LINKING GLOBAL CIRCULATION MODEL SYNOPTICS AND PRECIPITATION FOR WESTERN NORTH AMERICA

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ABSTRACT

Synoptic downscaling from global circulation models (GCMs) has been widely used to develop local and regional-scale future precipitation scenarios under global warming. This paper presents an analysis of the linkages between the Canadian Centre for Climate Modelling and Analysis first version of the Canadian Global Coupled Model (CGCM1) 2000 model output and local/regional precipitation time series. The GCM 500 hPa geopotential heights were visually classified for synoptic patterns using a geographical information system. The pattern frequencies were statistically compared with historical data from Changnon et al. (1993. Monthly Weather Review 121: 633–647) for the winter period 1961–85. The CGCM1 synoptic frequencies compare favourably with the historical data, and they represent a substantial improvement over the 1992 Canadian Climate Centre Global Circulation Model synoptic climatology output. The CGCM1 output was used to forecast future winter precipitation scenarios for five geographically diverse climate stations in western North America. Copyright © 2002 Royal Meteorological Society.

KEY WORDS: North America; synoptic classification; downscaling; GCM; precipitation scenarios; climate change; winter precipitation

1. INTRODUCTION

A key issue in forecasting future water supplies from alpine areas in western North America is predicting future winter precipitation scenarios under forecast climate warming. Spring runoff is important in western North America for agriculture (irrigation), ecosystem protection and human consumption. Nearly 85% of the area’s total annual streamflow is derived from the snowpack (Grant and Kahan, 1974); thus, it is important to understand the fluctuations in winter precipitation that may occur due to global warming. A better understanding of winter climate variability will impact policy decisions concerning water resource management and will aid in anticipating extreme events.

Global circulation model (GCM) precipitation output is typically unreliable at the regional and local scales for hydrological analysis (Von Storch et al., 1993; Saunders and Byrne, 1994). The horizontal resolution of present-day coupled GCMs is still in the order of hundreds of kilometres; hence, current techniques such as synoptic downscaling from GCMs have been adopted to refine further local and regional scale monthly or seasonal precipitation scenarios (Konrad, 1997; Byrne et al., 1999; Krichak et al., 2000).

Atmospheric circulation patterns govern the climatic conditions during the winter season in western North America. Previous studies (e.g. Yamal and Diaz, 1986; Trenberth, 1990; Latif and Barnett, 1996; Byrne et al., 1999) have documented variability in these atmospheric circulation patterns over space and time, and have shown the linkages between the variations in synoptic pattern frequency/duration and winter precipitation. Policymakers and stakeholders are interested in the effects of climate variability at regional and local scales (Giorgi and Mearns, 1997), and hence much research

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has been conducted in the area of climate downscaling. These studies attempt to identify the effects of large-scale spatial and temporal climate fluctuations on small-scale geographic regions (e.g. Hewitson and Crane, 1996; Cavazos, 1997) with the objective of carrying out integrated regional assessments of climate variability and change; and finally, defining the eventual physical and socioeconomic impacts (Easterling, 1997).

Changnon et al. (1993) defined seven dominant synoptic flow patterns (Figure 1) for western North America for the period of October 1950 to March 1985. These synoptic patterns control the spatial distribution/volume of winter precipitation in the Rocky Mountain states. A GCM that effectively replicates the historical frequencies of these seven patterns can be utilized to develop future precipitation scenarios. A previous study (Byrne et al., 1999) used the Canadian Centre for Climate Modeling and Analysis (CCma) GCM2 1992 model run with good results; however, this model is now outdated and has been superseded by the more comprehensive (CCma) first generation coupled general circulation model (CGCM1).

In this paper, we developed winter (October to March) precipitation scenarios using synoptic downscaling techniques based on output from the CGCM1. Precipitation scenarios were developed for five climate stations in diverse locations in western North America (Figure 2).

It is important to note that the application of present-day climate statistics to future climate is our only means of developing future climate scenarios. However, the reader should recognize that the statistical relationships based on historical analysis could change under climate warming. The future conditions may not exist as historically recorded.

