Extreme Winter Warming Events over the Mackenzie Basin: Dynamic and Thermodynamic Contributions

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(Manuscript received 4 January 1999, in revised form 19 February 2001)

Abstract

The Mackenzie River of Canada is one of the great rivers of the world. Its basin is characterized by a highly variable topography and its climate is subject to many important cold-region phenomena. Over the last few decades, the Mackenzie Basin has also been experiencing a pronounced winter warming. In this study, a number of extreme basin warming events and related processes during the winter are investigated using surface and rawinsonde data. By documenting these events, we have found that the basin warming is mainly associated with low pressure systems in and near the basin, and with extratropical and subpolar high pressure systems in the vicinity of the basin.

The dynamic and thermodynamic contributions (due to atmospheric circulations, topography, low-level temperature inversion and their interactions) to the basin warming are also examined. It is shown that basin warming events occur through the horizontal advection of warm air from west and south of the basin, and through adiabatic descent induced by both the topography and the low and/or high pressure system, particularly when the low-level temperature inversion occurs.

1. Introduction

Observations over the last few decades indicate that a warming trend of surface air temperature is significant during the winter over the northern Hemisphere (e.g., Wallace et al. 1995, 1996). Results of numerical studies using a number of different climate models also show that atmospheric warming is expected to be pronounced in the winter (e.g., IPCC 1990, 1992; Manabe and Stouffer 1980; Ingram et al. 1989).

Although various forcings are generally expected to raise global temperatures, scientists are uncertain how the entire climate system will change, especially at regional levels (Pilifosova et al. 1997). As a result, there is an ever-increasing concern of the impacts of global climate changes on regional-

scale water resources and their associated features. To address such issues, regional climate change scenarios must be developed, although this in turn requires better understanding and parameterizing multi-scale processes at regional-scale levels. This is one of the most difficult tasks for the climate research community.

A few studies, although not many, on regional climate change have been documented in the literature. For example, studies have been carried out on regional climate changes in Switzerland (Beniston et al. 1994; Beniston and Rebetez 1996) and in Kazakhstan (Pilifosova et al. 1997), anomalous warming in the Canadian prairie provinces (Majorowicz and Skinner 1997), and spatial and temporal changes in extreme air temperatures in the Arctic (Przybylak 1997). In this study, we will pay particular attention to regional-scale climate changes over the Mackenzie Basin of northwestern Canada, especially to a number of extreme warming events that have occurred during last few decades.

The Mackenzie (Fig. 1a) is one of the great river basins of the world, ranking tenth largest by drain-

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Fig. 1.(a) The Mackenzie Basin and its vicinity.

Fig. 1.(b) Geographical distribution of the terrain over the Mackenzie Basin. The contour interval is 200 m and spatial resolution is 50 km. The data of terrain height are obtained from Canadian Regional Finite Element (RFE) model output fields archived for the Mackenzie GEWEX Study.

age area, twelfth by sediment discharge, and fifteenth by mean annual discharge (Milliman and Meade 1983). The Mackenzie is also the largest North American river basin emptying fresh water into the Arctic Ocean. Within the Mackenzie Basin, there are many important cold-region phenomena such as snow and ice processes, permafrost, Arctic water vapor, clouds and radiation interactions, etc., that must be properly handled within a global climate system model.

It should also be emphasized that the Mackenzie Basin has several other important features. As shown in Fig. 1b, the basin is a region with highly variable terrain, and more than half of the basin is occupied by topography over 200 m. In the winter, this region is commonly associated with a low-level temperature inversion. In addition, the Mackenzie Basin is experiencing a profound winter warming trend with a maximum value up to $1.3 \text{ K decade}^{-1}$ (see Fig. 4 of Stewart et al. 1998). Furthermore, over the Mackenzie Basin substantial anomalies of

monthly mean surface air temperature have been observed during the last few decades (see Fig. 2a). These anomalies refer to the departure from the normal that is a 30-year average from 1961 to 1990. The terminology of *positive anomalies* are hereafter used interchangeably with the term “warming events”. As shown in Fig. 2a, warming events have been more frequent in recent years than ever. As a counterpart, the anomaly of the 1000-mb geopotential height over the basin (Fig. 2b) shows the increasing of interannual variability during recent years. In particular, the variability of geopotential height anomalies is more substantial in the winter than other seasons. Therefore, the increasing interannual variability of circulation systems may be closely associated with the recent frequent occurrence of winter warming events.

