Hydrological Budgets and Surface Energy Balance of Seven Subbasins of the Mackenzie River from the ECMWF Model

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ABSTRACT

The liquid and frozen hydrological budgets and the surface energy budget from seven subbasins of the Mackenzie River are analyzed using hourly integrals from the operational European Centre for Medium-Range Forecasts model from September 1996 to August 1998. The model budgets give estimates of precipitation (rainfall and snowfall), surface evaporation (of water and snow), runoff, and melt terms in the spring. On a basin scale and monthly timescale, the model precipitation correlates well with observations but has a 40% positive bias. On an annual basis, evaporation has a 60% positive bias. Although the annual runoff for the Mackenzie as a whole is close to the annual stream flow, this condition is not true for the subbasins. In the liquid water budget, nudging of soil water compensates for basin errors in runoff. The model snow budget is not closed because each new snow analysis depends heavily on climatological means. The surface energy balance on the basin scale also is analyzed. Although the model gradients of net radiation probably are realistic, the model evaporation bias means that sensible heat flux is negatively biased, especially in spring.

1. Introduction

The Global Energy and Water Cycle Experiment (GEWEX) has chosen several regions and river basins for study around the globe. One of these, the Mackenzie River GEWEX Study (MAGS) was chosen because the freshwater budget of the Arctic is an important component of the high-latitude climate system. The key objectives of MAGS (Stewart et al. 1998) are to understand and to model the hydroclimate behavior of this northern river and its subbasins, which flow from the North American continent into the Arctic Ocean. The Mackenzie basin is large (drainage area of 1.8×10^6 km^2), and surface and upper-air observations are relatively sparse, so models are essential to estimate the surface energy and water balance over the annual cycle. This paper summarizes the liquid and frozen surface water and energy budgets from the European Centre for Medium-Range Forecasts (ECMWF) operational model for two years from 1 September 1996 to 31 August 1998 for seven subbasins of the ECMWF model, shown in the model coordinate framework in Fig. 1. The budgets in this paper were not computed from the standard 6-hourly gridpoint operational archive. The ECMWF analysis system has the additional capability of archiving averages for grid points within quadrilaterals at hourly time resolution during the analysis cycle, provided the basins are defined beforehand. In the operational analysis cycle, these hourly basin integrals are stored for the daily forecasts from the 1200 UTC analysis time. For these MAGS basins, hourly basin integrals for the quadrilaterals shown were combined from the 11–35-h forecasts (made from the 1200 UTC analysis time every day) to give a continuous hourly time series of surface meteorological variables and accumulated surface energy and water fluxes. In Fig. 1, basin 1 is the Peel River and Mackenzie delta, basin 2 is the Great Bear Lake subbasin, basin 3 is the Great Slave Lake subbasin, basin 4 is the Liard River, basins 5 and 6 are eastern and western sections of the Peace River, and basin 7 is the Athabasca River. The model integrals include all grid points (shown as shaded dots) within each quadrilateral, so that some approximation of the basin areas is involved. Note that the number of grid points on a latitude circle decreases toward the poles. Table 1 lists the basin drainage areas and their approximation in the ECMWF model. All the results will be presented as area averages, based on the model areas for model results and the basin drainage areas for ob-

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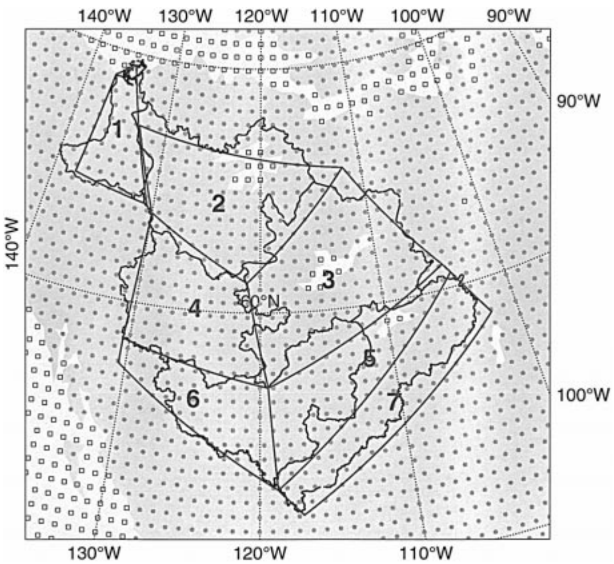

FIG. 1. Representation of seven subbasins of the Mackenzie River by curvilinear quadrilaterals in the ECMWF operational model. The dots are the model physics land grid points; open squares are water points.

servations. Basin 7 for the Athabasca is represented poorly because the model curvilinear coordinates were mistakenly not considered properly in the initial definition. For the Peace River drainage, the partition into eastern and western sections corresponding to the model quadrilaterals also is approximate. Improvements will be made in the representation of the subbasins in future reanalyses.

