GIS ASSESSMENT OF GCM FORECASTS OF UPPER AIR CIRCULATION AND EXPECTED IMPACTS ON WINTER PRECIPITATION IN WESTERN NORTH AMERICA.

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ABSTRACT

This study assesses the impact of global warming on northern Rocky Mountain States April 1 snowpack as influenced by 50 kPa synoptic fields for 1x and 2x CO2 warming scenarios generated by the CCC GCM-II. The synoptic pattern observed was subjectively classified into one of seven 50-kPa winter time synoptic patterns that explained almost ninety percent of the non-average annual snowpack patterns in the study area. Two analysis were completed: first to compare the 1xCO2 predictions of synoptic type frequency to historical data, and secondly to compare 1xCO2 predictions to the 2xCO2 simulation. The 1xCO2 run of the GCM was found to statistically simulate the historical patterns well for all but one of the seven synoptic patterns. Comparison of the 2x and 1x run of GCM indicates a statistically significant increase in a synoptic pattern associated with wet conditions in the north of the study region and dry conditions in the south, and a decreased frequency of patterns resulting in dry conditions in northern regions and relatively wet conditions in the south. From this analysis is expected that the decrease in mid-latitude jet occurrence over the southern regions of the study area could result in lower snowpack conditions over this region in a warmed scenario.

INTRODUCTION AND BACKGROUND

Most of the natural streamflow that occurs over the western plains of Canada and the United States is derived from snowpack that accumulates over winter in the Rocky Mountains. This water supply provides for millions of acres of irrigation, potable water for urban and rural municipalities, industrial use, and sometimes provides for minimal aquatic ecosystem maintenance. The human and natural systems to the east of the Rocky Mountains have evolved based on a reliable snow melt water supply.

Increases in atmospheric concentrations of greenhouse gases have raised serious concerns with respect to change in regional climate and hydrology. The science community has forecast that increased CO2 concentrations in the atmosphere will result in global climate warming.

General Circulation Models (GCMs) have been found to provide a reasonable, physically based approach for simulating future climatic scenarios at a subcontinental and larger scale. However, GCMs are not successful at simulating some climate variables for smaller geographic regions. Saunders and Byrne (1994) found the Canadian Climate Centre GCM-II (referred to hereafter as the CCC GCM - - the CCC GCM is described in McFarlane et al. 1992) did not accurately simulate historical precipitation time series for Western Canada. Overall, precipitation simulation in GCMs is not entirely successful as many of the processes controlling precipitation occur at scales not accounted for in a GCM.

To overcome this drawback attempts have been made to downscale local climatic variables from synoptic pressure fields (Von Storch et al. 1993). Saunders and Byrne (1996) found CCC GCM synoptic flow patterns simulated historical conditions accurately for a window centred on the prairie provinces and adjoining portions of BC, NWT and the northern US. This strong relationship allowed them to generate regional precipitation scenarios with CCC GCM 50 kPa fields. They stated the generated monthly precipitation scenarios "tracked observed (precipitation) quite closely, only differing in May. " This appears to be in direct contradiction to the analysis of McKendry et al.

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(1995) who reported that CCC GCM 50-kPa pressure fields did not agree well with control data for a GCM window centred on the pacific northwest coastline (including British Columbia, Washington State, northern Oregon and a large portion of the eastern Pacific ocean). However, their window was essentially a maritime climate, and circulation is likely controlled by the vast ocean surface to the west of their window. In the study of Saunders and Byrne (1996), the window focused on a broad region dominated by continental climate controls, and included the interior of BC, a transition zone between the maritime and continental climates.

The conclusions of both Saunders and Byrne (1996), and McKendry et al. (1995) are somewhat dependent on the size of the window. We argue that neither selected a window of sufficient size to adequately capture true synoptic scale circulation at the 50-kPa level. Our analysis minimizes the "window" impact by adopting a very large North American window of the CCC GCM to assess climate change impacts on winter precipitation for five Rocky Mountain northern states.

