Water Vapor Fluxes over the Saskatchewan River Basin

JINLIANG LIU AND RONALD E. STEWART

Climate Processes and Earth Observation Division, Meteorological Service of Canada, Environment Canada, Downsview, Ontario, Canada

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ABSTRACT

The NCEP–NCAR reanalysis data were used to calculate the atmospheric moisture fluxes into and out of the Saskatchewan River basin for the period 1948–2001. Although bias exists in the estimated moisture flux divergence, the data are still very useful for characterizing the general features of the basin's water vapor fluxes. The direction of the meridional moisture fluxes over the Saskatchewan River basin changes with seasons, but that of the zonal moisture fluxes does not. Moisture flows into the basin from the west (the Pacific Ocean) during all seasons. Moisture influxes from the south in early summer are usually related to the long-distance meridional transport of water vapor from the Gulf of California and the Gulf of Mexico. Moisture flows into the basin from the north in all seasons except for late spring and early summer. The moisture outflow to the east mainly arises from the extensive zonal transport across the basin in all seasons, although this is most pronounced in late summer and autumn. In addition to the two primary moisture sources, the Pacific Ocean and the Gulf of Mexico, the Arctic Ocean is also a moisture source for the Saskatchewan River basin during most seasons. Hudson Bay is another moisture source although this occurs infrequently. Moisture fluxes for the Saskatchewan River basin show some similarities with and differences from those experienced by the Mackenzie River basin. Differences in topography and surface properties between these two basins are key factors generating the differences in water vapor transport. Differences also exist in moisture sources for the two basins. However, there are connections between them through seasonal moisture exchange across the shared boundary.

1. Introduction

Water vapor transport into and out of a region is a major factor associated with its climate. Extensive water budget analyses have been carried out over a number of regions around the world such as the Arctic (Walsh et al. 1994; Serreze et al. 1995; Cullather et al. 2000), Mississippi River basin (Roads et al. 1998; Betts et al. 1999; Roads and Betts 2000; Roads 2002; Roads et al. 2002, and many others), and the Mackenzie River basin (Walsh et al. 1994; Smirnov and Moore 1998; Stewart et al. 1998; Strong and Proctor 1998; Proctor et al. 1999; Betts and Viterbo 2000; Stewart 2000; Stewart et al. 2002; Cao et al. 2002; Liu et al. 2002; Roads 2002; Roads et al. 2002). Many of these regional studies are components of the Global Energy and Water Cycle Experiment (GEWEX).

Compared with these extensive studies, little research has been carried out over the Saskatchewan River basin of western Canada, one of the most ecologically diverse basins in North America (http://www.saskriverbasin.ca/STORY/index.htm). This basin is an international watershed that spans more than 420 000 km^2, encompassing parts of three Canadian Prairie Provinces and the state of Montana. The Saskatchewan River is also Canada's fourth longest. This basin is immediately south of the Mackenzie River basin, the focus of ongoing Canadian GEWEX studies (Fig. 1). The basin is bounded by the Rocky Mountains to the west, the boreal forest to the north and east, and grassland and agricultural land to the south.

Other studies (Kendrew and Currie 1955; Longley 1972; Hare and Thomas 1979, 100–104; Phillips 1990; Bullas 2001) have pointed out that this region is often quite dry although none of these studies approached the problem from the water vapor budget point of view. The few studies over this region that are associated with water vapor transport are limited to case studies at hourly and daily scales (Strong 1996; Barr and Strong 1996) based on data obtained during the Regional Evapotranspiration Study (RES). These studies focused on diurnal features of local water vapor fluxes. The most relevant study to this paper, Raddatz (2000), studied the summer rainfall recycling in the Canadian Prairies for three summers (1997–99) and concluded that the Canadian Prairies were dry during these periods according to both recycling model results and water budget estimates from the Canadian Global Environment Multiscale model (GEM; Côté et al. 1998) gridded data.

Corresponding author address: Dr. Jinliang Liu, Environmental Monitoring and Reporting Branch, Ministry of the Environment, 125 Resources Road, East Wing, Toronto, ON M9P 3V6, Canada.
E-mail: Jinliang.Liu@ene.gov.on.ca

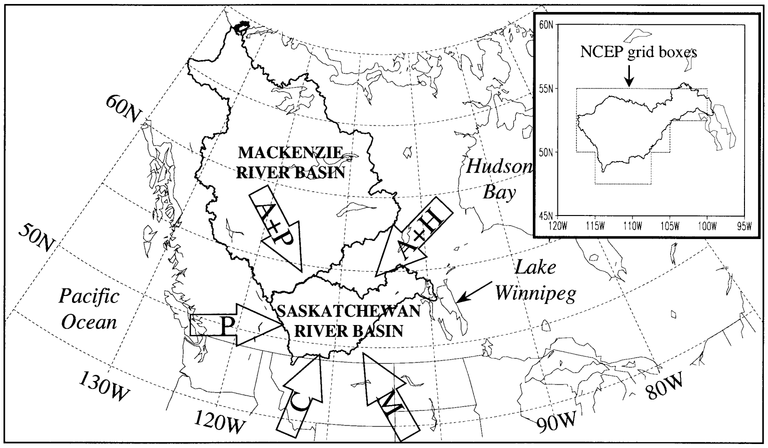

FIG. 1. Diagram showing the approximate location of the Saskatchewan River basin and the neighboring Mackenzie River basin. Arrows illustrate the moisture sources of the Saskatchewan River basin, and A, C, M, H, and P represent the moisture sources from the Arctic Ocean, Gulf of California, Gulf of Mexico, Hudson Bay, and Pacific Ocean, respectively. Also shown at the upper-right corner is a close-up of the Saskatchewan River basin with the NCEP grid boxes used for calculation in this paper.

In this study, the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay et al. 1996; Kistler et al. 2001) are used to calculate the water vapor transport for the period 1948–2001. Critical aspects of the water vapor transport into and out of the Saskatchewan River basin will then be examined: 1) long-term features; 2) short-term features; and 3) comparison with results over the Mackenzie River basin.

2. Data and methodology

NCEP and NCAR have produced reanalysis datasets for many years using a frozen state-of-the-art global data assimilation system, a database as complete as possible, and an advanced quality control system (Kalnay et al. 1996; Kistler et al. 2001). Many variables are archived from the NCEP T62/28-level global spectral model. However, only four atmospheric variables are used for this study, the specific humidity q, the west–east wind u, the south–north wind v, and the surface pressure Ps. Variables u, v, and q are located on a 144×73 horizontal grid with a resolution of $2.5° \times 2.5°$ of latitude by longitude, and on eight levels in the vertical, 1000, 925, 850, 700, 600, 500, 400, and 300 hPa because the air above 300 hPa is very dry and contributes little to water vapor transport. The four-times-daily (6 hourly) data were used for this study.

On a specific pressure level, moisture flux is simply the product of the specific humidity q and the horizontal wind vector $\mathbf{V}$ defined as

$$\mathbf{Q} = q\mathbf{V} = qu\mathbf{i} + qv\mathbf{j}, \tag{1}$$

where u and v are, respectively, the zonal and meridional wind components of the horizontal wind field. Consequently, qu and qv are usually called, respectively, zonal and meridional moisture transport.

Vertical integration of moisture fluxes across the four main boundaries is calculated by integrating qu and qv with respect to pressure along corresponding boundaries.

$$\mathbf{Q}_\varphi = -\frac{1}{g}\int_{p_{\rm sfc}}^{p_{\rm top}} (qu)\, dp \quad \text{along the western and eastern boundaries,} \tag{2}$$

$$\mathbf{Q}_\lambda = -\frac{1}{g}\int_{p_{\rm sfc}}^{p_{\rm top}} (qv)\, dp \quad \text{along the southern and northern boundaries.} \tag{3}$$

Horizontal moisture flux divergence over the Saskatchewan River basin was estimated by using Green's theorem as in Liu et al. (2002):

$$\iint \nabla \cdot (q\mathbf{V})\, dS = \oint_{\rm outer} (q\mathbf{V}) \cdot \mathbf{n}\, dl - \oint_{\rm inner} (q\mathbf{V}) \cdot \mathbf{n}\, dl, \tag{4}$$

where vector $\mathbf{n}$ is a unit vector normal to the domain boundaries, dl is a line segment of the domain boundaries, the subscripts inner and outer refer to the inner and outer boundaries, respectively, and S is the area closed by the inner and outer boundaries. The outer boundary is simply the NCEP grid boxes shown in Fig. 1, but the inner boundary changes with height and is determined by the ratio $\sigma = P_k/P_s$, where P_k is the pressure on the current level at that point. If $\sigma > 1$, the grid is underground. The inner boundaries enclose all the underground grid points. The right-hand side of (4) is used to estimate the moisture flux convergence on each pressure level, then vertical integration of the moisture flux convergence over the basin is calculated by using similar procedures to those shown in Eqs. (2) and (3).