Similar recent studies that used nine years of the ECMWF 15-yr reanalysis (abbreviated as ERA-15) have been completed for the subbasins of the Mississippi (Betts et al. 1998a, 1999a). Although the hydrometeorological behavior of the Mississippi differs considerably from that of the Mackenzie, some of the model issues are global in nature. Others, in particular the errors in the representation of the frozen hydrological processes and the boreal forests in the model, are much more important for the Mackenzie. These papers showed that, for the Mississippi basin as a whole, the monthly model precipitation for the 12–24-h forecast, when compared with gridded rainfall observations, had a positive bias of about 20% and a correlation coefficient of over 90%. For the subbasins, the biases were more variable, and the correlation was a little lower. For the Mackenzie basin, precipitation observations are less dense than they are over the Mississippi basin, and the annual snowfall is much higher (and more difficult than rainfall to measure accurately), so that the rainfall and snowfall forecast by a high-resolution model may give useful estimates of precipitation at high spatial and temporal resolution. However, the density of upper-air observations used in the analysis cycle also is lower over the Mackenzie (one per 300 000 km^2) than over the Mississippi

TABLE 1. Mackenzie subbasin drainage areas and their model approximation.

Subbasin	Drainage area (km^2)	ECMWF model area (km^2)
1 Peel/Delta	117 127	106 950
2 Great Bear Lake	421 191	344 630
3 Great Slave Lake	378 245	421 489
4 Liard	273 395	283 828
5 Peace (E)	186 237	260 712
6 Peace (W)	132 873	186 007
7 Athabasca	285 111	228 839
Total	1 791 857	1 832 455

(one per 140 000 km^2). In addition, we have reason to believe the evaporation errors are larger over the boreal forest than over the central United States, which introduces a larger systematic bias in the precipitation (see below). These same papers concluded that the runoff in the ECMWF model (which is all deep runoff from the base layer, because the surface runoff scheme is not activated) is less than the observed stream flow for the Mississippi basins. They also showed how the nudging of soil water plays an important role in the modeled liquid hydrological budget. It prevents long-term drifts of soil water, but it also attempts to compensate for model systematic errors in evaporation and runoff. Betts et al. (1999a) discussed briefly the model's frozen hydrological budget for the upper Mississippi basin. The model frozen hydrological budget is not in balance, because there is a new snow analysis at each analysis time, based on observations and climatological mean values.

A recent extensive study of Arctic precipitation and evaporation (Walsh et al. 1998) that compared 10-yr runs from 24 climate models with observations found that most of the models overestimated the precipitation over the American watershed of the Arctic Ocean. The climate model runs came from the Atmospheric Model Intercomparison Project (AMIP) for the period of 1978–88. Walsh et al. (1998) also found that the difference between precipitation and evaporation ($P - E$) generally was overestimated by the climate models at high latitudes. One of the AMIP models was a low-resolution version (T-42) of the ECMWF model with the land surface scheme of Blondin (1991), an earlier version than the one used in this study (see section 1a). Precipitation over the American watershed of the Arctic Ocean in the ECMWF AMIP output was much higher than climate values, but $P - E$ was slightly lower than the observed mean stream flow of the Mackenzie River. This positive precipitation bias is present in this study with a later version of the operational model, and some of the causes and the model improvements under development will be discussed.

Using a Cressman analysis of radiosonde data and rain gauge observations, Walsh et al. (1994) estimated the atmospheric moisture convergence and precipitation and obtained evaporation as a residual for 18 years over the Mackenzie River basin. The annual mean values are

249, 336, and 87 mm, respectively, but the range of interannual variability is about ±50% of the annual mean. Mean monthly moisture convergence in summer is small and positive, but values for any given year can range from −20 to 30 mm, implying that climatological means are not representative of a given year.

Stendel and Arpe (1997) compare the precipitation of ECMWF and National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) atmospheric reanalyses over the Mackenzie River basin with rain gauge–based climate means. ERA-15 monthly mean precipitation ranges from 22 mm in winter to 50 mm in summer, with a 10% positive bias when compared with the climate values; NCEP–NCAR winter values are similar to those of ERA-15, but summer values are close to 100 mm month^{-1}. ERA-15 values of runoff compare well with stream flow measurements (Stendel and Arpe 1997).