OBJECTIVE

This paper assesses the impact of global warming on northern Rocky Mountain States April 1 snowpack as influenced by 50 kPa synoptic fields for 1x and 2x CO_2 warming scenarios generated by the CCC GCM.

The rationale for pursuing this objective is twofold. First, intensity and frequency of mid latitude jetstreams over a location controls synoptic precipitation (orographic and cyclonic) during winter months at that location (Ahrens, 1994). Second, the majority of winter precipitation is synoptic (either cyclonic or orographic), particularly within western North American alpine regions.

STUDY REGION

The area of interest for this study is the northern Rocky Mountain states (Colorado, Utah, Idaho, Montana and Wyoming). The historical snowpack analysis of this region was carried out by Changnon et al (1993) using 275 long-term alpine snow courses scattered over the five states. The five states are shaded in Figures 1 through 7.

METHODOLOGY

The CCC GCM-II model, as described by McFarlane et al (1992), is a second generation GCM that evolved from the 1984 CCC GCM-I. The second generation model includes: interactive cloud parameterization; and has improved means of calculating solar and terrestrial radiative exchange; better simulation of land surface processes; and a simple ocean-surface mixed layer model including a thermodynamic sea ice routine. The CCC GCM-II also has a finer horizontal scale grid simulation compared to the 1984 CCC GCM-I (McKendry et al, 1995).

The first step in the methodology required we define the daily 50 kPa pressure fields for the North American window. The Canadian Climate Centre provided the daily simulation data for the CCC GCM. The data simulations are on a twelve-hour time step; however we chose to use only one daily data set. The daily data for eight years for the months of November, December, January, February and March were imported into the PAMAP GIS for analysis of the pressure fields. Script command files were written to carry out the following steps to define the daily pressure fields.

- Import the 50-kPa gridded elevation point data set from the CCC GCM database.
- Define the daily 50-kPa surface as a spatial elevation model using surface fitting techniques available in the GIS.
- Define the location(s) of the principal westerly jet - - the zone of greatest wind velocity was defined with surface slope analysis techniques in the GIS. Slope in the GIS was calculated as rise/run expressed as a percentage. The zone of greatest surface slope was defined as the core of the westerly flow i.e. steep pressure gradients creates the strongest winds (Lutgens and Tarbuck, 1995).

Synoptic patterns associated with a range of winter precipitation in the Rocky Mountain states were evaluated by Changnon et al (1993). They found that three basic and persistent patterns of snowpack values were notable:

- years with a consistent anomaly over the entire region (wet or dry years);
- years with a distinct north to south gradient; and
- average years.

Changnon et al. (1993) stated that seven 50-kPa winter time synoptic patterns explained almost ninety percent of the non-average annual snowpack patterns in the study area. In this study, we adopted the patterns defined by Changnon et al (1993) for our analysis of the GCM 1x and 2x CO_2 output. Obviously, in order to have faith in the GCM forecast of synoptic conditions under the 2x scenario, we had to evaluate whether the GCM 1x output simulated the historical patterns in terms of pattern types; and frequency of pattern type occurrence. If the GCM 1x CO_2 output simulated historical 50 kPa pattern types and frequencies, then one may place sufficient confidence on the GCM 2x CO_2 output to build future precipitation scenarios based on pattern types/frequencies.

Figures 1 through 7 are the synoptic patterns identified by Changnon et al (1993) as related to inter-annual and long-term variability in April 1 snowpack in the Rocky Mountain States under consideration. The daily GCM forecast of the 50 kPa circulation pattern for 1x CO_2 conditions was visually assigned to one of seven classes as illustrated in Figures 1 through 7. Circulation patterns not fitting any of the seven were classified as undefined. Association statistics were used to evaluate whether the 1x CO_2 output accurately simulated the pattern types and occurrence frequencies reported by Changnon et al. (1993).

The same visual classification method was used to evaluate the pattern types and frequencies under a 2x CO_2 climate scenario.