We understand that two important factors could affect our results. First, vertical integration by using pressure-level data could introduce more errors than by using sigma-level data. However, we do not have access to the NCEP–NCAR reanalysis on sigma levels. Second, mass balance correction might be important for the calculation of moisture fluxes, especially for the convergence over complex terrain. However, a comparison shows only slight differences over the study area between our result (using pressure-level data and without mass balance correction) and the mass balance corrected moisture fluxes by using sigma-level data from Trenberth (http://www.cgd.ucar.edu/cas/catalog/tn430/ncep/t42f/index.html). The difference in moisture fluxes is within about $\pm 10\%$. All of these points imply that the previous two issues are not significant over our study area and the data are quite acceptable for moisture flux analyses, the major objective of this study.

However, we also understand that this modest difference in moisture flux could translate into a significant difference in moisture flux divergence because any divergence calculation, at its core, represents the relatively small difference between two large flux terms. Therefore, while the previously mentioned two factors did not greatly affect the moisture flux calculation, they could be a significant source of the moisture flux divergence bias. When presenting the time series of moisture flux divergence in this article, we are more interested in its relative interannual variability than its absolute values.

3. Long-term features

Monthly and annual means of moisture flux divergence will be presented first in this section to assess the bias in the divergence estimation from the NCEP–NCAR reanalysis data over the basin. Then the discussion will focus on moisture fluxes and transports. These include moisture sources for this specific basin, as well as the horizontal and vertical variations of moisture fluxes and their annual cycles.

a. Moisture flux divergence and its bias

Figure 2 shows the time series of the monthly mean (line) and annual mean (dots) moisture flux divergence over the Saskatchewan River basin estimated from the NCEP–NCAR reanalysis data from 1948 to 2001. The monthly means change dramatically from month to month, but usually the results indicate water vapor divergence during the summer and autumn and small moisture convergence during the winter and spring.

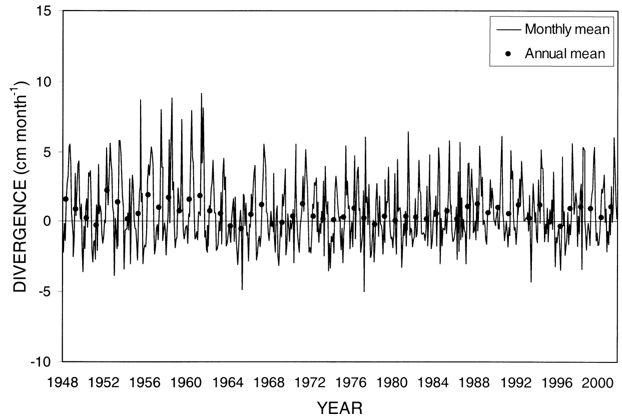

FIG. 2. Time series of the monthly mean (line) and annual mean (dots) moisture flux divergence (cm month^{-1}) over the Saskatchewan River basin from 1948 to 2001.

However, the previous conclusion on a long-term average of divergence over the basin is inconsistent with the general hydrology: water flows out of the basin through the Saskatchewan River although this region is usually dry. Therefore, there should be a long-term average moisture convergence over the basin. This implies that there must be a bias in our moisture flux divergence estimation. Theoretically, the long-term average of moisture flux divergence must be equal to the long-term average of discharge. The long-term average river flow is about 0.4 cm month^{-1} at Grand Rapids in Manitoba, which is near the mouth of the Saskatchewan River. In contrast, the 54-yr average of the estimated moisture flux divergence shown in Fig. 2 is approximately 0.6 cm month^{-1}. Therefore, there is a significant bias of $\sim$1 cm month^{-1} in the estimation of the moisture flux divergence over this basin.

This significant bias is probably a result of several factors. One of these factors is the small size of the calculation domain with respect to the low spatial and temporal resolution of the reanalysis data used. The basin only covers about 15 grid boxes of the data with only three or four grid points along some boundaries. As well, the relatively coarse temporal (6-hourly) and spatial ($2.5° \times 2.5°$ in horizontal and eight pressure level in vertical) resolutions are certainly not sufficient to completely capture the diurnal cycle or to represent the local convective events, which could cause significant differences in local water content from the model estimates. The complex topography at the western boundary of the basin may represent another problem. The high wall-like topography at the western boundary of the basin leads to difficulties in determining moisture fluxes across this boundary at the lowest levels. While the best efforts were made to exclude any contribution from underground levels, underestimates could be possible for the moisture fluxes across the western boundary at the lowest levels (Liu et al. 2002). This topography issue is actually related to the two factors we mentioned at the end of section 2. Using sigma-level data and the mass-balanced method could somehow reduce the bias in moisture flux divergence due to complex topography.

As pointed out by Serreze and Hurst (2000), the high land evaporation bias of the NCEP–NCAR reanalysis data is likely acting to reduce the precipitation less evaporation ($P - E$), and hence possibly contributing to the moisture flux divergence bias estimated in this study, as well.

Another region-specific source for this bias is the reduced availability of observations over the studied region in the early stage (1948–61) of the study period. The time series of the observation counts in the concerned region (not shown) indicates a big jump in 1962. The average counts for the period from 1948 to 1961 are about 3, while the average counts are around 10 after that. This could have resulted in the higher divergence values in the period from 1948–61 during which the mean annual moisture flux divergence is about 1.1 cm month^{-1}. The highest mean annual moisture flux divergence (1.4 cm month^{-1}) is also found for the period from 1956 to 1961 when observation counts are the least. In contrast, the mean annual moisture flux divergence is only about 0.4 cm month^{-1} for the period from 1962 to 2001. Consequently, the bias is 1.5, 1.8, and 0.8 cm month^{-1}, respectively, for the periods from 1948 to 1961, from 1956 to 1961, and from 1962 to 2001. Due to its smaller bias, the 40-yr period from 1962 to 2001 will be used for most of the rest of this paper while some presentations still retain the whole 54-yr period for documentation purpose.

Even though bias exists in the moisture flux divergence estimation, the NCEP–NCAR reanalysis data can still be used to characterize the general features of the basin's water vapor features in terms of moisture fluxes or transports, which will be the focus for the rest of this paper. Such an analysis of the moisture fluxes over this region has never been carried out before.

b. Vertically integrated moisture fluxes

The vertically integrated water vapor fluxes into (negative) or out of (positive) the basin across the four main boundaries were plotted in Fig. 3. It is quite clear from this scatterplot that there are always moisture influxes to the basin from the western boundary, whereas there are always moisture effluxes across the eastern boundary. The overall magnitude of the effluxes at the eastern boundary is larger than that of the influxes at the western boundary.

The moisture transport is much more complicated in the south–north direction. The nature of moisture fluxes changes from month to month across the northern and southern boundaries of the basin, that is, influxes in some months and effluxes in other months. A closer study of Fig. 3 confirms that influxes to the basin across the southern boundary occur only in early summer months and effluxes occur in other months. In contrast, across the northern boundary, effluxes occur only in early summer with influxes during all other months. These features are more clearly seen in the annual cycles. The net moisture gain or loss in the south–north direction will be determined by the balance of the moisture transport across the southern and northern boundaries. This will be discussed in more detail later in this paper from a perspective of the dynamic circulation.

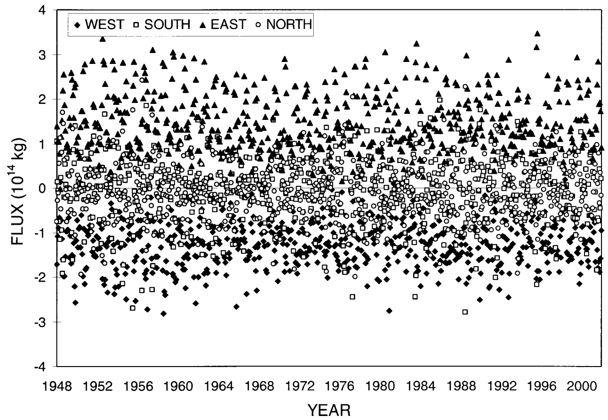

FIG. 3. Time series of the monthly means (kg) of the water vapor fluxes across the four main boundaries, west (diamond), east (triangle), south (square), and north (circle).

The 40-yr normals of the summer zonal and meridional moisture transport are plotted in Fig. 4. This figure illustrates that the zonal moisture transport increases from the west to the east, or, in other words, the magnitude of the effluxes at the eastern boundary of the basin is larger than that of the influxes at the western boundary from the Pacific Ocean. The meridional moisture transport shows a strong belt originating over the Gulf of Mexico and another relatively strong transport belt originating over the Gulf of California. This latter moisture is in good agreement with Schmitz and Mullen (1996), who concluded that moisture at lower levels over this core region of the North American monsoon system is mainly from the Gulf of California. Figure 4 also shows that the Gulf of California appears to be a more significant moisture source to the Saskatchewan River basin during summer than the Gulf of Mexico, even though one would intuitively expect the opposite.