This paper will discuss the model liquid and frozen hydrological budgets and surface energy balance for the Mackenzie basin, a GEWEX study area with relatively sparse data sources. In addition to the use of climatological validation data for the Mackenzie, corrected precipitation averages for six subbasins for the first 16 months (September 1996–December 1998) derived for MAGS by Hogg et al. (1996) and stream flow data for a similar period were available. These data, together with a study comparing the model with a long time series of tower flux measurements over the boreal forest, are sufficient to confirm the precipitation and evaporation biases in the model. When the 1998 precipitation and stream flow data become available in a year or so, output from the new ECMWF 40-yr reanalysis (ERA-40) should be available for a longer-term comparison.

a. *ECMWF model land surface scheme*

The current land surface scheme (Viterbo and Beljaars 1995) became operational in August 1993. The nudging of soil water based on short-term forecast errors in low-level humidity was introduced in November 1994 (Viterbo and Courtier 1995). This nudging is an addition of soil water to the model root zone, which is necessary to prevent the downward drift of soil water brought about by model errors, including the low rainfall in the 6-h analysis cycle (which in turn is related to the fact that the model dynamic fields take at least 24 h to ‘‘spin up’’ to an equilibrium in which the model hydrologic cycle is in close balance). As a result, however, the model analysis cycle does not conserve water. Soil water freezing and a revised stable boundary layer were introduced in September 1996 (Viterbo et al. 1999), and the albedo model for the boreal forests was changed in December 1996 (Viterbo and Betts 1999). This December 1996 change reduced the albedo of the boreal forests in the presence of snow from 70%–80% to about 20%. The albedo calculation after December 1996 accounts for the forested areas, but the evaporation calculation for snow (which is based on a potential evaporation calculation at the model skin temperature) is not aware that the snow is shaded partially by the canopy. This lack leads to high snow evaporation in the model (Betts et al. 1998b). A large part of the Mackenzie basin is boreal forest. The ECMWF model for the 1996–98 time period calculates evapotranspiration by using only a single vegetation type (nominally grassland). The surface evapotranspiration algorithms do not allow for the tight stomatal control of coniferous forests (Jarvis et al. 1997; McCaughey et al. 1997), so the model evaporative fraction is higher in summer than is observed at a boreal spruce forest site (Betts et al. 1998b). Although soil freezing was introduced into the model thermal budget, no change has been made yet to the model hydrological processes, so soil water continues to drain in winter even when the soil is frozen. The analysis covers only two years, September 1996–August 1998, because the only change in the ECMWF land surface model during this period was the snow albedo change in December 1996, and this change had limited impact, since it was made early in the winter. We intend to analyze a longer period using ERA-40 data, which are based on an improved snow and forest model.

The deficiencies pointed out above will be addressed in a substantial revision of the land surface model that is currently under development for ERA-40. An optimal interpolation scheme (Douville et al. 2000) will replace the current nudging scheme to initialize soil water. A ‘‘tile’’ scheme will be used for the soil–vegetation–atmosphere interface. Each land grid point will be divided into a maximum of six fractions (shaded and exposed snow, snow-free low and high vegetation, wet canopy, and bare soil), and each fraction will have a separate energy balance, that is, separate skin temperatures and surface fluxes. A low and high dominant vegetation type will characterize each point, with appropriate evaporative control functions. A new snow model will have prognostic albedo, density, and temperature, in addition to the current evolution equation for snow mass.

b. *Available observations*

The observations available to validate the model are limited. In addition to the climatological precipitation and stream flow for the Mackenzie, monthly basin-averaged corrected precipitation (Hogg et al. 1996) for the years 1996–97 is available. Monthly stream flow data for the same years are available also and have been used to estimate both the annual stream flow for most of the subbasins and the monthly stream flow for the Mackenzie as a whole. The data for 1998 are not available yet. For comparison with model runoff, all stream flow estimates were converted to mm by dividing by the area drained by a given gauge. Table 2 lists the gauges, with their location and drainage area, and for which basin comparisons they were used.

We estimated the monthly stream flow (converted to

TABLE 2. Stream flow gauges used for basin estimations.

Gauge	Location	Drainage (km²)	Basin estimation
10LC014 Mackenzie River at Arctic Red River	67°27′30″N, 133°44′41″W	1 680 000	Mackenzie, sum of 2, 3, 4, 5, 6, 7
10MC002 Peel River above Fort McPherson	67°14′56″N, 134°52′59″W	70 600	Mackenzie and 1
10LA002 Arctic Red River near the mouth	66°47′24″N, 133°04′54″W	18 600	Mackenzie and 1
10GC001 Mackenzie River at Fort Simpson	61°52′07″N, 121°21′25″W	1 270 000	Sum of 3, 4, 5, 6, 7
10ED002 Liard River near the mouth	61°44′34″N, 121°13′40″W	275 000	4
07KC001 Peace River at Peace Point	59°06′50″N, 112°25′35″W	293 000	5 + 6
07HA001 Peace River at Peace River	56°14′41″N, 117°18′46″W	186 000	6
07DA001 Athabasca River below McMurray	56°46′50″N, 111°24′00″W	133 000	7