April 1 snowpack for the study area was linked to the dominance of patterns in a given winter by Changnon et al. (1993). For purposes of the analysis here, we presumed these linkages would hold in a warmed atmosphere. Intuitively, one may argue a warmer climate could result in more precipitation associated with some/all the synoptic patterns (greater water vapor storage at higher air temperatures), but some of this precipitation would fall as rain rather than snow. Rainfall-runoff and snowmelt-runoff ratios are substantially different. Typically, snowmelt-runoff ratios are much higher than rainfall-runoff ratios. Additional rain in a warmed environment may not convert to additional runoff. To account for runoff differences due to precipitation phase state work on a detailed alpine hydrometeorology model is being completed.

The forecasts of April 1 snowpack conditions for 2x CO_2 scenarios is related to conditions based on the frequency of given synoptic patterns occurring over the study area.

RESULTS AND DISCUSSION

In the absence of normality for the 1x GCM and 2x GCM distributions (given the limited number of years simulated), the structure and differences in the annual frequencies of each of the synoptic 50 kPa pressure patterns was assessed with non-parametric methods. The first stage of the analysis was concerned with exploring whether or not the 1x CO_2 run of the GCM was inconsistent with the historical data of Changnon et al. (1993). We compare both the differences in distributional characteristics and differences in central tendency for the annual frequencies of each of the synoptic types—employing a Kolmogorov-Smirnov (K-S) test for the former, and a Mann-Whitney U-test (M-W) for the latter (Tables 1 and 2). A second stage analysis, using the same methods, compared the 2x CO_2 run of the GCM with the historical data in order to identify significant changes in the synoptic types under the simulated warmer scenario (Tables 3 and 4).

Table 1.
K-S test for Differences in Distribution of 1x GCM and Historical 50kPa Pressure Fields

	DR	NWM	NWW	NWZ	SWS/SWC	SWT
K-S, Z	1.285	1.239	.848	.939	.793	.204
Sig. (2 tailed)	.074	.093	.469	.342	.556	.000

Table 2.
M-W test for Differences in Average Annual Frequency of 1x GCM and Historical 50kPa Pressure Fields

	DR	NWM	NWW	NWZ	SWS/SWC	SWT
M-W	80.0	82.0	106.0	91.0	549.5	22
Sig. (2 tailed)	.061	.070	.288	.123	.907	.000

Table 3.
K-S test for Differences in Distribution of 2x GCM and Historical 50kPa Pressure Fields

	DR	NWM	NWW	NWZ	SWS/SWC	SWT
K-S, Z	1.722	.556	2.014	.529	1.750	2.041
Sig. (2 tailed)	.005	.917	.001	.943	.004	.000

Table 4.
M-W test for Differences in Average Annual Frequency of 2x GCM and Historical 50kPa Pressure Fields

	DR	NWM	NWW	NWZ	SWS/SWC	SWT
M-W	59.0	139.0	16.0	127.0	21.0	11.0
Sig. (2 tailed)	.011	.957	.000	.682	.000	.000

Because the SWS and SWC synoptic patterns were difficult to clearly differentiate from the GIS output of the simulated data, these two were combined into a single group for purposes of this analysis. Changnon et al. (1993) also grouped these two synoptic types, since they provided similar precipitation patterns.

Tables 1and 2 provide a quantitative basis for the claim that 1x GCM simulates the historical patterns quite well. In terms of distribution and average annual frequency, all of the synoptic patterns except for SWT display no significant differences to the historical pattern. We cannot ascertain whether the inconsistency between the historical and 1x CO_2 for the SWT pattern is a function of subjective misclassification of GIS output or a failure of the GCM to adequately differentiate SWT patterns. Further work is required to investigate the explanations for this inconsistency. Nevertheless, given that the majority of synoptic types are simulated reasonably well under the 1x CO_2 run of the GCM, we proceeded to the second stage analysis in which we were concerned to identify whether this level of consistency in 50kPa synoptic patterns is still evident under the climatic 2x CO_2 simulation.