Figure 1. The seven dominant synoptic 50 kPa patterns as defined by Changnon et al. (1993). The ridge pattern (DR) is associated with dry anomalies over the entire region. The split-flow pattern (SWS) is associated with wet anomalies across southern regions. The cutoff pattern (SWC) is associated with wet anomalies across southern regions. The trough pattern (SWT) is associated with wet anomalies across southern regions. The meridional northwest pattern (NWM) is associated with wet anomalies across northern regions. The west-northwest pattern (NWW) is associated with wet anomalies across northern regions. The zonal pattern (NWZ) is associated with wet anomalies across northern regions.
2. TYPES OF DOWNSCALING

2.1. Manual

Manual classification is familiar to most synoptic climatologists (Wilby, 1995; Frakes and Yarnal, 1997). In this method, investigators subjectively classify the atmospheric continuum into a number of map-pattern categories. There are several well-known regional manual classifications, such as the Lamb weather types for the British Isles (Lamb, 1972) or the Muller classification for the USA Gulf Coast (Muller and Wax, 1997). For this study we used synoptic classifications by Changnon et al. (1993) for western North America.

Manual classifications are useful (Yarnal, 1993). They are conceptually straightforward, and therefore easier for non-climatologists to understand. Only climatologists, however, should carry out this process. Most classifications are unique and tailored to the specific research or region (Wilby et al., 1994; Yarnal and Frakes, 1996). For the purpose of this study, a set of manual classifications previously outlined for western North America was used. Manual classification was the easiest and most efficient way to produce results, as previous experiments had been done. There are inherent advantages to manual classification: the climatologist is comfortable with the regional climate and likely makes better decisions about pattern type than would a black box statistical method. In fact, statistical methods have been shown to fail in some classifications schemes (Blair, 1998).

An important strength of manual classification is the omnipotence it grants to the investigator (Frakes and Yarnal, 1997). Through prolonged contact with the data, the investigator develops an intuitive understanding of the regional climate system. Further, while maintaining a regional focus, the investigator is free to expand the spatial and temporal window of observation, integrating knowledge of past and future weather conditions up and downstream.

Some authors considered manual classification to be quite tedious and time consuming (Frakes and Yarnal, 1997). Our innovation, of using a geographical information system (GIS) to produce the images rapidly (essentially push button), has made the process much more efficient and timely.

2.2. Computer-based classifications

The alternative to manual classification is computer-based classification. One of the most popular is the correlation-based method (Lund, 1963; Kirchhofer, 1973). The reason for its popularity is that it is essentially a computerized pattern-recognition algorithm. Time spent on getting the first classifications can be duplicated perfectly in minutes. Also, adjustments or even new correlation-based classification can take minutes to a few
hours to perform (Frakes and Yarnal, 1997). The Kirchhofer technique for analysing lattice data standardizes observed values at each location based on normalization scores. The lattice of normalized values is compared with other lattices to calculate a summary Kirchhofer score. The score is used to classify daily synoptic patterns. Further detailed information about this method can be found in Kirchhofer (1973) and Kaufmann et al. (1999).

A number of authors (Key and Crane, 1986; Yarnal and White, 1987; Yarnal et al., 1988; Huth, 1996) have demonstrated that the results of these schemes are highly subjective and that the number of synoptic types and days classified vary with a number of investigator-controlled variables. One of the biggest complaints is that the investigator cannot control the patterns generated. The number and size of groups identified by the Kirchhofer technique depends on the threshold and minimum group size (Key and Crane, 1986). There are no criteria to choose these parameters. As a result, analysts cannot be sure whether the synoptic patterns identified by the Kirchhofer technique represent groups that are generated by a meaningful meteorological phenomenon or whether they emerge due to random change. Patterns can be easily missed; configurations with little climatic significance are often present; and the expertise of the investigator does not enter into the classification process. Investigators do not become as familiar with the data they are working with (Frakes and Yarnal, 1997).