mm month^{-1}) for the Mackenzie River near its mouth by summing the first three subbasins in Table 1. For all the subbasins except basin 2 (Great Bear Lake), estimates of the *annual* stream flow (converted to mm by dividing stream flow by drainage area) from selected gauges were made as indicated in Table 2. Basin 1 was estimated by summing the Peel River and Arctic Red River (which does not include the Mackenzie delta). For basin 2, the Mackenzie River flow at Fort Simpson was subtracted from that at the Arctic Red River. For basin 3 no estimate is available, primarily because of missing data at the Mackenzie gauge near Fort Providence (not shown). The Liard River gauge near the mouth is representative of that basin. The Peace River at Peace Point gives the sum for basins 5 and 6. An estimate for the western half of the Peace basin was made from the gauge at Peace River. An estimate for the eastern basin 5 was then found by taking a difference. The last gauge was used as representative of the Athabasca basin, although it has a smaller drainage area than the model basin, which is displaced a little to the south.

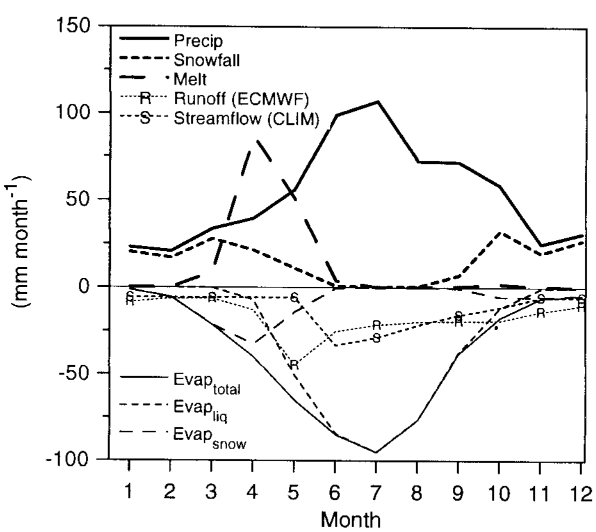

FIG 2. Two-year monthly average precipitation, snowfall, evaporation, snowmelt, and runoff for the Mackenzie from the ECMWF model, and climatological stream flow.

2. Mackenzie basin monthly surface hydrological description

Results for the entire Mackenzie basin, the two-year average, the separate liquid and frozen budgets (including a comparison of model runoff and stream flow), and the comparison of modeled and observed precipitation will be shown first.

a. Two-year mean annual cycle in the model

Figure 2 shows key terms in the modeled mean hydrological budget for the whole Mackenzie basin (mm month^{-1}). A two-year average is given for the whole basin. The heavy solid line is the annual cycle of precipitation, showing a summer maximum of around 100 mm month^{-1}. From November to March, almost all this precipitation is snowfall in the model (heavy short dashes). Evaporation (thin solid line) is plotted as negative and is subdivided into liquid evaporation and evaporation of snow, which has an April peak. Snowmelt, which also has a large April peak in the model (near 80 mm month^{-1}) is shown with long, heavy dashes. The model runoff (labeled as *R* and plotted as negative) peaks a month later, in May; this runoff is all drainage from the model's deepest layer, which is parameterized to increase rapidly once a threshold soil water is reached in the model base layer (100–289 cm). Although the model has a surface runoff parameterization, it hardly ever is activated, because of an inadequate representation of subgrid-scale precipitation. There is no river routing scheme in the current ECMWF model. For comparison, the climatological stream flow (1972–90 mean) of the Mackenzie River above the Arctic Red River, which peaks a month later (in June), is shown. Although the spring peak is a month early, the model runoff for these two years is comparable to (but a little higher than) the observed climatological stream flow. A recent study by Oki et al. (1999) shows that using a simple model to route gridded runoff delays the spring runoff peak for the Mackenzie by about one month, into June, as observed.

TABLE 3. Monthly hydrological balance for Mackenzie basin from the ECMWF model. Obs. = observed data.