The objectives of this study are to investigate the monthly-scale warming events over the Mackenzie Basin in relation to atmospheric circulations, topography, and the low-level temperature inver-

Fig. 2.(a) Monthly-scale anomalies of surface air temperature over the Mackenzie Basin. These are calculated by subtracting the normal (30 year average from 1961 to 1990) from the actual monthly average.

Fig. 2.(b) Monthly-scale anomalies of the 1000-hPa geopotential height over the Mackenzie Basin. These are calculated by subtracting the normal (30 year average from 1961 to 1990) from the actual monthly average.

sion; and to understand some of the dynamic and the thermodynamic processes that are operating in these situations.

The monthly time scale has been chosen because there are strong signals of positive anomalies in the monthly average fields of surface air temperature and consistent patterns of anomalies in both the temperature and the pressure fields. The signals of the temperature anomalies over seasonal or annual scales are weaker than those over the monthly scale simply because positive and negative anomalies are averaged out over these longer periods. On the other hand, within a month, there is some variability in the temperature and pressure fields on daily or weekly scales, and those fluctuations are filtered out in this study. It is generally believed that the monthly time scale is appropriate for a substantial amount of climatic change research (Robeson 1993), and that for example, the monthly scale temperature is one of the most important climatic elements for representing a regional climate (Murata 1993). Particularly in extreme cases, such a scale indicates unusual weather conditions that have a tremendous impact on society (Murata 1993).

This study will be comprised of two main components. First, the relationships will be identified between each of the monthly-scale warming events and the corresponding circulations. Second, special attention will be paid to the effects of the local topography and to the commonly-occurring low-level temperature inversion in the basin.

To carry out this study, both surface observational data and the upper-air rawinsonde data are required. The data used in this study are described in Section 2. The results are presented in Section 3. The diagnoses and physical interpretation are discussed in Section 4. Finally, the conclusions are given in Section 5.

2. Data

2.1 Surface data

Two sets of data are used in this study. Set 1 contains 45-year (1950–1994) monthly mean surface climate parameters which are derived from Environment Canada climate stations. Temperature measurements, recorded with at least daily frequency at about 150 locations in and near the Mackenzie Basin, provide the basic data. These data are used to generate values on a grid with 50 km spacing by employing statistical optimal interpolation (Alaka and Elvander 1972) and by follow-

ing a strategy of using a first guess field and interpolating residuals to this field. A similar method was used by Yamamoto and Hoshiai (1980) to interpolate Northern Hemisphere mean surface air temperature fields. If the first guess field is chosen well, residuals are homogeneous and isotropic (essential for proper statistical optimal interpolation), the expected patterns of the parameters are preserved, and interpolation errors over the data sparse Mackenzie Basin are minimized. For monthly mean maps of surface climate parameters, gridded estimates of 30-year normals (1961–1990) are used as the first guess field in this study.

2.2 Upper-air data

Set 2 contains all regular daily reports (00 and 12 UTC) from the North American rawinsonde network over the period 1946 to 1994 (49 years). The rawinsonde observations are interpolated using a method called bivariate interpolation and smooth surface fitting, developed by Akima (1978). This method has been widely tested and implemented (NCAR graphics 1995; IMSL 1989). The interpolated rawinsonde data include geopotential height, zonal and meridional components of velocities, temperature, and dew point temperature. The rawinsonde observations are interpolated on the mandatory levels: 1000, 850, 700, 500, 400, 300, 250, 200, 150, and 100 hPa pressure surfaces. The horizontal domain of all interpolated fields is within the rectangle of 28–70°N and 68–130°W, where higher density rawinsonde observations are available (see Fig. 3). The horizontal resolution of the interpolated data is 1.55 degree latitude $\times$ 1.05 degree longitude.