A detailed analysis of the long-term averaged monthly horizontal distributions of moisture transport reveals that, in January–May, November, and December, the zonal moisture transport (Fig. 5a) has an almost uniform distribution over the basin. This is why the symmetry exists between the annual cycles of the moisture fluxes across the western and the eastern boundaries. A similar case occurs in the meridional moisture transport (Fig. 5b), in which the strong moisture transport belt from the Gulf of Mexico is also far away from the basin for the months mentioned earlier in the zonal transport. As

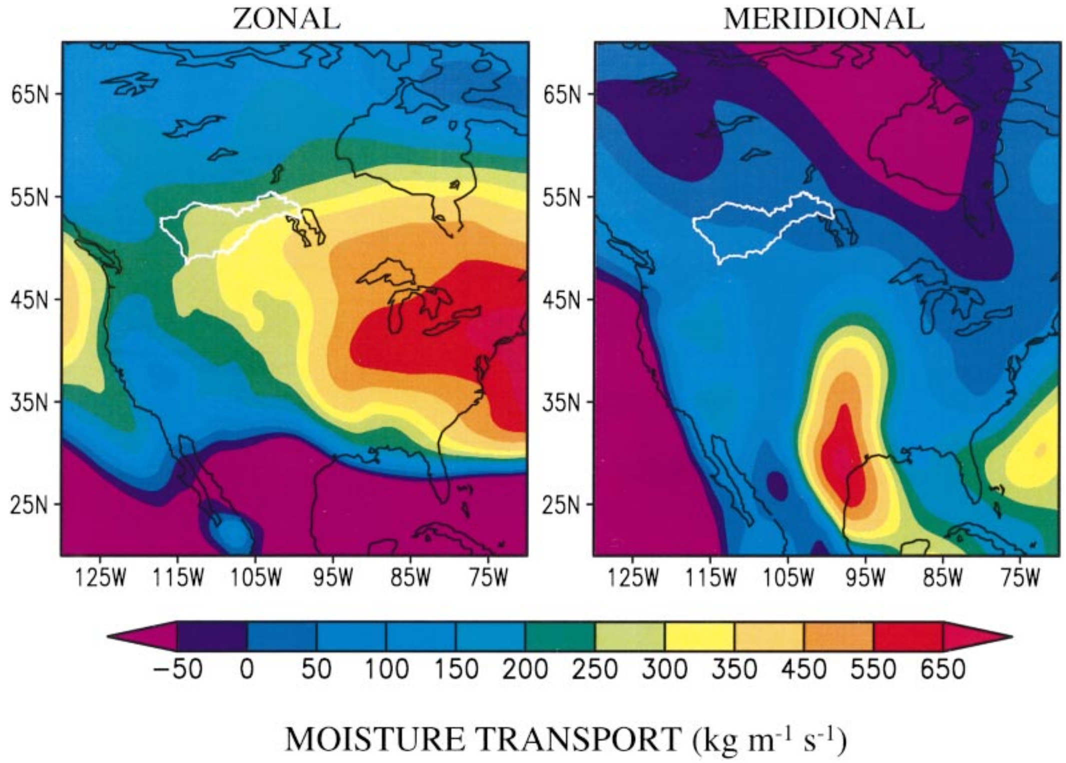

FIG. 4. The 54-yr (1948–2001) normal of (left) zonal and (right) meridional moisture transport (kg m^{-1} s^{-1}) for summer. Boundaries of the Saskatchewan River basin are shown in white.

well, the meridional moisture transport has an almost uniform distribution over the basin and this characteristic leads to the symmetry between the moisture fluxes across the southern and the northern boundaries. These uniform horizontal distributions of the zonal and meridional moisture transport over the basin are not favorable for the basin to exhibit a significant moisture flux convergence.

Beginning in June (Fig. 5a), the strong zonal moisture transport belt extends further to the west and begins to influence the basin. With the horizontal distribution pattern in June, July, and August, substantial moisture convergence does not occur over the basin because it is experiencing small moisture inflows from the west as well as much larger outflows at the eastern boundary. This could, in part, be associated with the impact of the mountain cordillera at the western edge of the basin. The zonal airflows are blocked or slowed down by the mountains and a very limited amount of moisture can be carried over the mountains and into the basin. In most cases, much of the moisture has been lost as precipitation on the west side of the mountains before the air reaches the basin.

After passing over the mountains, the airflow is speeded up in the lee of the mountains as evident in Fig. 6. In this figure, the meridional averages across the basin of the 850-hPa zonal wind and the whole wind speed are shown from the 20-yr (1979–98) climatology of the NCEP–NCAR reanalysis data. The zonal component u increases from 4.0 m s^{-1} at the western boundary to 5.9 m s^{-1} at the eastern boundary, whereas the magnitude of the wind increases from 4.4 to 7.2 m s^{-1} across the basin. However, the change in u is not linear; it has a maximum at 107.5°W. This distinction might be related to other dynamic or thermodynamic factors associated with gradients in pressure (or height) and temperature. Of course, the influxes from the meridional direction must also play a role for this process according to mass conservation.

As the strong zonal moisture transport belt extends to the west, the strong meridional moisture transport belt extends farther to the north and begins to affect the basin in May (Fig. 5b). Again, the Gulf of California is shown to be a more significant moisture source than the Gulf of Mexico during June–August. However, it is actually very difficult to separate the impacts from these two gulfs on the moisture influxes because moisture influxes from the south are usually a combination from these two regions. In May–August, the basin gains moisture in the south–north direction because it is experiencing large moisture influxes across its southern boundary and smaller moisture effluxes across its northern boundary. In July and August, the intersection of the southward and northward meridional moisture transport results in net moisture gains over the basin in the south–north direction. Beginning in September, the

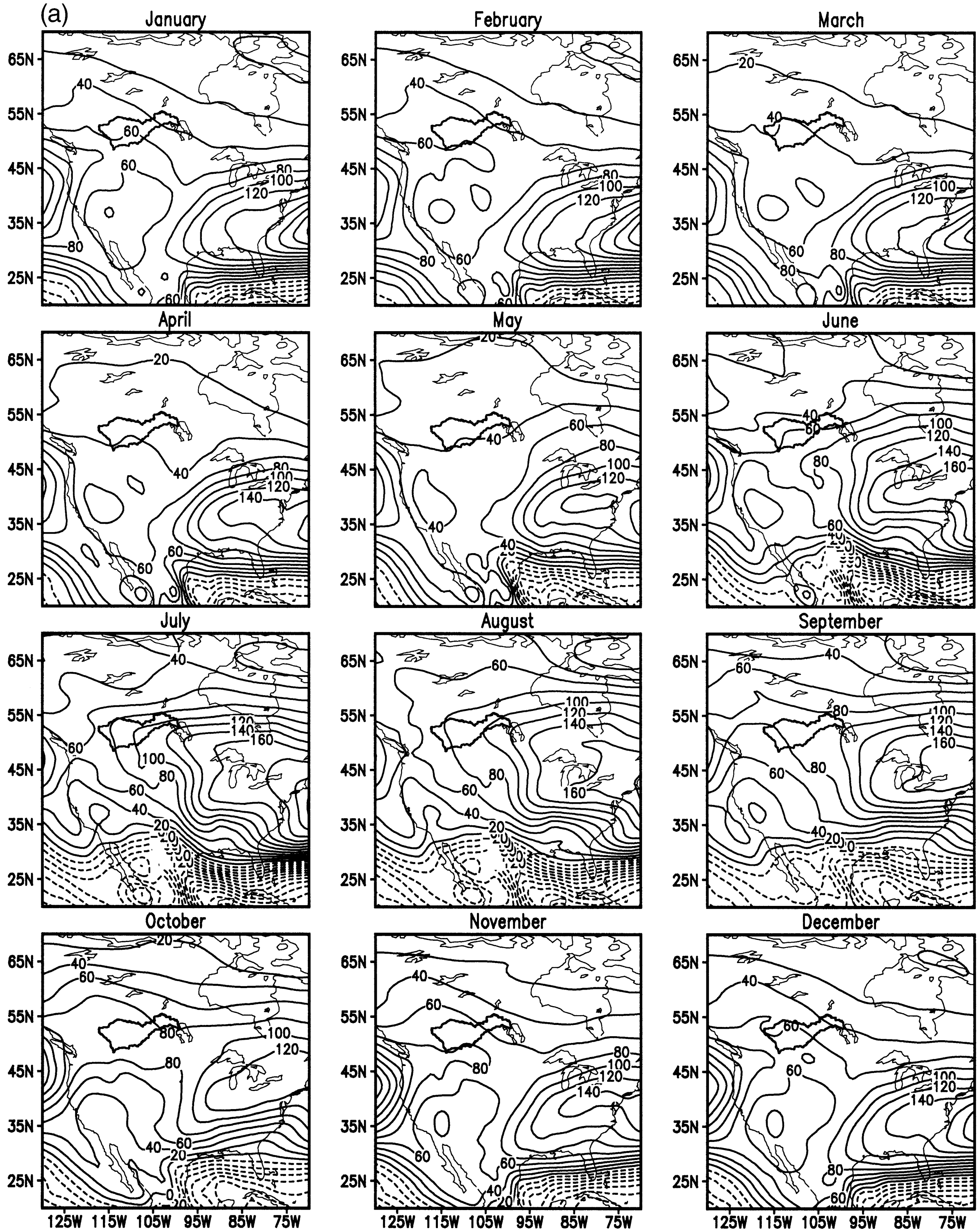

FIG. 5a. The 54-yr (1948–2001) normals of monthly means of zonal moisture transport (kg m^{-1} s^{-1}). Boundaries of the Saskatchewan River basin are also indicated.