Year	Month	Obs. precip	Precip	Rain	Snow	$\mathrm{Evap_{liq}}$	$\mathrm{Evap_{snow}}$	Melt	Runoff	Obs. stream flow	Δ(SW)	$\Delta(\mathrm{SWE_{anal}})$	Σliq	Σfrozen	Σtotal
1996	9	59.1	66.1	59.3	6.9	−37.6	−0.7	0.2	−14.4	−24.1	6.7	0.3	0.8	5.6	6.4
1996	10	37.4	46.4	20.9	25.5	−12.1	−4.5	0.7	−17.6	−15.8	2.8	16.8	−11.0	3.5	−7.5
1996	11	31.3	26.0	3.9	22.0	−0.3	−5.0	0.0	−13.0	−6.9	−13.0	43.3	3.7	−26.3	−22.6
1996	12	29.6	22.8	1.6	21.2	0.0	−2.1	0.0	−10.3	−8.3	−8.3	28.4	−0.3	−9.2	−9.6
1997	1	22.3	26.0	3.6	22.4	0.0	−1.7	0.0	−8.4	−8.8	−5.9	16.9	1.1	3.7	4.8
1997	2	16.4	22.8	4.2	18.7	0.0	−6.4	0.0	−6.6	−6.8	−4.4	−2.5	1.9	14.7	16.6
1997	3	24.3	41.5	5.8	35.7	−0.1	−20.8	7.1	−6.6	−7.0	1.3	0.1	4.9	7.6	12.5
1997	4	18.0	44.8	17.6	27.3	−3.6	−36.7	67.9	−9.6	−6.3	55.0	−36.0	17.2	−41.2	−24.1
1997	5	34.1	60.4	43.7	16.6	−39.2	−20.1	61.1	−42.9	−29.5	8.4	−59.7	14.4	−4.9	9.4
1997	6	82.0	104.8	103.8	1.0	−82.6	−0.7	5.0	−29.2	−38.7	−10.9	−7.8	7.9	3.1	11.1
1997	7	78.7	118.2	118.0	0.2	−89.4	0.0	0.0	−21.8	−32.3	−2.7	0.0	9.6	0.1	9.8
1997	8	51.9	74.0	73.7	0.3	−70.9	0.0	0.0	−21.4	−29.8	−4.1	0.0	−14.4	0.2	−14.2
1996/97		485.1	654.0	456.3	197.7	−336.0	−98.7	142.1	−201.8	−214.3	24.8	0.0	35.8	−43.2	−7.4
1997	9	53.3	77.5	70.6	6.9	−37.4	−0.6	0.9	−24.6	−22.2	−7.4	0.5	17.0	4.9	21.8
1997	10	44.8	70.6	31.3	39.3	−12.0	−6.6	2.9	−20.9	−18.4	−10.6	9.6	12.0	20.1	32.1
1997	11	17.4	23.5	6.4	17.1	−1.2	−6.1	0.7	−15.0		−16.9	18.8	7.8	−8.4	−0.6
1997	12	24.4	38.7	6.6	32.1	−0.2	−7.5	0.0	−10.5		−10.2	25.2	6.0	−0.6	5.4
1998	1		19.9	2.1	17.8	0.0	−1.3	0.0	−8.4		−7.3	31.7	1.0	−15.2	−14.2
1998	2		18.5	3.3	15.2	0.0	−4.7	0.0	−6.4		−4.2	16.9	1.1	−6.4	−5.4
1998	3		25.5	5.7	19.8	−0.3	−21.7	10.1	−6.3		4.7	−9.0	4.4	−3.0	1.4
1998	4		33.8	18.6	15.2	−10.7	−28.9	105.5	−16.5		71.1	−44.7	25.8	−74.5	−48.7
1998	5		51.3	46.0	5.3	−62.4	−8.5	41.0	−46.6		−36.0	−46.0	14.0	1.8	15.8
1998	6		93.0	92.6	0.4	−86.3	−0.3	2.4	−21.6		14.9	−3.0	−27.8	0.7	−27.1
1998	7		96.0	95.6	0.3	−100.9	0.0	0.0	−21.4		−8.1	0.0	−18.5	0.3	−18.2
1998	8		70.9	70.4	0.5	−81.9	−0.1	0.0	−18.2		2.6	0.0	−32.3	0.4	−31.8
1997/98			619.2	449.3	169.9	−393.3	−86.2	163.6	−216.2		−7.2	0.0	10.5	−79.9	−69.4

b. Monthly liquid and frozen hydrological budget for the Mackenzie River

Table 3 shows the key terms in the ECMWF model's monthly liquid and frozen hydrological budget for the entire Mackenzie basin, as well as two columns for the observed precipitation and stream flow. The annual totals for the two "water years," each from September to August, are included. The balance of terms in the liquid hydrological budget is given by

$$\begin{aligned}\text{Residual} &= \sum \text{Liquid}\\ &= \sum [\text{Rain} + \text{Melt} + \text{Evap}_{\text{liq}} + \text{Runoff}\\ &\qquad - \Delta(\text{SW})]. \qquad (1)\end{aligned}$$

The sign convention is that Rain and Melt, which supply liquid water at the surface, are positive, and Evap_{liq} and Runoff are negative in Eq. (1) and Table 2. Further, Δ(SW) is the total soil water storage change.