2.3 Quality of surface and upper-air data and their interpolations

a. Topographic variability

The topography has a substantial influence on surface air temperature fields if a spatial interpolation is applied onto raw data of surface air temperature. The topographic effect on spatial variability of anomalous fields, however, can be dramatically reduced by removing a mean from the raw data and interpolating the anomaly only (Robeson 1993). This operation is part of the procedure for using the statistical optimal interpolation (Alaka and Elvander 1972) in this study. In addition, the effect of the topography on the mean of these temperature fields is corrected using the formula of Soulis et al. (1994), in which the effect of station elevation is taken into account.

Fig. 3. (a) Distribution of surface meteorological stations denoted by circles in 1988 in and near the Mackenzie Basin. The solid lines are the boundary of the Mackenzie Basin. The rows and columns are represented by grid lines drawn across the map. The distance between two grids is 50 km. The numbers labeled along the abscissa and the ordinate are grid points from the origin (at the bottom and left corner). (b) Distribution of 130 rawinsonde stations in January 1969 indicated by solid circles. The dark solid lines are the boundary of the Mackenzie Basin.

b. Station inhomogeneities

Station inhomogeneity (Mitchell 1953; Jones et al. 1986; Hansen and Lebedeff 1987; Legates and Willmott 1990) is mainly caused by changes in instrumentation, station location, observation time and the methods used to calculate monthly means, and environmental factors such as urbanization (Karl and Jones 1989). As pointed out by Jones et al. (1986), there is no simple way to quantify the magnitude of changes in instrumentation, and it is also rare for a sufficient number of overlapping readings to be taken in order to evaluate possible seasonal differences in correction factors between different locations. The errors due to different observation times and the methods used to calculate monthly means, as suggested by Jones et al. (1986), can be considerably reduced if all fields are transformed to anomaly values from a common reference period. Since in this study, we focus on anomalies of surface air temperature field, the corresponding errors should be small for the fields of these anomalies. Jones et al.'s (1986) homogeneity analysis also shows that urbanization effects are very small for most Arctic locations, at least for annual mean data.

Although corrections can be made with respect to the biases mentioned above, and the correction procedure can be objective, there are many subjective judgments needed in deciding which stations are in error, which stations to use in correction, and whether or not to correct (Jones et al. 1986). Therefore, no correction was made in Legates and Willmott's (1990) paper and others because there is no viable means of correcting these biases. Like most available data sets, the data used in this study are not systematically corrected with respect to station inhomogeneities although these biases can be considerably reduced by using anomalous fields (Jones et al. 1986).

c. Network bias

Another central issue on data and their interpolations is whether samples are spatially uneven. Methods for examining network variability have been developed, although questions regarding air temperature network adequacy may never be fully answered due to insufficient data (Robeson 1993). The cross validation is one of the methods that has been widely used for determining network adequacy (Diaconis and Efron 1983; Efron 1982; Elsner and Tsonis 1991; Robeson 1993). The network bias due to spatial variations of station numbers and distributions occurs when the calculation is

made of an area-averaged quantity or area-averaged-related time series. However, in this study, we will investigate the spatial distribution of surface air temperature anomalies, and relate them to spatial patterns of circulations.

3. Surface air temperature anomalies and their relation to circulation systems

Surface air temperature anomalies over the Mackenzie Basin have been examined for all of the winter months (November through March) during the last few decades (from 1958 to 1994). It is found that 50% of the warming events are related to low pressure systems in the basin; 50% and 20% of the warming events are associated with, respectively, extratropical and subpolar high pressure systems adjacent to the basin. Because of overlapping, one warming event may be related to two different pressure systems, and so the total percentage is greater than 100%. As well, the term "subpolar high pressure systems" used in this study refers to high pressure systems centered (to the east of the basin) between 60.0° and 66.5°N, and "extratropical high pressure systems" refer to those centered (to the southeast/south of the basin) south of 60.0°N.

In this paper, we will present six *extreme* warming events. Each of the extreme events selected in this study satisfied the criterion that all areas of the basin had a positive monthly mean temperature anomaly. These events are also representa-

Table 1. List of extreme winter warming events presented in this study. The magnitude shows the maximum departure from the normal (30-year average from 1961 to 1990). The anomaly is calculated using surface air temperatures derived from Environment Canada climate stations, described in section 2 of the text. L and H indicate low and high pressure systems. MB, SP, and EX represent the Mackenzie Basin, subpolar, and extratropical regions, respectively, of the dominant large scale pressure systems, as described in the text.