3. METHODOLOGY

The seven historical winter upper-air synoptic patterns defined by Changnon et al. (1993) were adopted for our analysis of the CGCM1. Changnon et al. (1993) found three basic and persistent patterns of snowpack values:

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

The CCCma CGCM1 model simulates climate conditions for 48 latitude by 96 longitude grid points on a 3.75° by 3.75° Gaussian grid with ten vertical levels (Flato et al., 2000). Three available simulations have been run for three 200-year (1900–2100) transient simulations (Boer et al., 2000). Transient simulations assume a steady rate of CO2 increase in the atmosphere over time. The three available simulations are (CCCMA, 2000):

- control — greenhouse gas concentrations and other external forces of change were held constant at present-day concentrations;
- GHG — considers only increases in greenhouse gas concentrations at a rate of 1% per year from the observed 1900 until the year 2100, converted to an equivalent concentration of CO2;
- GHG + A — the effects of greenhouse gases and an additional factor, the direct effect of sulphate aerosols.

For the analysis herein, we chose to use the GHG + A simulation. Atmospheric concentrations of greenhouse gases and aerosols in GHG + A correspond to historical concentrations from 1900 to present, and a CO2 increase at a rate of 1% thereafter until 2100. The time of CO2 doubling is approximately 2050 (Boer et al., 2000). The direct effect of sulphate aerosols (A) is also included by increasing the surface albedo (Reader and Boer, 1997). The indirect effect of sulphate aerosols on the optical properties and lifetime of clouds was not included, since estimates of this forcing effect are highly uncertain (Houghton et al., 1996).

In this paper we selected the CGCM1 model output for the years 1961–85 to represent historic conditions (1 × CO2) conditions. This period represents a time frame of minimal increases of CO2 concentrations in the atmosphere. For the warmed period, we selected 2021–50; this time frame represents an approximate 2 × CO2 atmospheric condition.

Arc Macro Language (AML) routines were developed to import the daily CGCM1 upper air data (500 hPa surface) for the years 1961 through to 1985 for the months of October through to March into ArcInfo, as this was the longest time period where the GCM and historical analysis overlapped. The geopotential heights were analysed using the ArcInfo at 30 m elevation intervals. The location(s) of the principal westerly jet
(the zone of greatest wind velocity) was defined by visual inspection of the daily elevation fields. The zone of greatest contour density was defined as the core of the westerly flow, i.e. steep elevation gradients are assumed to represent the mid-latitude jet stream. The daily pattern displayed over North America on the screen was compared with each of the seven patterns described by Changnon et al. (1993). The screen pattern was assigned to whichever pattern type it most closely resembled. Patterns not clearly resembling any of the seven patterns types were assigned as unclassified or other. For the $1 \times CO_2$ data, about 2% of the days were unclassified. For the $2 \times CO_2$ data, less than 1% of the days were unclassified. Therefore, we assume any effects of unclassified days to be negligible, and in the analysis we only use the statistics for the seven patterns. This assumption is supported by the nature of the pattern form on unclassified days where the jet stream effectively disappears, indicating no meaningful synoptic control on weather (precipitation) on those few days.

The Changnon and CGCM1 historical (1961–85) pattern frequency data must display similar distribution characteristics and central tendencies (numbers that represent the centre or typical value of a frequency distribution, such as mode, median, and mean) before the model can be considered valid in representing present and future scenarios. Independent $t$-tests and Kolmogorov–Smirnov (K–S) tests were conducted between the CGCM1 historical and Changnon frequency data to determine whether the $1 \times CO_2$ (1961–85) output accurately simulated the pattern types and occurrence frequencies reported by Changnon et al. (1993). The same visual classification technique was used to evaluate the pattern types and frequencies under a $2 \times CO_2$ climate scenario (2021–50).