Figure 3 shows the two-year cycle of these terms in the modeled liquid hydrological budget: rainfall, snowmelt, runoff, liquid evaporation, soil water storage change, and the residual for the whole Mackenzie basin. The *x* axis is year and month, with "97" marking January 1997. Snowmelt initially recharges the soil water reservoir in April and then runs off through deep drainage (in the model) in May. The observed stream flow (for the time period for which data are available) is the thin solid line, which peaks a month later, in June. For 1996/97, the annual runoff and stream flow are close (Table 3), but this result is not true for the subbasins (see section 3a). Snowmelt came earlier in the model in 1998 than in 1997 (because air temperatures were higher), and the spring runoff peak was a little higher. The modeled liquid hydrological behavior is not, however, conservative. The liquid residual from (1) is shown as dotted, and it is largest in the warm season. The annual sum of the liquid residuals is

$$\begin{aligned}\sum \text{Residual} &= 456 + 142 - 336 - 202 - 25\\ &= 36\ \text{mm} \quad \text{for 1996/97}\\ &= 449 + 164 - 393 - 216 + 7\\ &= 11\ \text{mm} \quad \text{for 1997/98.}\end{aligned}$$

The residual is about 3%–10% of the rainfall in these two years.

This liquid hydrological budget is not in balance for two reasons: the spinup of the model hydrologic cycle and the imbalance in the model analysis cycle. The model analysis cycle is not closed, because soil water is added through a nudging term calculated from short-term forecast errors in the humidity at the lowest model level, as discussed above in section 1a. In fact, the nudging also appears to compensate for other errors in the model physics in evaporation and runoff (Betts et al. 1998a, 1999a). For the Mackenzie subbasins, the analysis cycle terms were not all archived, so an estimate for the addition of water by nudging or for the rainfall in the analysis cycle is not available. Based on these earlier studies (Betts et al. 1998a, 1999a), the rainfall in (1), which is from the 11–35-h forecast, may be on

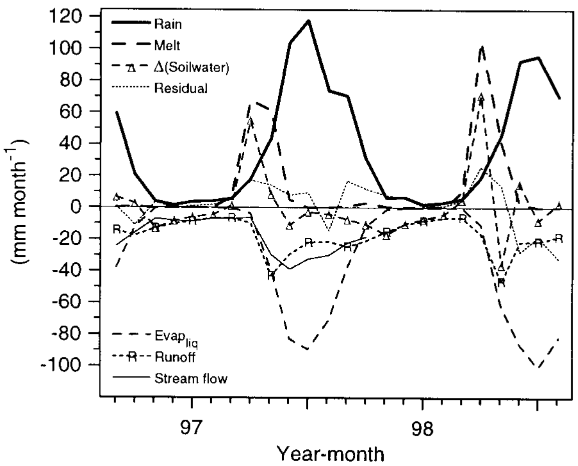

FIG. 3. Key terms in the monthly liquid hydrological budget for the Mackenzie from Sep 1996 to Aug 1998, and observed stream flow.

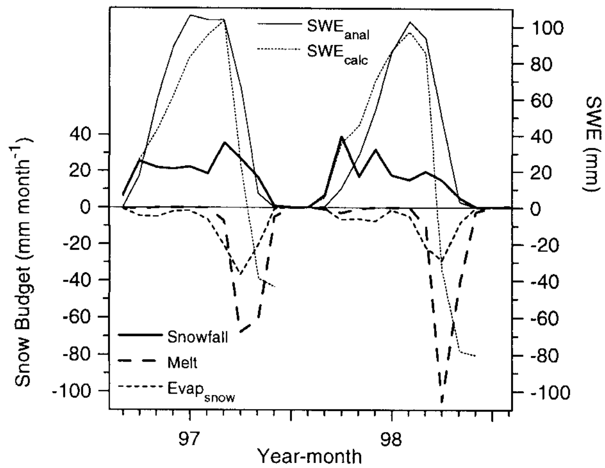

FIG. 4. As in Fig. 3 for key terms in the frozen hydrological budget.

the order of 25% greater than the rainfall in the analysis cycle. These two earlier studies (of the Mississippi basins) showed that the terms other than precipitation have a much smaller spinup in the first 24 h of the model forecast.