Period (month/year)	Magnitude (K)	System	Origin
12/87	10	L	MB
2/77	17	L	MB
12/86	11	L	MB
2/78	12	H	EX
2/87	12	H	SP
11/68	3	L, H	MB, EX

Fig. 4. Spatial distribution in December 1987 of (a) the anomaly of surface air temperature at an interval of 1 K, (b) the monthly average of the 1000-hPa geopotential height at an interval of 5 gpm, and (c) the anomaly of the 1000-hPa geopotential height at an interval of 5 gpm. The darker solid lines are the boundary of the Mackenzie Basin. Dashed lines denote negative values.

Fig. 5. Spatial distribution in December 1987 of (a) the difference of the monthly averaged air temperature between the 850-hPa and 1000-hPa at an interval of 1 K, and (b) the monthly average of the 850-hPa geopotential height at an interval of 5 gpm. The darker solid lines are the boundary of the Mackenzie Basin. Dashed lines indicate negative values.

tive of the various types of circulation systems that are dominant during the warming periods. Table 1 shows the time periods, magnitudes of the surface air temperature anomalies, (i.e., maximum anomalies), dominant pressure systems and their origins. The warming events and associated pressure systems presented in the following subsections are organized by pressure systems and their locations with respect to the basin.

3.1 Low pressure systems in the Mackenzie Basin

Low pressure systems typically develop on the lee

side of the Rocky Mountains, and these lead to the horizontal advection of warm air into the basin. In addition, their associated vertical motion is significantly modified by topography (Hobbs et al. 1996). The topographically-induced vertical velocity can affect the surface temperature field through vertical advection and adiabatic heating. Some typical events related to this scenario are documented in this subsection.

December of 1987. The Mackenzie Basin experienced a substantial positive anomaly of surface air

Fig. 6. Same as Fig. 4 except in February 1977.

Fig. 7. Spatial distribution in December 1986 of (a) the anomaly of surface air temperature at an interval of 1 K, and (b) the monthly average of the 1000-hPa geopotential height at an interval of 5 gpm. The darker solid lines are the boundary of the Mackenzie Basin.

temperature in December 1987. The detailed structure of this anomaly can be seen in Fig. 4a. In most regions of the basin, the anomaly was greater than 5 K with a maximum value of about 10 K. Comparisons between Fig. 4a and Fig. 4b–c indicate that the basin warming was very closely related to the low pressure system and to a negative anomaly of the 1000-hPa geopotential height over the basin. The well-organized low pressure system (Fig. 4b) in the basin was associated with the horizontal advection of warm air both from the west and from the south of the basin. If the low pressure system interacted with the Rocky and Mackenzie Mountains located in the western part of the Mackenzie

Basin, the vertical velocity induced by the mountains may be important for the surface air temperature anomaly.

In contrast to the adiabatic warming induced by the downslope winds, adiabatic cooling related to upward motions in the region of the low pressure system may impact the surface temperature field as well. To understand if this adiabatic cooling is important, we examine the vertical structure of the low pressure system. Figure 5a shows the monthly-averaged temperature difference between the 850 and 1000-hPa pressure surfaces. The positive values mean that temperature increases with height; and negative values indicate that tempera-

ture decreases with height. As shown in Fig. 5a, the low-level temperature increased with height over the region where the low pressure system developed. The maximum temperature difference was 8 K. Due to this low-level temperature inversion, the atmosphere was very stable, and the vertical motion directly induced by the low pressure system was probably small and so was adiabatic cooling. In addition, the low pressure system that developed in the region of the low-level temperature inversion was very shallow. This shallow system was also evident from Fig. 5b where the 850-hPa trough was positioned ahead of the 1000-hPa low (compare Fig. 5b with Fig. 4b).

February of 1977. The difference between this event and the previous one is that the negative

anomaly of the 1000-hPa geopotential height in this case was more intense (compare Fig. 6c with Fig. 4c), and corresponding positive anomalies of the surface air temperature were more significant (compare Fig. 6a with Fig. 4a). The maximum anomaly of surface air temperature in the present case reached 17 K within the basin, which was about 1.7 times of that in December 1987. As shown in Fig. 6, there was a good relationship between the low pressure system and the temperature anomalies. Although physical processes contributing to this warming event are probably similar to those in December 1987, the horizontal advection of warm air from the west and the south of the basin is likely stronger than in the previous event since the gradients of 1000-hPa geopotential height

Fig. 8. Same as Fig. 7 except in February 1978.