Winter precipitation accumulations (1 October to 31 March) for five geographically diverse mountain locations in western North America (Figure 2) were linked to the Changnon et al. (1993) dominant synoptic pattern frequencies, using stepwise linear regression for the 1950–85 $1 \times CO_2$ data series (See Tables VI and VII). These sets of pattern frequencies are significant predictors of winter precipitation accumulations for this series. These models were also assumed to be true under $2 \times CO_2$ conditions.

The linkage between winter synoptic patterns and precipitation for five mountainous locations (Lake Louise, Alberta; West Glacier, Montana; Steamboat Springs, Colorado; Yreka, California; and Moran, Wyoming) were determined using historical daily precipitation and the historical pattern-type frequency data of Changnon et al. (1993) using statistical analysis (stepwise multiple linear regression).

4. RESULTS AND DISCUSSION

Using the CGCM1 to forecast future conditions requires that the model demonstrates a reasonable ability to replicate historical conditions. Hence we compared the CGCM1 $1 \times CO_2$ pattern frequency distribution to the historic Changnon et al. (1993) frequencies. Presuming the CGCM1 accurately portrays the historical frequencies, we may then assume validity of the $2 \times CO_2$ frequency distribution. Any substantive changes in the $1 \times$ and $2 \times CO_2$ frequencies represent likely changes in future synoptic conditions, and hence linkages between precipitation and synoptic frequencies may be used to develop future precipitation scenarios.

The comparison of the Changnon historical synoptic and $1 \times CO_2$ synoptic frequency distributions is presented in Tables I and II. The differences in both central tendencies and distributional characteristics for the average annual frequencies of each synoptic type were tested using an independent $t$-test and K–S test respectively. In order to determine that the model has sufficiently represented historic data the overall pattern frequency distributions and means must have a $p > 0.05$, meaning that no significant difference exists. The data in Table I show that only one significant difference exists between the historical and $1 \times CO_2$ patterns (NWZ has $p = 0.043$; note this only misses significance by 0.007). Hence the $t$-test argues, for all intents and purposes, that the central tendencies of the pattern frequencies from the CGCM1 $1 \times CO_2$ period are the same as those of the historical data. The ‘near’ significance of the NWZ pattern does not alter the analysis: NWZ occurs only about 4% of the time. Hence, the NWZ pattern does not substantially influence precipitation in our study region.

The K–S test results (Table II) reveal that there are no significant differences between the frequency distribution characteristics for all $1 \times CO_2$ model data when compared with the historical data.
There are significant changes in synoptic pattern frequencies that occur in the $2 \times CO_2$ synoptic frequency distribution. Change is evident in the central tendencies (Table III) and distribution characteristics (Table IV) for the DR, NWW, SWT and SWC patterns.

Table V shows the actual differences in the average frequencies of each pattern between the CGCM1 $1 \times CO_2$ and CGCM1 $2 \times CO_2$ and the historical, 1950–85 Changnon data. The ratio of changes ($2 \times CO_2/1 \times CO_2$) for DR, NWW, SWT and SWC are 2.22, 1.21, 0.75 and 0.38 respectively. These changes will be discussed in light of the statistical analysis presented below.
Stepwise multiple linear regression techniques were utilized to develop a model to forecast future winter precipitation. A series of regression models were developed using historical precipitation data (Environment Canada, 1999; NCDC, 2000) and Changnon’s historical synoptic data. The dependent variable in each model was the accumulation of annual wintertime precipitation (October through to March) at a given climate station; the independent variables were Changnon’s synoptic pattern frequencies. For the historical analysis, daily precipitation data were available between 1950 and 1985 \((n = 35)\) for each of the five stations chosen. Relationships between annual historical winter precipitation and historical synoptic-type frequencies were developed using stepwise regression to establish which combination of pattern type(s) affected winter precipitation values at each station (Table VI).

It is important to note that forced origin multiple regression was used to develop these models. Forced origin assumes there is little variability that is not explained by the independent variables. This is the case herein: the unclassified days would be the only variables that argue for a constant in the regression to account for unexplained variability. The unclassified days account for less than 2% of the cases. For this reason, we applied the forced origin model. This assumption makes climatological sense as well. Virtually all of the winter precipitation in alpine environments in western North America is under synoptic (orographic or convergent) control. Convective precipitation is minimal in winter.