The model frozen hydrological balance in Table 3 is given by

$$\begin{aligned}\text{Residual} &= \sum \text{Frozen}\\ &= \sum [\text{Snowfall} - \text{Melt} + \text{Evap}_{\text{snow}}\\ &\qquad - \Delta(\text{SWE}_{\text{anal}})]. \end{aligned} \tag{2}$$

The sign of the melt term is negative in this equation since it removes snow. The term $\Delta(\text{SWE}_{\text{anal}})$ is the change in the snow water equivalent (SWE in millimeters of water) of the snowpack in the analysis. Figure 4 shows the budget terms, Snowfall, Melt, and Evap$_{\text{snow}}$ on the left-hand scale. On the right-hand scale are two estimates of snowpack SWE. The model has an independent snow analysis at each model analysis time, based on observations of snow cover and snow depth where available (otherwise based on climatological means). These analysis values SWE$_{\text{anal}}$ are shown (light solid line) for the end of each month. For each winter, the accumulated sum of the model source and sink terms also are shown as a model calculation of the corresponding snow water equivalent at the end of each month (light dotted line)

$$\text{SWE}_{\text{calc}} = \sum (\text{Snowfall} - \text{Melt} + \text{Evap}_{\text{snow}}). \tag{3}$$

During the accumulation phase (October–March), the ''analysis'' snowpack and the calculated SWE are in fair agreement (for the basin as a whole). The sum of the model terms, however, representing *loss of snow* ($-$Melt + Evap$_{\text{snow}}$) in April and May greatly exceeds SWE at the end of March, whether based on analysis or model calculated, with the largest error in April. That the subbasins differ in this error signature will be shown later. Mahfouf and Viterbo (1996) discuss the ECMWF snow analysis scheme and its dependence on a rather poor low-resolution snow mass climate description developed by Brankovic and van Maanen (1985). Mahfouf and Viterbo (1996) also show examples over the French Alps, where the spring snowmelt occurs too early in the model.

The annual sum of the frozen residuals is

$$\begin{aligned}\sum \text{Residual} &= 198 - 142 - 99\\ &= -43 \text{ mm} \quad \text{for 1996/97}\\ &= 170 - 164 - 86\\ &= -80 \text{ mm} \quad \text{for 1997/98.}\end{aligned}$$

Spring snowfall was less in 1998 than in 1997, and the melt came earlier, because air temperatures were higher, as mentioned above. Snow losses exceed snowfall by 20% the first year and by 45% the second year; this large imbalance is possible because of the independent snow analysis. The next section will show that the imbalance differs among the subbasins.

The sum of the residuals is the last column in Table 3:

$$\begin{aligned}\sum \text{Total} &= \sum [\text{Precip} + \text{Evap}_{\text{liq}} + \text{Evap}_{\text{snow}} + \text{Runoff}\\ &\qquad - \Delta(\text{SoilWater}) - \Delta(\text{SWE}_{\text{anal}})]\\ &= -654 - 336 - 99 - 202 - 25\\ &= -7 \text{ mm} \quad \text{for 1996/97}\\ &= -619 - 393 - 86 - 216 + 7\\ &= -69 \text{ mm} \quad \text{for 1997/98.}\end{aligned} \tag{4}$$

The residuals in the liquid and frozen budgets partly cancel, so that the annual total precipitation, evaporation, and runoff from these 11–35-h forecasts balance to within about 10% of the precipitation.

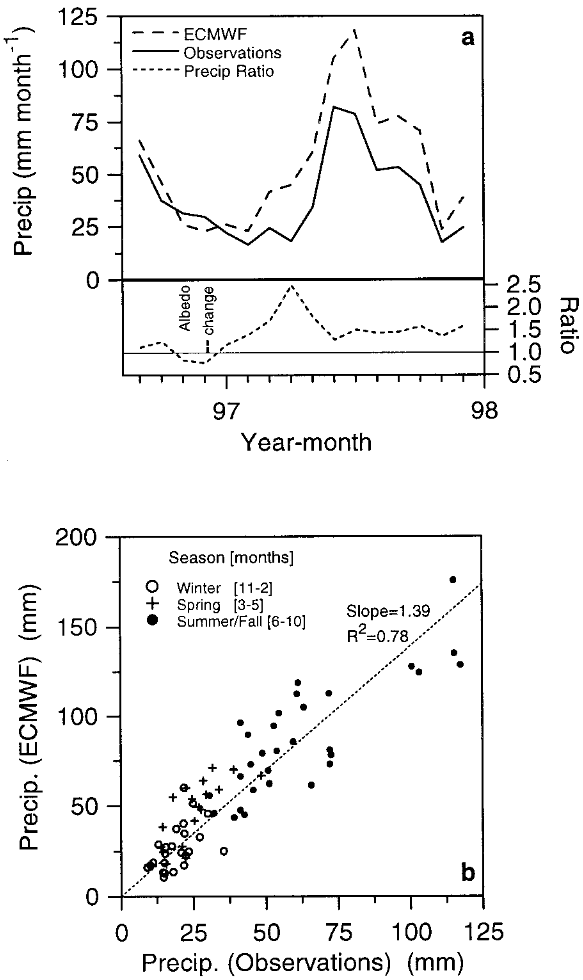

FIG. 5. (a) Comparison of ECMWF precipitation for Mackenzie with observations, and ratio of the two. (b) Scatterplot of monthly ECMWF precipitation versus observations for the subbasins, subdivided by season.