Fig. 9. Same as Fig. 7 except in February 1987.

(see Fig. 6b) are larger (see Fig. 4b). As well, a ridge to the southwest of the basin appeared in both cases, and it played an important role in the horizontal transport of warm air into the basin.

December of 1986. This is another example showing that the warming signal in December 1986 was strongly linked with a low pressure system in the basin (Fig. 7a–b). Since horizontal winds are, as a first order approximation, determined by gradients of geopotential heights on a constant pressure surface, in a region of the intersection between the low pressure system and the ridge, the gradients are larger and so are the horizontal winds. Hence, the combination of the low pressure system in the basin and the ridge to the southwest of the basin were favourable for warm air advection into the basin.

The entire Mackenzie Basin experienced positive anomalies of surface air temperature with a maximum value of about 11 K, which occurred in the intersection between the low pressure system and the ridge (comparing Fig. 7a with Fig. 7b).

3.2 Extratropical and subpolar high pressure systems in the vicinity of the Mackenzie Basin

Other types of circulation patterns that occur near the Mackenzie Basin during the winter are extratropical and subpolar high pressure systems in the vicinity of the basin. These types of circulations are also associated with positive anomalies of surface air temperature. Two cases related to these situations are presented in this subsection.

February of 1978. The positive anomalies of sur-

Fig. 10. Same as Fig. 7 except in November 1968.

face air temperature that occurred in February 1978 (Fig. 8a) were distributed in a symmetric manner across the basin in that they mainly increased from the boundary of the basin toward its center (with a maximum anomaly of 12 K). The circulation over the basin during February 1978 was dominated by the extratropical high pressure system (Fig. 8b) centered to the southeast of the basin.

February of 1987. In February 1987, the entire basin experienced substantial positive anomalies of surface air temperature (Fig. 9a). The anomalies were in the range of 3 to 12 K. These anomalies were likely influenced by at least two different pressure systems. For the eastern part of the basin, the temperature anomalies were associated with the high pressure system centered over the east of the

basin, whereas for the western part of the basin, they were associated with a high pressure system located over the southern part of the Mackenzie Basin.

3.3 Combined systems of 3.1 and 3.2 types

As discussed in the previous sections, anomalies of surface air temperature over the Mackenzie Basin during the winter are sensitive to the presence of different low/high pressure systems. In fact, the dominant pressure systems during basin warming periods can be combinations of these different pressure systems. It is illustrative to examine the responses of the surface air temperature anomalies to such a situation. For example, in November 1968, a low pressure system developed in the

basin, and a high pressure system in the extratropical region (Fig. 10b). It is evident that there was a consistent relationship between these two pressure systems and the surface air temperature anomalies. This indicates that the low pressure system in the basin and the high pressure system in the extratropical region were responsible for this warming event. As a result, the whole basin experienced positive anomalies of surface air temperature with a maximum value of 3 K (Fig. 10a).

4. Discussion of the effects of circulation systems, topography, low-level temperature inversion, and their interactions on the surface air temperature anomalies

As presented in section 3, recently frequent appearance of quasi-stationary cyclones and anticyclones is closely linked with positive anomalies of surface air temperature during the winter over the Mackenzie Basin. The changes of circulations (Fig. 2b) associated with these quasi-stationary flows lead to substantial changes in the temperatures through heat advection into high latitudes of Northern America, particularly over the Mackenzie Basin. The changes of these quasi-stationary cyclones and anticyclones documented in this paper are well simulated by the Geophysical Fluid Dynamics Laboratory (GFDL) coupled ocean-atmosphere GCM in a global warming scenario with gradually increasing of CO₂ amount (Stephenson and Held 1993). They found that a large part of the change is described by an equivalent-barotropic stationary wave with a high over eastern Canada and a low over southern Alaska. It is therefore suggested that global warming with increase of CO₂ amount leads to changes of circulation patterns in the northern Hemisphere, particularly over the high latitudes, which in turns triggers local warming events. The Mackenzie Basin is one of the examples, where this process operates.