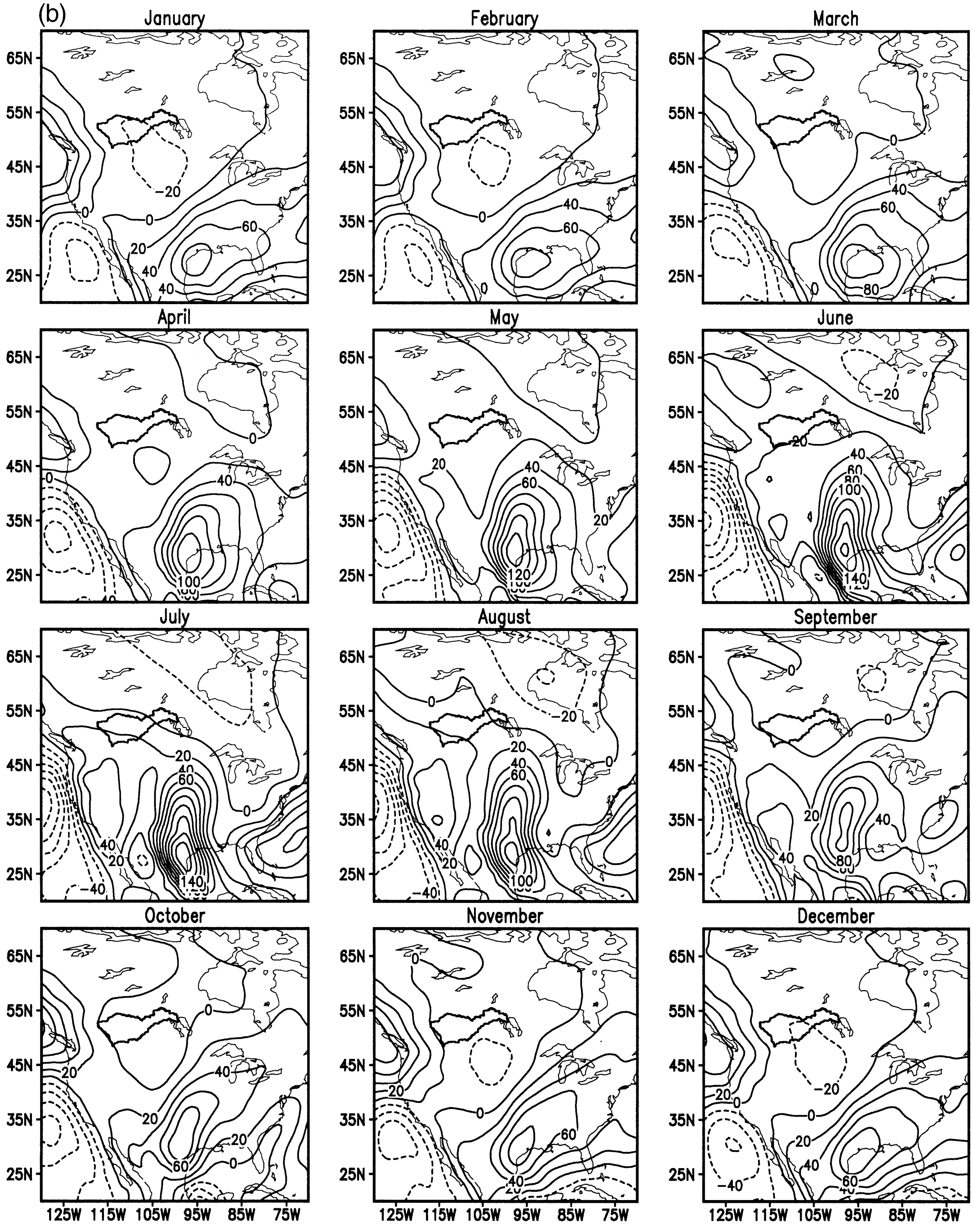

FIG. 5b. Same as in Fig. 5a but for meridional moisture transport (kg m^{-1} s^{-1}).

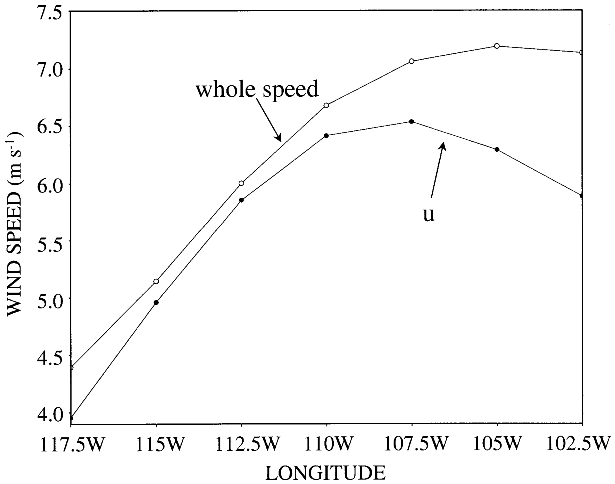

FIG. 6. The meridional average across the basin of the zonal wind component u (m s^{-1}) and the complete wind speed (square root of $u^2 + v^2$, in m s^{-1}) extracted from the 20-yr (1979–98) climatology of the 850-hPa wind field from the NCEP–NCAR reanalysis data.

strong meridional moisture transport belt initiated in the Gulf of Mexico changes its axis from south–north to southwest–northeast. This allows the southward meridional moisture transport band (negative) to move into the basin from the north. During this movement, the basin has a weak net moisture gain in the south–north direction in September, and almost nothing in October and November.

c. Moisture sources

The Saskatchewan River basin has four moisture sources. First, the basin receives moisture from the Pacific Ocean in all seasons. However, the amount of the moisture flux varies with the season. Strong moisture transport was observed in summer and late autumn with the maximum occurring in October. Relatively weak fluxes occur during other seasons, especially during late spring and early summer (February–May) when the zonal wind is usually weak over this region.

Second, the combination of Gulf of California and Gulf of Mexico is another major moisture source to the basin from the south, especially in summer. But is this a moisture source for the basin every year? This will be determined by the strength of the Great Plains low-level jet during the development of the North American monsoon system and the dynamic circulation pattern over this region. To assess this, an annual–monthly plot of the moisture flux across the basin's southern boundary is shown in Fig. 7 for the 54-yr period from 1948 to 2001. It is evident that moisture influxes do not always occur across the southern boundary during summer. Some examples of this are 1950 and 1992. In fact, there are a wide variety of situations. In some years, such influxes occur each month during the summer.

Hudson Bay is also a moisture source for the Saskatchewan River basin. Instances of this occur when the synoptic pattern is such that the Bay is at the north of a deep low pressure system or at the south of a high pressure system. The strong northeasterly flow at the northwestern portion of the low pressure system or at the southeastern portion of the high pressure system brings moisture from the Bay to the Saskatchewan River basin. Figure 8 shows a good example of this in June 1998. Such instances have usually been observed during late spring and early summer according to some analysis over the 54 yr.

The Arctic Ocean is another moisture source for the Saskatchewan River basin during most months except the early summer. Moisture from the Arctic Ocean can reach the basin after passing over the Mackenzie River basin. This will be discussed in more detail in the section on the comparison between the Saskatchewan River basin and the Mackenzie River basin.

d. Vertical variation

Analysis of the vertical structure can provide additional insights into moisture transport. In this section, long-term averaged monthly mean vertical profiles will be examined.