The winter precipitation at Lake Louise (Alberta), West Glacier (Montana) and Yreka (California) are all dominantly controlled by the NWW pattern. The winter precipitation at Steamboat Springs (Colorado) and Moran (Wyoming) is controlled by the SWT pattern. We might have expected more than a single pattern to influence precipitation strongly at each station; however, for our purposes, none of the models included more than one significant independent variable. These models, therefore, argue for local and regional control of precipitation by single synoptic pattern types. Similar results were found by Byrne et al. (1999), where spring runoff peaks in two major watersheds (the Upper Colorado River in Western Colorado and the Oldman River in Southern Alberta) were significantly connected to only one synoptic pattern. We must note that, in some cases, the regression statistics reported more than one significant independent variable. However, the inclusion of more than one independent variable made only trivial (approximately 1%) improvements in the model. For example, for West Glacier, NWW and SWT were significant variables in the regression model. However, the addition of SWT only improved the explanation of the variability by 1%. NWW accounts for 96% of the variability. We opted for the simpler model.

There is quite a strong relationship between pattern occurrence and winter precipitation. However, an anonymous reviewer suggested a meaningful additional check on this relationship using subsets of the samples. A random subset of 50% of the sample pairs was selected and the stepwise linear regression was run on the subset. For all five stations for the period of 1961–85, the same dominant pattern prevailed for the subset analysis.

Future winter precipitation values were developed using the stepwise regression equations previously described with adjustments to historical seasonal pattern frequency data as follows (Table VII).

Table VI. Results of the stepwise multiple linear regression to develop equations for predicting average winter precipitation amounts based on historical pattern occurrence for the five climate stations. Forced origin multiple regression analysis was used; thus the values of \(R^2\) cannot be compared with those models that include a constant

<table>
<thead>
<tr>
<th>Station</th>
<th>Regression equation</th>
<th>(R^2)</th>
<th>Significance</th>
<th>SE of Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Louise</td>
<td>(P = 16.476 \text{NWW})</td>
<td>0.92</td>
<td>(p &lt; 0.05)</td>
<td>0.848</td>
</tr>
<tr>
<td>West Glacier</td>
<td>(P = 18.67 \text{NWW})</td>
<td>0.959</td>
<td>(p &lt; 0.05)</td>
<td>0.695</td>
</tr>
<tr>
<td>Steamboat Springs</td>
<td>(P = 13.05 \text{SWT})</td>
<td>0.925</td>
<td>(p &lt; 0.05)</td>
<td>0.667</td>
</tr>
<tr>
<td>Moran</td>
<td>(P = 14.132 \text{SWT})</td>
<td>0.934</td>
<td>(p &lt; 0.05)</td>
<td>0.653</td>
</tr>
<tr>
<td>Yreka</td>
<td>(P = 16.872 \text{NWW})</td>
<td>0.908</td>
<td>(p &lt; 0.05)</td>
<td>0.962</td>
</tr>
</tbody>
</table>
Table VII. Comparison of 1951–85 winter precipitation amounts, October through to March, for the five stations under historical (actual precipitation) and 2 × CO2 conditions, based on multiple linear regression equations

<table>
<thead>
<tr>
<th>Station name</th>
<th>Winter precipitation (mm)</th>
<th>Historical (1951–85)</th>
<th>Adjusted 2 × CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Louise</td>
<td></td>
<td>376</td>
<td>534</td>
</tr>
<tr>
<td>West Glacier</td>
<td></td>
<td>429</td>
<td>609</td>
</tr>
<tr>
<td>Steamboat Springs</td>
<td></td>
<td>338</td>
<td>250</td>
</tr>
<tr>
<td>Moran</td>
<td></td>
<td>365</td>
<td>270</td>
</tr>
<tr>
<td>Yreka</td>
<td></td>
<td>389</td>
<td>552</td>
</tr>
</tbody>
</table>