Further examinations on the interaction among these quasi-stationary circulation systems, local topography and temperature inversion are carried out to provide more insight into the warming mechanisms. Over the Mackenzie Basin, circulations are frequently modified by two important elements, the topography and the low-level temperature inversion. As a forcing, the topography is usually considered to provide upward or downward motion over the basin, which has a significant impact on the surface air temperature anomaly through vertical advection and adiabatic cooling or heating. The topographically-induced vertical velocity

ω is highly dependent on the gradient of the terrain height along the horizontal wind direction as well as on the magnitude of horizontal velocity itself, which can be written as follows:

$$\omega = -\rho g \vec{v}_h \cdot \nabla h, \quad (1)$$

where the data of terrain height h are obtained from Canadian Regional Finite Element (RFE) model output fields archived for the Mackenzie GEWEX Study.

During the winter, the Mackenzie Basin often experiences a temperature inversion in the lower troposphere up to 700 hPa or so, and the circulation systems are therefore very shallow under the constraint of this temperature structure. As a result, the anomalies of surface air temperature are influenced by the combined effects of the circulation systems, the topography, and the temperature inversion. The topography and the temperature inversion modify the circulations, and the modified circulations in turn affect the surface air temperature anomalies.

Figure 11 shows vertical cross sections along 57°N in December 1987 of monthly-averaged temperature, vertical velocity, velocity vectors and their anomalies with zonal and vertical wind components. The vertical motion is computed from the horizontal divergence by vertically integrating the continuity equation except the topographically-induced vertical velocity is calculated using Eq.(1). It is evident that there was a low-level temperature inversion, with maximum strength at 850 hPa, over most areas of the Mackenzie Basin (Fig. 11a). The low pressure system was very shallow, and the updraft associated with it was, to a large extent, below 700 hPa (Fig. 11b). The effect of adiabatic cooling was therefore less important than the other factors such as horizontal advection. As can be seen in Figs. 11b–c, downward motion occurred in a very shallow layer, with significant values (–1.0 to –2.5 cm s^{–1}) mainly between 850 hPa and 700 hPa. This descending motion was induced through interactions among the low pressure system, the topography, and the low-level temperature inversion.

One contribution to the vertical motion is due to the interaction between the low-level temperature inversion and the topography. Klemp and Lilly (1975) showed that lee waves can be trapped and amplified by a strong elevated inversion, giving rise to severe wind storms. It was also pointed out by Carruthers and Choularton (1982) that a much thicker and more intense inversion layer can lead

Fig. 11. The vertical cross sections along 57°N in December 1987 of (a) monthly-averaged temperature with the contour interval of 4 K, (b) monthly-averaged vertical velocity with the contour interval of 1 cm s^{-1} (solid and dashed lines denote upward and downward motions, respectively), (c) monthly-averaged velocity vectors with zonal component and vertical component, and (d) anomalies of velocity vectors with zonal component and vertical component. To see vectors in (c) and (d) clearly, the vertical components of velocity vectors are multiplied by a factor of 100. In other words, all vertical components of velocity vectors are in the unit of cm/s whereas all zonal components are in the unit of m/s . The darker solid lines are outlines of the mountains.

to more rapid descent down the lee side. This situation occurs over the Mackenzie Basin since the inversion layer is typically well positioned in the region of the downward motion (compare Fig. 11a with Fig. 11c).

In addition, the vertical motion is enhanced when the low pressure system and the inversion simultaneously occur over the mountainous basin. To understand this, we have calculated the total velocity anomalies for this warming event. Figure 11d shows anomalies of velocity with zonal and vertical components. An interesting feature shown in Fig. 11d is a return flow. Due to the inversion, the anomalous easterly flow associated with the low pressure system is enhanced near the top of the inversion. The anomalous easterly wind was bounded by the mountains so that an anomalous return flow was formed at a lower level. This return flow also made a positive contribution to the descending motion on the lee side of the mountains.