To demonstrate the impact from the observation counts on the moisture flux calculation, Fig. 9 shows the vertical profiles of long-term averaged annual mean moisture fluxes across the four main boundaries of the basin and the net moisture flux to the basin for the early period from 1948 to 1961, the latter period from 1962 to 2001, and the whole 54-yr period from 1948 to 2001. Generally, the net moisture flux is simply the sum of the fluxes from the four boundaries. Symmetric features between the fluxes at the western and eastern boundaries only occur on levels at and above 700 hPa; a symmetric relation between the southern and northern counterparts exists only at 925 hPa. The geometry of the basin itself is very important in this regard. The high wall-like topography of the mountain cordillera at the western boundary is associated with a jump in the moisture flux from 850 to 700 hPa. In contrast, there is no such jump for the moisture outflow at the eastern boundary because it is far away from the western cordillera. This topography-induced difference in the fluxes between the western and eastern boundaries is responsible for the sign change in the net moisture flux over the basin from 850 to 700 hPa; the magnitude of meridional fluxes is much smaller than that of the zonal fluxes and, therefore, meridional fluxes usually cannot change the sign of the net flux.

Comparison among the three periods gives similar conclusions to those of the moisture flux divergence discussion. The profile shapes are more or less the same, while the magnitudes of the profiles during the early period (1948–61) are slightly larger than those during the latter (1962–2001) and the whole (1948–2001) periods. This is mainly due to the less observation avail-

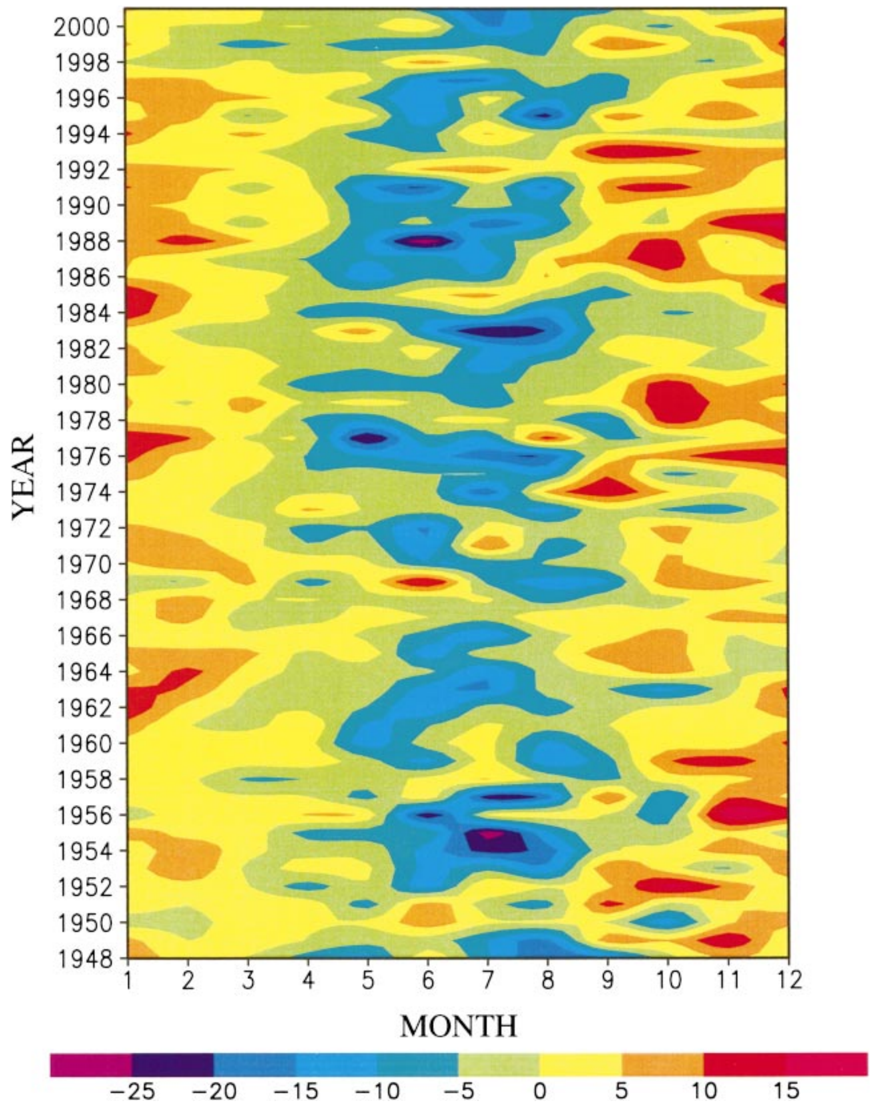

FIG. 7. Annual variation of the monthly mean moisture flux ($\times 10^{13}$ kg month^{-1}) across the southern boundary of the Saskatchewan River basin.

ability during the early period. Profiles during the latter period are almost identical with those during the whole period. Nevertheless, the latter 40-yr period (1962–2001) will be used for the remaining discussion in this paper.

The shapes of the vertical profiles indicate that the magnitudes of the fluxes at the southern and northern boundaries do not change much from month to month (Fig. 10). However, the magnitudes of the western and eastern ones have substantial seasonal variations. Beginning in January, the profiles are being squeezed towards zero and the envelope becomes thinner and thinner until April and May when the profiles are most ''compact.'' Then the envelope grows wider and becomes widest in July and August. After that, the envelope begins to become thinner again. This evolution is actually more controlled by the changes in zonal moisture transport than those in meridional transport.

The net moisture flux for the basin is an important feature. It indicates that moisture influxes occur above 700 hPa and moisture effluxes below this level.

e. Annual cycles

To better understand when the basin experiences the greatest moisture exchanges with its environment, the annual cycles of the vertically integrated moisture fluxes across the four main boundaries and the net moisture flux over the basin are plotted in Fig. 11. There is a symmetric relation between the fluxes across the western and eastern boundaries, and between those across the southern and northern boundaries, especially for the

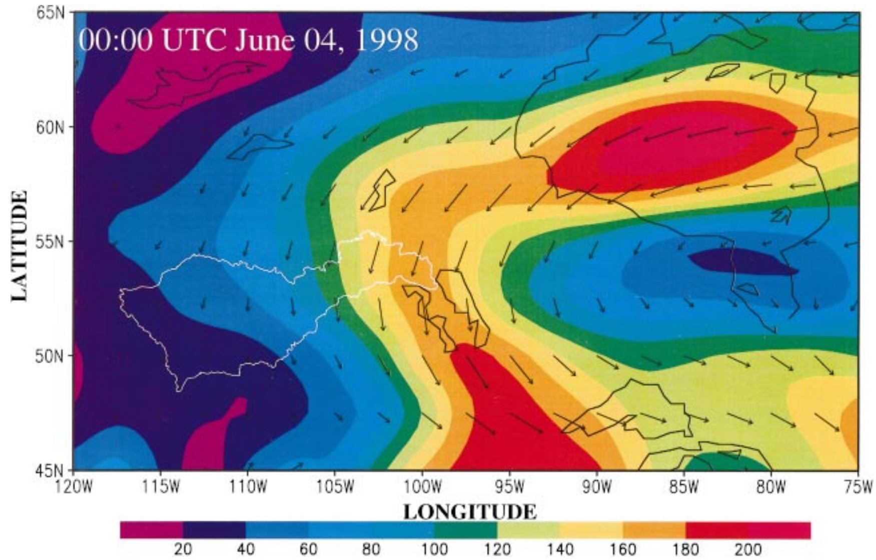

FIG. 8. An example in Jun 1998 showing that Hudson Bay is a moisture source for the Saskatchewan River basin. Plotted is the moisture transport vectors and their magnitude (color shaded, in kg m^{-1} s^{-1}) at 0000 UTC 4 June 1998. Boundaries of the Saskatchewan River basin are shown in white.

nonsummer months (January–May and October–December). It is very clear in Fig. 11 that 1) the basin gains moisture from its western boundary all year long, with maximum values occurring in October. 2) Moisture flows out of the basin across its eastern boundary during the whole year, with maximum values in July. 3) At its southern boundary, the basin gains moisture in late spring and summer (April–August) and loses moisture during other months. 4) The basin loses moisture at its northern boundary only in April–June, and gains mois-

