223	1.000	
S2	-0.061	-0.106	-0.228	1.000

Zumbro River

	FLOW	S0	S1	S3
FLOW	1.000			
S0	0.643	1.000		
S1	0.096	-0.024	1.000	
S3	0.186	-0.101	-0.034	1.000

Appendix B cont.

Moisture Surplus/River Flow Partial Correlation Coefficients (PCC)
Partial Correlations with Mean Flow

Baptism River
Model Independent Variables = S0, S3

Variable(s) held constant	PCC Computed for Variable	Partial Correlation Coefficient
S3	S0	-0.899
S0	S3	-0.284

Blue Earth River
Model Independent Variables = S0, S1

Variable(s) held constant	PCC Computed for Variable	Partial Correlation Coefficient
S1	S0	0.874
S0	S1	0.391

Cottonwood River
Model Independent Variables = S0, S1

Variable(s) held constant	PCC Computed for Variable	Partial Correlation Coefficient
S1	S0	0.804
S0	S1	0.212

Elk River
Model Independent Variables = S0, S1

Variable(s) held constant	PCC Computed for Variable	Partial Correlation Coefficient
S1	S0	0.857
S0	S1	0.356

Matrices of Partial Correlation Coefficients (cont.)

Mississippi River (near Anoka)
Model Independent Variables = SU0, SL1, SL2, SL3, SU4

Variable(s) held constant	PCC Computed for Variable	Partial Correlation Coefficient
SL1, SL2, SL3, SU4	SU0	0.799
SU0, SL2, SL3, SU4	SL1	0.478
SU0, SL1, SL3, SU4	SL2	0.347
SU0, SL1, SL2, SU4	SL3	0.213
SU0, SL1, SL2, SL3	SU4	0.278

Mississippi River (at St. Paul)
Model Independent Variables = SC0, SL1, SL2, SU4

Variable(s) held constant	PCC Computed for Variable	Partial Correlation Coefficient
SL1, SL2, SU4	SC0	0.711
SC0, SL2, SU4	SL1	0.556
SC0, SL1, SU4	SL2	0.230
SC0, SL1, SL2	SU4	0.436

Red Lake River
Model Independent Variables = S0, S1, S2, S3, S4

Variable(s) held constant	PCC Computed for Variable	Partial Correlation Coefficient
S1, S2, S3, S4	S0	0.785
S0, S2, S3, S4	S1	0.379
S0, S1, S3, S4	S2	0.190
S0, S1, S2, S4	S3	0.145
S0, S1, S2, S3	S4	0.343

Matrices of Partial Correlation Coefficients (cont.)

St. Louis River
Model Independent Variables = S0, S1, S2

Variable(s) held constant	PCC Computed for Variable	Partial Correlation Coefficient
S1, S2	S0	0.915
S0, S2	S1	0.361
S0, S1	S2	0.173

Zumbro River
Model Independent Variables = S0, S1, S3

Variable(s) held constant	PCC Computed for Variable	Partial Correlation Coefficient
S1, S3	S0	0.777
S0, S3	S1	0.231
S0, S1	S3	0.313