5. Concluding remarks

Extreme warming events during the winter over the Mackenzie Basin have been examined using surface and rawinsonde observations, and particular

attention have been paid to their relation with atmospheric circulations in and near the basin. Basin warming is mainly associated with low pressure systems in the Mackenzie Basin, and high pressure systems adjacent to extratropical and subpolar regions (Fig. 12).

As summarized in Fig. 12, the basin warming is mainly attributed to horizontal advection of warm air from west and south of the basin, and to the adiabatic heating induced by topography and the circulation systems. Further examination of the warming events suggests that interactions among the circulation systems, the topography, and the low-level temperature inversion are also critical. It was found that the surface-level descending motion induced by the topography leads to significant warming over the basin.

As a complement to the study of warming events, all of the winter cooling events over the Mackenzie Basin during the last few decades were also examined although they were not presented in this study. It was found that almost all of the cooling events were related to high pressure systems that originated in the polar regions, and these advected cold polar air into the region where there was either no

Fig. 12. A schematic diagram showing physical processes responsible for extreme winter warming events over the Mackenzie Basin. H and L represent high and low pressure systems, respectively, and large arrows indicate the flows associated with these systems. Small arrows represent the descending motion associated with the mountains labelled by M.

or a weak low-level temperature inversion. It is interesting to note that the warming and the cooling events are linked with different circulation systems, and they are also linked with different intensities of low-level temperature inversion.

In summary, this study has shown that extreme winter warming events over the Mackenzie Basin are associated with distinct patterns in regional scale circulations that are modified by regional topography and the low-level temperature inversion. The modified circulations in turn influence the surface air temperature anomalies. This study is, to our knowledge, the first to specifically examine the extreme warming events over the Mackenzie Basin of Canada and their associated formation mechanisms, and it has therefore advanced our understanding of regional scale temperature anomalies and the processes that contribute to them.

Acknowledgments

This research was supported by the Canadian GEWEX (MAGS) project and the Panel on Energy Research and Development (PERD). We would like to thank Paul Louie for generously providing us with Fig. 2a. Thanks are also extended to Walter Skinner for his valuable discussions, and to Robert Crawford for assisting us with topographic information. The authors would also like to thank the anonymous reviewers for their very helpful comments and suggestions that significantly improved this paper.

References

- Akima, H., 1978: A method of bivariate interpolation and smooth surface fitting for irregularly distributed data points. *ACM TOMS*, **4**, 148–159.
- Alaka, M.A. and R.C. Elvander, 1972: Optimum interpolation from observations of mixed quality. *Mon. Wea. Rev.*, **100**, 612–624.
- Beniston, M., M. Rebetez, F. Giorgi and M.R. Marinucci, 1994: An analysis of regional climate change in Switzerland. *Theor. Appl. Climatol.*, **49**, 135–159.
- and M. Rebetez, 1996: Regional behavior of minimum temperature in Switzerland for the period 1979–1993. *Theor. Appl. Climatol.*, **53**, 231–243.
- Carruthers, D.J. and T.W. Choularton, 1982: Airflow over hills of moderate slope. *Quart. J. Roy. Meteor. Soc.*, **108**, 603–624.
- Diaconis, P. and B. Efron, 1983: Computer-intensive methods in statistics. *Sci. Amer.*, **248**, 116–130.
- Efron, B., 1982: *The jackknife, the bootstrap and other resampling plans*. SIAM, 92pp.
- Elsner, J.B. and A.A. Tsonis, 1991: Comparisons of observed Northern Hemisphere surface air temperature records. *Geophys. Res. Lett.*, **18**(7), 1229–1232.
- Hansen, J. and S. Lebedeff, 1987: Global trends of measured surface air temperature. *J. Geophys. Res.*, **20**, 13345–13372.
- Hobbs, P.V., J.D. Locatelli and J.E. Martin, 1996: A new conceptual model for cyclones generated in the lee of the Rocky Mountains. *Bull. Amer. Meteor. Soc.*, **73**, 1962–1970.
- IMSL, 1989: *User's Manual, IMSL Math Library*, Houston, Texas.
- Ingram, W.J., C.A. Wilson and J.F.B. Mitchell, 1989: Modeling climate change: An assessment of sea ice and surface albedo feedbacks. *J. Geophys. Res.*, **94**, 8609–8622.
- IPCC, 1992: *Climate change 1992, The Supplementary Report to the IPCC Scientific Assessment*. Cambridge University Press, 200pp.
- IPCC, 1990: *Climate change, IPCC Scientific Assessment*. Cambridge University Press, 364pp.
- Jones, P.D., S.C.B. Raper, R.S. Bradley, H.F. Diaz, P.M. Kelly and T.M.L. Wigley, 1986: Northern Hemisphere surface air temperature variations: 1851–1984. *J. Climate Appl. Meteor.*, **23**, 1520–1530.
- Karl, T.R. and P.D. Jones, 1989: Urban bias in area-averaged surface air temperature trends. *Bull. Amer. Meteor. Soc.*, **67**, 1370–1377.
- Klemp, J.B. and D.K. Lilly, 1975: The dynamics of wave-induced downslope winds. *J. Atmos. Sci.*, **32**, 320–339.
- Legates, D.R. and C.J. Willmott, 1990: Mean seasonal and spatial variability in global surface. *Theor. Appl. Climatol.*, **41**, 11–21.
- Majorowicz, J.A. and W.R. Skinner, 1997: Anomalous ground warming versus surface air warming in the Canadian prairie provinces. *Clim. Change*, **35**, 485–500.
- Manabe, S. and R.J. Stouffer, 1980: Sensitivity of a global climate model to an increase of CO₂ concentration in the atmosphere. *J. Geophys. Res.*, **85**, 5529–5554.
- Milliman, J.D. and R.H. Meade, 1983: World-wide delivery of river sediment to the oceans. *Journal of Geology*, **91**(1), 1–21.
- Mitchell, J.M. Jr., 1953: On the causes of instrumentally observed secular temperature trends. *J. Meteor.*, **10**, 244–261.
- Murata, A., 1993: Monthly-mean temperature anomalies in relation to spatial scale in Japan. *Int. J. Climatol.*, **13**, 329–341.
- NCAR Graphics, 1995: *User's guide for NCAR GKS*—