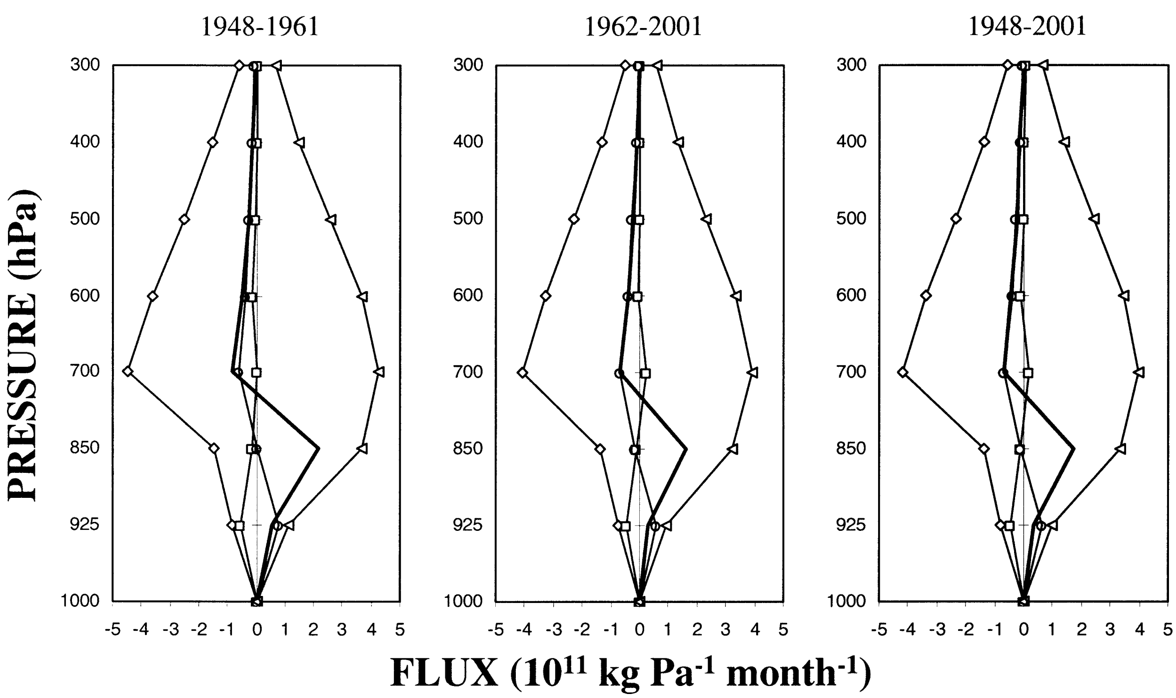

FIG. 9. Vertical profiles of the early period (1948–61), the latter period (1962–2001), and the whole period (1948–2001) averaged annual mean moisture fluxes ($\times 10^{11}$ kg Pa^{-1} $month^{-1}$) at the four main boundaries of the basin, west (diamond), east (triangle), south (square), north (circle), and the net moisture flux (thick line). Negative (positive) flux means moisture flowing into (out of) the basin. The vertical axis is pressure (hPa).

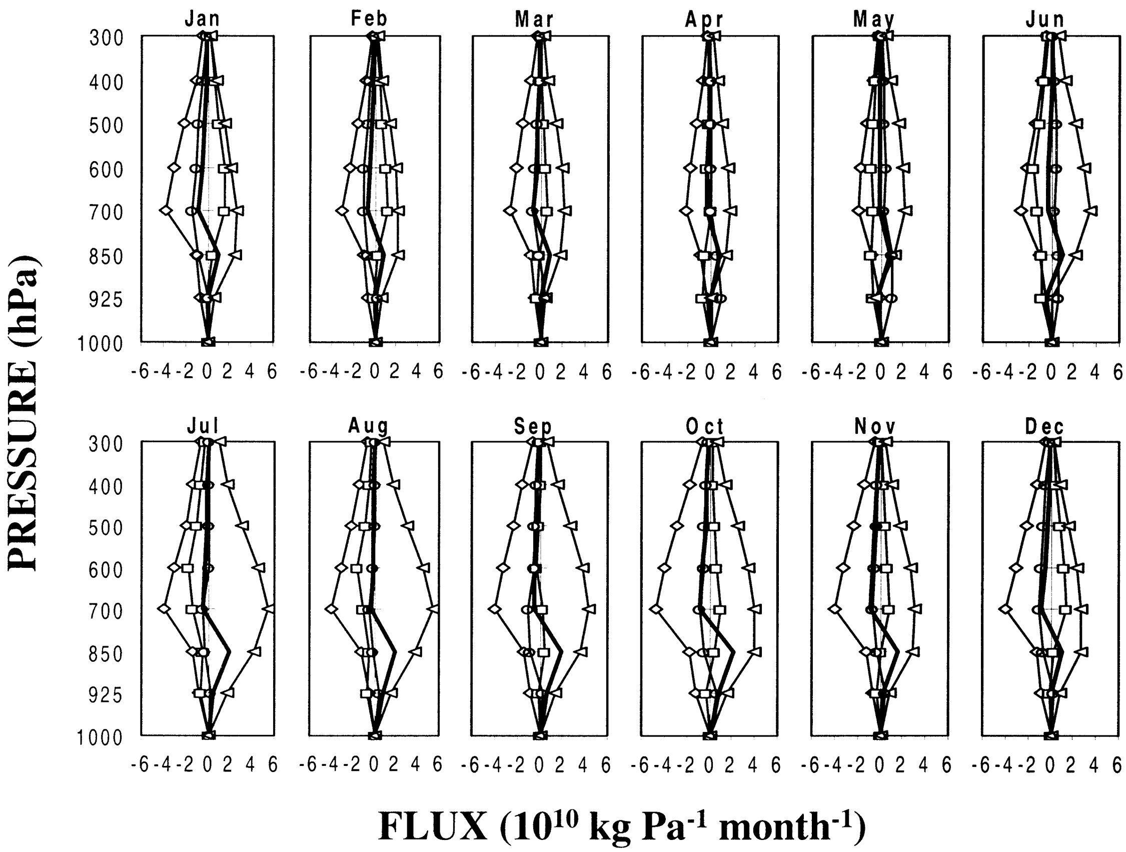

FIG. 10. Vertical profiles of the 40-yr averaged (1962–2001) monthly mean moisture fluxes ($\times 10^{10}$ kg Pa^{-1} month^{-1}) at the four main boundaries of the basin, west (diamond), east (triangle), south (square), north (circle), and the net moisture flux (thick line). The vertical axis is pressure (hPa).

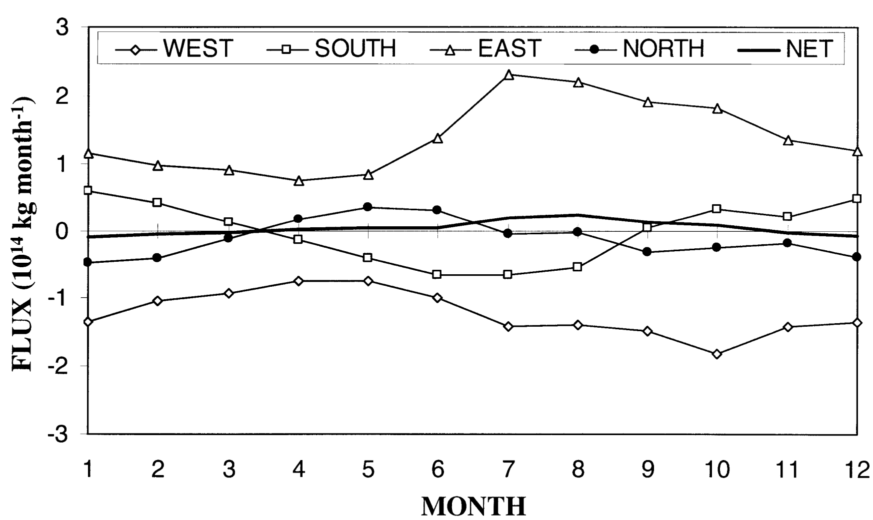

FIG. 11. The 40-yr averaged (1962–2001) annual cycles of the vertically integrated moisture fluxes ($\times 10^{14}$ kg month^{-1}) across the four main directions, west (diamond), east (triangle), south (square), north (dot), and the net (thick line).

ture during other months. 5) The basin experiences weak moisture influxes during winter and weak effluxes during other seasons with maximum in July and August.

4. Years with extreme fluxes

Although we are concerned about the overall bias in the moisture divergence calculation, we nonetheless feel that a limited examination of extreme years is insightful. Consequently, 1971 and 1965 are chosen; these, respectively, were characterized by the maximum inferred divergence and the maximum inferred convergence during the later period (1962–2001).

Comparisons between the vertical profiles of the monthly mean moisture fluxes in 1971 and 1965 lead to the observations:

- Moisture effluxes across the eastern boundary were greater in 1971 than in 1965, especially during the months from June to December, but the moisture influxes from the west were about the same.
- In most months of 1971, the basin experienced a much larger moisture efflux across the northern boundary at lower levels than in 1965, and sometimes at all levels.
- There is a clearer symmetry between the south and north fluxes during 1971 than during 1965. That is, there was little net moisture gain from the south–north fluxes in 1971.
- As a result of these features, the basin experienced much larger net moisture effluxes in the lower levels in 1971 than in 1965 (Fig. 12).