Tables 3 and 4 suggest that, apart from the SWT problem identified above, there are indeed some additionally significant changes in synoptic patterns apparent under the scenario of CO_2 doubling. More specifically, a comparison of the 2x CO_2 GCM with the historical data of Changnon et al. (1993) shows that the DR, NWW, and SWS/SWC patterns are significantly different ($p<0.05$) in terms of both distributional characteristics and average annual frequency. Table 5 shows the differences in the relative frequency of each of the synoptic patterns between the 2x CO_2 GCM and the historical data. It also underscores the important changes that occur for the DR, NWW, and SWS/SWC patterns.

The annual change in frequency of the DR, NWW and SWS/SWC synoptic patterns from the historical to the 2x simulation is +6.9, +24.0% and –10.9% respectively. In the study completed by Changnon et al. (1993) dry precipitation anomalies across the study area are associated with an increased frequency of DR patterns, wet north and dry south conditions are expected in years with increased frequency of NWW synoptic patterns, and dry north wet south years are expected with increases in the frequency of SWC and SWS patterns. If the frequency of the patterns identified by Changnon et al. (1993) account for the snowpack patterns observed under a warmed climate, the results reported above will have important implications to the region of study.

Table 5.
Average Annual Frequency (%) for the Historical and 2x 50 kPa Synoptic Patterns.
(Note: annual values do not add to 100% due to unclassified days)

	DR	NWM	NWW	NWZ	SWS/SWC	SWT
Average Annual Frequency, Historical	10.7	15.2	21.9	3.3	21.1	25.5
Average Annual Frequency, 2xCO2	17.6	15.0	45.9	3.7	10.2	15.9

The increased occurrence of the DR pattern simulated in 2x run of the GCM suggest that dry precipitation anomalies across the study area may become more frequent. It is also expected that the increased occurrence of the NWW pattern and decreased occurrence of the SWC and SWS patterns will result in more years with wet north and dry south snowpack conditions. At the present time very little work has been completed to understand the effect of climate warming on the amount of snowpack that could potentially be available due to potentially higher amounts of precipitation falling as rain rather than snow. However, from the results of this analysis, it is expected that the decrease in mid-latitude jet occurrence over the southern regions will result in lower snowpack conditions for this area.

SUMMARY AND CONCLUSIONS

Most of the natural streamflow that occurs over the western plains of Canada and the United States is derived from snowpack that accumulates over winter in the Rocky Mountains. Increases in atmospheric concentrations of greenhouse gases have raised serious concerns with respect to change in regional climate and hydrology. An accepted method of assessing the implications of climate warming due to increasing atmospheric concentrations of greenhouse gases is with general circulation models. Unfortunately, many GCMs have not been entirely successful at simulating features such as precipitation. For this reason many studies have focused on downscaling climatic variables such as precipitation from better simulated synoptic pressure fields. In this study the impact of global warming on northern Rocky Mountain States April 1 snowpack as influenced by 50 kPa synoptic fields for 1x and 2x CO2 warming scenarios generated by the CCC GCM-II was assessed.

The synoptic pressure field output from the CCC GCM-II was analysed using a GIS to identify the location of the mid-latitude jet. The circulation pattern observed was classified into one of seven 50-kPa winter time synoptic patterns described by Changnon et al. (1993). The relative frequencies of these seven patterns were found to explain almost ninety percent of the non-average April 1 snowpack patterns in the study area.

In order to evaluate the potential impact of climate warming on the study area, two analysis were completed. First the simulated 1xCO2 predictions of synoptic type frequency was compared to historical data. If the model was able to accurately forecast historical data, we can place more trust in the simulations at 2xCO2. Secondly, the 1xCO2 simulated data was compared to the synoptic frequencies at 2xCO2.

The 1xCO2 run of the GCM was found to statistically simulate the historical patterns well for all but one of the seven synoptic patterns. Therefore we compared the 1x run of the CCC GCM-II to synoptic type frequencies simulated at 2xCO2. Comparison of the 2x and 1x run of GCM indicate a statistically significant increase in a synoptic pattern associated with wet conditions in the north of the study region and dry conditions in the south, and a decreased frequency of patterns resulting in dry conditions in northern regions and relatively wet conditions in the south. From this analysis is expected that the decrease in mid-latitude jet occurrence over the southern regions of the study area could result in lower snowpack conditions over this region in a warmed climate.

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