- 0A graphics. NCAR Scientific Computing Division, P.O.Box 3000, Boulder, CO80307-3000.
- Pilifosova, O.V., I.B. Eserkepova and S.A. Dolgih, 1997: Regional climate change scenarios under global warming in Kazakhstan. *Clim. Change*, **36**, 23-40.
- Przybylak, R., 1997: Spatial and temporal changes in extreme air temperatures in the Arctic over the period 1951-1990. *Int. J. Climatol.*, **17**, 615-634.
- Robeson, S., 1993: *Spatial Interpolation, Network Bias, and Terrestrial Air Temperature Variability*. C.W. Thornthwaite Associates, New Jersey, 51pp.
- Soulis, E.D., S.I. Solomon, M. Lee and N. Kouwen, 1994: Changes to the distribution of monthly and annual runoff in the Mackenzie Basin under climate change using a modified square grid approach. *Proceedings of the Sixth Biennial AES/DIAND Meeting on Northern Climate and Mid Study Workshop of the Mackenzie Basin Impact Study, Yellowknife, NWT., Canada*, pp 197-209.
- Stephenson, D.B. and I.M. Held, 1993: GCM response of northern winter stationary waves and storm tracks to increasing amounts of carbon dioxide. *J. Climate*, **6**, 1859-1870.
- Stewart, R.E., H.G. Leighton, P. Marsh, G.W.K. Moore, W.R. Rouse, E.D. Soulis, G.S. Strong, R.W. Crawford and B. Kochtubajda, 1998: The Mackenzie GEWEX Study: the water and energy cycles of a major North American river basin. *Bull. Amer. Meteor. Soc.*, **79**, 2665-2683.
- Wallace, J.M., Y. Zhang and J.A. Renwick, 1995: Dynamic contribution to hemispheric mean temperature trends. *Science*, **270**, 780-783.
- , ——— and L. Bajuk, 1996: Interpretation of interdecadal trends in Northern Hemisphere surface air temperature. *J. Climate*, **9**, 249-259.
- Yamamoto, R. and M. Hoshiai, 1980: Fluctuations of the Northern Hemisphere mean surface air temperature during recent 100 years estimated by optimum interpolation. *J. Meteor. Soc. Japan*, **58**, 187-193.