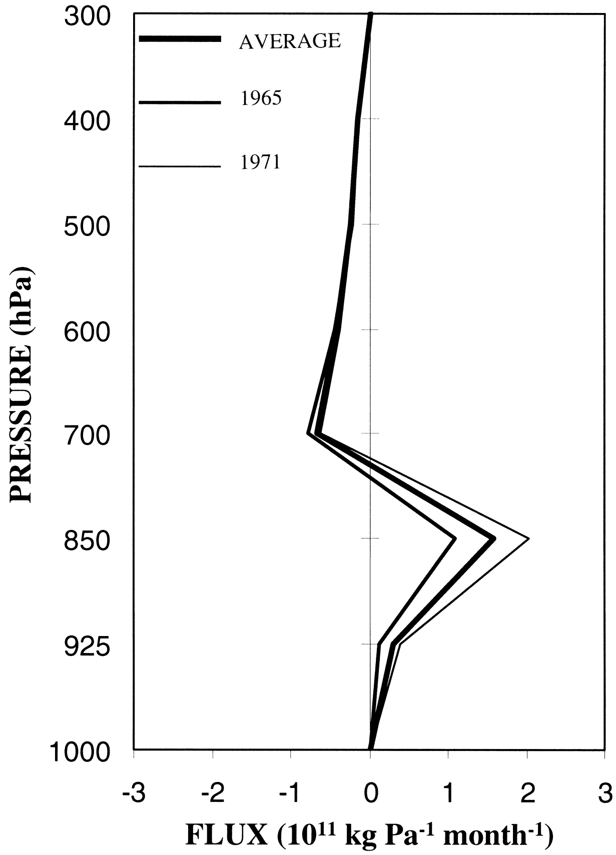

FIG. 12. Vertical profiles of the annual mean of the net moisture fluxes ($\times 10^{11}$ kg Pa^{-1} month^{-1}) for the driest year (1971; thin line), the wettest year (1965; thick line) during the 40-yr period (1962–2001), and the 40-yr period average (thickest line).

Given the fact that there was little difference in the pattern at levels above 700 hPa among 1971, 1965, and the long-term averaged vertical profiles of moisture fluxes (Fig. 12), significant differences at levels below 700 hPa played a determinative role as to the net moisture flux over the basin. During summer and autumn months, the basin had a net moisture influx at 925 hPa in 1965 (April–May, July–September), but a large moisture efflux in 1971 (July–October). Both profiles of long-term averages, 1971 and 1965 are associated with moisture effluxes at both 850 and 925 hPa, whereas the magnitude of the moisture efflux in 1971 was larger than the long-term average, and much larger than in 1965.

Other important differences between 1965 and 1971 were found in the vertical profiles in May and July (not shown). In May of 1965, the basin gained moisture from all directions at 925 hPa and this yielded the largest moisture influx of that year at this level. In July of 1965 at 925 hPa, the basin gained moisture from both the south and north and this resulted in a relatively large moisture gain. The basin also had a net moisture gain at 925 hPa in April, August, and September of this year. These favorable conditions for the basin to gain moisture never occurred during 1971 and, therefore, the basin lost moisture at 925 hPa in all months of 1971. Again, this is mainly controlled by the zonal and meridional moisture transports, which are directly related to the dynamic circulation features over the basin and its vicinity.

5. Comparison with the Mackenzie River basin

Another purpose of this study is to begin to compare the characteristics of the Saskatchewan River basin with those of the Mackenzie River basin. Hence, several aspects of the water vapor fluxes were analyzed and are discussed in this section.

Moisture sources vary somewhat for these two basins. The Pacific Ocean is a moisture source for both basins (the P arrow in Fig. 1). The combination of the Gulf of California and the Gulf of Mexico is another major moisture source (the C and M arrows in Fig. 1) for the Saskatchewan River basin in summer, although not always. As well, Hudson Bay is a moisture source for the Saskatchewan River basin when the Bay is at the north of a low pressure system or at the south of a high pressure system (the A + H arrow in Fig. 1; e.g., also see Fig. 8). No countersituations of the Hudson Bay being a moisture source for the Mackenzie River basin have yet been found. During most seasons, the Arctic Ocean

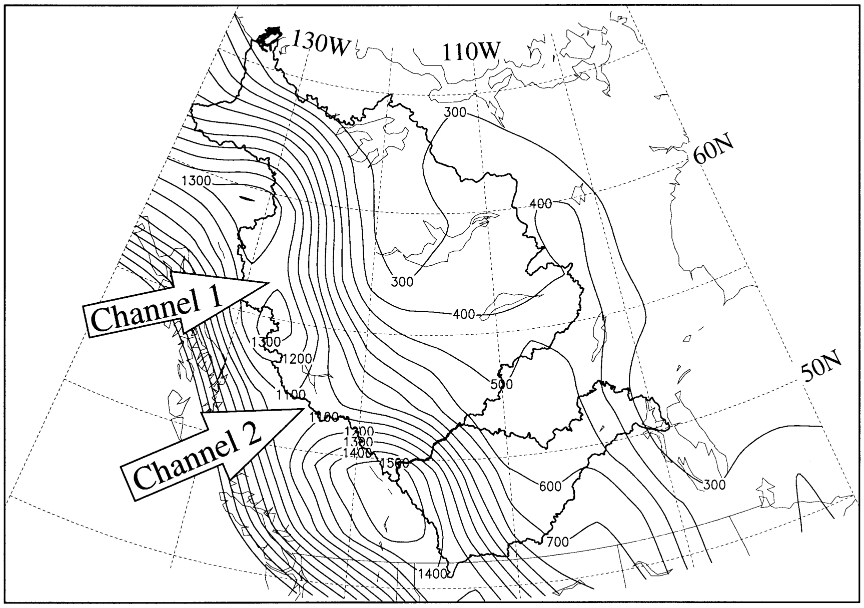

FIG. 13. Topography over the Mackenzie River basin and the Saskatchewan River basin. Plotted is the geopotential height (m) from the NCEP–NCAR reanalysis data, at a horizontal resolution of 2.5° × 2.5° lat × lon. The labeled arrows point locations of moisture passes or channels for the Mackenzie River basin.

is also a moisture source for the Saskatchewan basin. Moisture from the Arctic Ocean reaches the Saskatchewan basin after passing over the Mackenzie basin. The Mackenzie River basin has the Arctic Ocean as its other primary moisture source, and also sometimes benefits from the Gulf of Mexico during summer.

Given its greater number of moisture sources, it appears that it would be easier for the Saskatchewan River to acquire moisture than the Mackenzie River basin. However, topography (Fig. 13) plays a major role in this regard. For example, the relatively flat topography of the Saskatchewan River basin makes it easy for moisture from the Gulf of Mexico to pass over the basin without significant loss. As well, the west/high–east/low slopelike topography (>2000 m at the west and continuously sloping to between 300 and 500 m at the east) does not provide any topographic forcing on its easterly flank to initiate precipitation. In contrast, the topography in the Mackenzie River basin is much more complicated than the Saskatchewan River basin, especially in the wide upland area on its western flank. As well, the topography of Mackenzie River basin is more basinlike in the west–east direction (>2000 m at the west, <100 m in the middle, and 300–500 m at the east) than that in the Saskatchewan River basin. This topographic shape is more favorable for a moisture convergence since, although small, it will systematically lead to a location for precipitation initiation.

Stewart (2000) and Cao et al. (2002) pointed out other effects of topographic features on the water cycle of the Mackenzie River basin. The blocking effect of the western mountainous topography is believed to contribute to the major differences in low-level moisture advection between the two basins (Fig. 14). The Mackenzie River basin experiences moisture influx at these levels, whereas the Saskatchewan River basin experiences moisture efflux. The magnitude of this low-level moisture efflux over the Saskatchewan basin is smaller in extreme years with less inferred moisture divergence, and larger in extreme years with larger inferred moisture divergence. The western boundary of the Mackenzie River basin is much longer than that of the Saskatchewan River basin. This provides greater potential for the Mackenzie River basin to benefit from the Pacific Ocean moisture source than is the case for the Saskatchewan River basin. As well, across the western boundary of the Mackenzie River basin, there are passes or channels (Fig. 13; also, see Cao et al. 2002) where moisture can be efficiently brought into the basin at relatively low levels. In contrast, the higher ''wall-like'' topographic barrier at the western boundary of the Saskatchewan River basin, without any such avenues for moisture flow, significantly reduces the amount of moisture brought into the basin from the Pacific Ocean at the relatively low levels. Therefore, differences in topography and surface properties between these two basins are key factors generating the differences in the water vapor transport; they affect whether the moisture may be available and how much of it can reach the basin from the sources.