For Steamboat Springs, the regression equation (Table VI) for winter precipitation $P$ as a function of historical pattern frequencies is

$$P = 13.05\text{SWT}$$

where SWT is the frequency of that pattern in any year. Hence for a year where SWT occurs 40% of the time, the winter precipitation for the year would be 522 mm. If SWT occurs 40% of the time, $P = 522$ mm. Under a 2 × CO2 climate, SWT would decrease by one-quarter of historical values (Table V). In Table VII, column 2 is the average annual winter (October–March) precipitation for 1950–85. Column 3 is the average 2 × CO2 winter (October–March) precipitation for the same time period. To estimate the changes in winter precipitation, the ratio between the 1 × CO2 and 2 × CO2 SWT mean frequency was used to adjust the historical SWT data. Therefore, the precipitation for Steamboat Springs is calculated by:

$$P = 13.05\text{SWT}(2 \times \text{CO}_2 \text{ SWT} / 1 \times \text{CO}_2 \text{ SWT})$$

This same procedure was used to compute the average 2 × CO2 winter precipitation for the remaining four climate stations.

6. DISCUSSION

There are significant differences shown in future precipitation amounts for the climate stations included in this analysis. Areas in which the NWW pattern is the driving force behind winter precipitation show increases in overall precipitation; SWT-dominated areas show an overall decrease in precipitation.

Time series of annual changes in winter precipitation for historical and 2 × CO2 conditions for each station are presented in Figure 3. The 2 × CO2 precipitation values were calculated using the station regression equations defined in Tables VI and VII. Figure 3 indicates that there will be significant overall fluctuations in future precipitation. Those stations predominantly influenced by the NWW pattern could experience major increases in overall precipitation compared with those influenced by SWT, where major decreases are expected.

These precipitation values are not representative of snow accumulation. Temperature change must also be taken into consideration when assessing precipitation into snowpack and into spring volumes.

7. SUMMARY

This study has adapted GCM downscaling analysis to develop winter precipitation scenarios for selected climate stations in western North America. The spatial characteristics of the CCCma CGCM1 were visualized
GCM SYNOPTICS AND PRECIPITATION

Figure 3. Historical and $2 \times \text{CO}_2$ forecast changes in winter precipitation (mm) for five climate stations: (a) Lake Louise, AB; (b) Steamboat Springs, CO; (c) Yreka, CA; (d) West Glacier, MT; (e) Moran, ID. The plots reflect ratio of change in precipitation applied to the historical period October 1, 1961–April 1, 1985. Note variation in y axis on each plot.

within a GIS, and circulation patterns were visually classified into one of seven mutually exclusive 500 hPa wintertime synoptic patterns described by Changnon et al., (1993). Historic synoptic pattern frequencies were found to explain at least 90% of the wintertime precipitation for the five climate stations chosen.

In order to determine whether the GCM was accurately displaying climate warming, we first had to validate the model with historic pattern frequencies. The simulated $1 \times \text{CO}_2$ synoptic frequencies were compared with historical data, and the GCM was found to be robust. Thus we could reliably employ the model for the forecasting of $2 \times \text{CO}_2$ scenarios. Pattern frequencies from $2 \times \text{CO}_2$ were compared with historic frequencies to determine which patterns were predicted to exhibit significant differences under a climate warming scenario. An interpretation of these differences in synoptic flows points to considerably wetter conditions in the north and the west coast of the study area, and considerably drier conditions in the central and southern areas of the study area.

Climate stations influenced by the NWW pattern (Lake Louise, West Glacier and Yreka) show an increase in winter precipitation of 40%. Stations controlled by the SWT pattern show a decline of about 30% in winter
precipitation (Moran and Steamboat Springs). Winter precipitation is critical to spring runoff and seasonal water supply in the regions studied here.

This analysis provides a basis for the rapid prediction of future winter precipitation for most locations in western North America. Our understanding of winter precipitation scenarios for western North America will be enhanced by expanding this type of analysis to a number of other locations and regions.

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