It is worth noting that the low horizontal resolution in the NCEP–NCAR reanalysis data also causes unrealistic smoothness of the mountain orography (Fig. 13). This unrealistic smoothness serves to ''spread out'' the east–west scale of the mountain rage. The over-extended

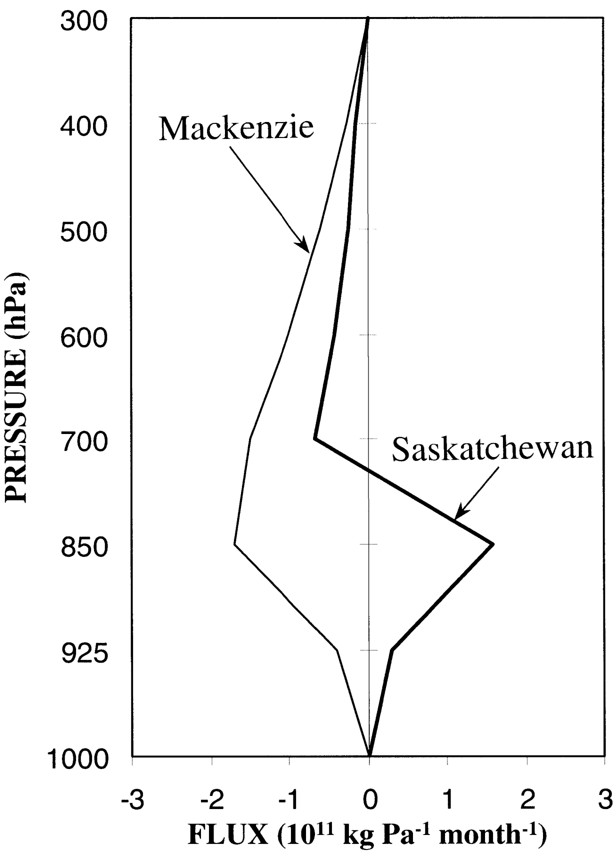

FIG. 14. Comparison of vertical profiles of the annual mean of the net moisture fluxes ($\times 10^{11}$ kg Pa^{-1} month^{-1}) for the Mackenzie River basin (thin line) and the Saskatchewan River basin (thick line).

east-west scale may act to improperly block the low-level summer-season moisture flux from the south and thus could have contributed to the bias in the moisture flux divergence.

The two basins are connected by a shared boundary. Part of the southern boundary of the Mackenzie River basin is the northern boundary of the Saskatchewan River basin. There is naturally an excellent match between the calculated outflows from (inflows to) the Mackenzie River basin and the calculated inflows to (outflows from) the Saskatchewan River basin (Fig. 15). In particular, the Saskatchewan River basin gains moisture from the Mackenzie River basin in January–March, and July–December, and the Mackenzie River basin receives moisture from the Saskatchewan River basin in April–June. Proctor et al. (1999) concluded that, according to their studies of 1994–99, the Mackenzie River basin usually loses moisture across its southeastern (or southern) boundary with June being an exception. In fact, this is not surprising because there are usually outflows in May and June across the northern boundary of the Saskatchewan River basin, which is the southern boundary of the Mackenzie River basin. The fact that influxes in April and May did not show up in their result is most likely due to different sample lengths for the calculations.

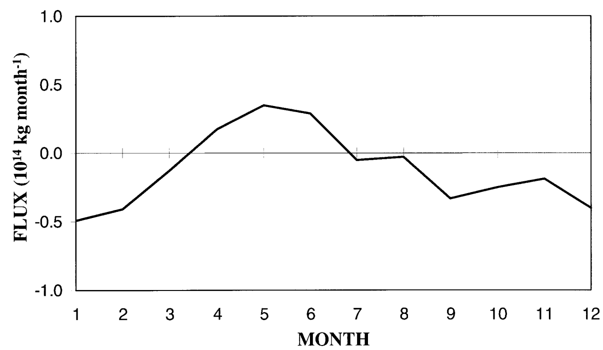

FIG. 15. Annual cycle of the moisture flux ($\times 10^{14}$ kg month^{-1}) across the shared boundary between the two basins. That is, part of the northern boundary of the Saskatchewan River basin is also part of the southern boundary of the Mackenzie River basin.

From an interannual variation perspective, the Mackenzie River basin gains much more moisture from its environment (Liu et al. 2002) than does the Saskatchewan River basin. Assuming that long-term averaged moisture convergence is equal to long-term averaged discharge, long-term annual average of convergence over the Mackenzie River basin is 176 mm, and only 50 mm over the Saskatchewan River basin.

6. Conclusions and discussion

Atmospheric moisture fluxes have been calculated from the NCEP–NCAR reanalysis data over a central Canadian basin, the Saskatchewan River basin, for the period 1948–2001. The analysis in this study indicates that there is an overall bias of $0.8 \sim 1$ cm month^{-1} in the calculated long-term average moisture flux divergence over this specific region. It is believed that this is mainly due to the small size of the basin with respect to the low spatial and temporal resolutions, less observation availability in the early period, and some inherent bias such as the high land evaporation bias in the reanalysis data. However, the data are still very useful for characterizing the general features of the basin's water vapor fluxes.

The Saskatchewan River basin has four moisture sources, the Pacific Ocean, the combination of the Gulf of California and the Gulf of Mexico, Hudson Bay, and the Arctic Ocean. It receives moisture from the Pacific Ocean in all seasons. However, the basin cannot always benefit from the Gulf of Mexico and Hudson Bay. The strength of the Great Plains low-level jet and the dynamic circulation pattern over the basin determine if the basin can tap the moisture from the Gulf of Mexico. The basin can obtain moisture from Hudson Bay only when the Bay is at the north of a deep low pressure system or at the south of a high pressure system. Moisture from the Arctic Ocean can reach the Saskatchewan River basin after passing over the Mackenzie River basin during most seasons except late spring and early summer.

The long-term averaged vertical profile of the net moisture flux over the Saskatchewan River basin exhibits a sine curve with its node between 850 and 700 hPa. It features moisture effluxes below the node and influxes above the node. The topography and geometry of the basin itself are very important for these moisture flux features. Given that the magnitude of the zonal moisture transport across the region is much larger than that of the meridional transport, the large topography-induced difference between the fluxes across the western and eastern boundaries plays an important role on the sign change of the moisture flux from 850 to 700 hPa.

Long-term analyses show a strong zonal moisture transport zone at the eastern edge of the basin; this is mainly associated with the extensive extratropical high pressure system over the southeastern United States during summer and autumn. Long-term meridional moisture transport shows strong transport belts from the Gulf of Mexico and the Gulf of California. Usually, the magnitude of the zonal transport is much larger than that of the meridional transport.

Seasonal analyses indicate that influx occurs during all seasons at the western boundary and efflux occurs during all seasons at the eastern boundary. However, the direction of moisture fluxes in the south–north direction changes with the seasons. In most months there is a moisture influx from the north to the basin, but an efflux from the basin in late spring and early summer. Moisture influxes dominate at the southern boundary in summer and effluxes in other seasons.

The large moisture efflux to the east is mainly due to the extensive zonal transport at the eastern boundary of the basin in late summer and autumn. The moisture influxes from the south in summer are usually related to the long-distance meridional transport of water vapor from the Gulf of California and the Gulf of Mexico. A strong meridional moisture transport belt originating from the Gulf of Mexico begins to develop in late spring and early summer when the Great Plains low-level jet is strong during the development of the North American monsoon system; it becomes strongest and begins to influence the basin in June. If a convergent circulation pattern exists over the basin, moisture convergence occurs. Otherwise, the moisture from the Gulf of Mexico just passes over the basin without significant loss in the form of precipitation within the basin.

Extreme years were examined to determine the significant moisture transport characteristics during years with maximum inferred divergence and maximum inferred convergence. Compared with the extreme years with large inferred moisture divergence, extreme years with large inferred moisture convergence are usually associated with less moisture effluxes at the eastern boundary, stronger influxes from the south, and less moisture effluxes at lower levels in the vertical profile of the net moisture flux.

Significant differences are found between the Mackenzie River basin and the Saskatchewan River basin in terms of temporal and vertical variations of water vapor fluxes. Differences in the vertical profiles are very evident. Moisture influx occurs at all levels for the Mackenzie River basin but only above 700 hPa for the Saskatchewan River basin. Topographic shape is believed to play a major role in defining this feature. Moisture sources are somehow different. The Mackenzie River basin has the Pacific Ocean and the Arctic Ocean as its two primary moisture sources, it also benefits from the Gulf of Mexico during early summer, but, so far at least, no instances have been found that Hudson Bay is a moisture source.

There are connections between these two basins through seasonal moisture exchange across their shared boundary. The Saskatchewan River basin receives moisture from the Mackenzie River basin over most periods of the year. In contrast, the Mackenzie River basin only receives moisture from the Saskatchewan River basin during late spring and early summer when the meridional moisture transport from the Gulf of Mexico is strong.

In summary, this paper has uncovered a number of critical aspects of the water vapor fluxes over the Saskatchewan River basin. This often-dry region receives water vapor from several sources but in general it is subjected to large swings in the features of its water vapor fluxes. Findings on similarities and differences between this basin and the Mackenzie River basin will further contribute to Canadian GEWEX studies associated with transferability between these basins.

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