The modeled annual precipitation for these two years, on the order of 640 mm, is substantially more than the recorded mean annual precipitation for the Mackenzie for the period 1961–90, which increases from below 300 mm in the north to over 600 mm in the southwest, with an estimated mean of 410 mm yr^{-1} (Stewart et al. 1998), although there is observational uncertainty because of inadequate sampling and gauge measurement errors in winter (Goodison 1978). For the water year 1996/97, the total model precipitation is 35% higher than the total corrected precipitation for the Mackenzie basin. For 1996 and 1997, precipitation observations are available for comparison.

c. *Comparison of model with Mackenzie precipitation observations*

Figure 5a compares precipitation from the model with corrected monthly observations (from Hogg et al. 1996) for the Mackenzie and six subbasins for the first 16 months, September 1996–December 1997. Corrected observations for 1998 are not available yet. The upper panel for the whole Mackenzie shows that the model has considerably more precipitation than do the observations, confirming the climatological comparison. The ratio of model precipitation to observed precipitation (dotted line) peaks at 2.5 in April 1997 (when the snow evaporation peaks in the model) and averages about 1.4 for the rest of 1997. The overestimate of precipitation is consistent with the model having too much evaporation in spring and summer (Betts et al. 1999b) over the boreal forest, and there being large evaporation–precipitation feedback. During 1996, before the reduction in the model forest albedo with snow (which affected the surface energy balance), there is some indication that the model precipitation bias was smaller. This evidence is consistent with the comparison of the precipitation in the ECMWF reanalysis over the Mackenzie River basin with rain gauge–based climatological data in Stendel and Arpe (1997).

Figure 5b is a scatterplot of the monthly basin precipitation from ECMWF versus observations for 1997, grouping the data into winter, spring, and summer–fall. Basins 5 and 6 have been combined into a single Peace River basin for this comparison with observations. The linear regression line has a slope of 1.39 $\pm$ 0.04 with an R^2 (correlation coefficient) of 0.78. In general, no significant difference in bias could be distinguished between basins, or between winter or summer, with this one-year comparison. However, the spring points (for March, April, and May except for the colder northern basins 1 and 2 in March) lie on or above the regression line, confirming that the larger model bias in spring was seen in all basins.

3. Interbasin variability

In addition to variability between the two years, the model shows the interbasin differences. Table 4 summarizes terms in the annual mean basin hydrological budget by hydrological year and by basin. The two columns marked ''obs.'' are the observed precipitation and stream flow for the periods and basins for which they are available. Annual precipitation increases from northeast to southwest as observed, although, as mentioned earlier, the model precipitation is higher than the observations by about 40% for all basins. The model runoff increases from about 20% of precipitation for the northern basins to about 45% of precipitation for the southern basins 5, 6, and 7. However, this variability in model runoff bears no relationship to the annual stream flow differences. There are also large residuals in both the liquid and frozen hydrological budgets for some basins. Runoff errors and residuals are related and are discussed in the next section. In the liquid hydrological budget, the residuals are largest in summer, and in the frozen budget the largest errors are at spring melt, as

TABLE 4. Liquid and frozen hydrological budget terms by year and by basin. Obs. = observed data.

Year	Basin	Obs. precip.	Precip	Rain	Snow	$Evap_{liq}$	$Evap_{snow}$	Melt	Runoff	Obs. stream flow	Δ(SW)	Σliq	Σfrozen	Σtotal
1996/97	1	368	511	315	197	−228	−43	59	−100	−357	−19	64	95	159
	2	381	437	293	144	−246	−68	133	−97	−168	−30	115	−58	57
	3	409	541	410	131	−348	−106	113	−119		65	−10	−87	−97
	4	550	793	539	254	−299	−76	130	−172	−343	2	195	48	243
	5	620	735	553	182	−411	−121	155	−305	−179	36	−74	−94	−168
	6	620	956	562	394	−335	−136	269	−397	−400	12	86	−10	75
	7	562	744	556	188	−428	−128	147	−321	−229	79	−125	−87	−211
1997/98	1		579	393	186	−281	−42	84	−142		31	21	61	82
	2		494	366	128	−325	−51	178	−110		96	13	−101	−88
	3		519	395	124	−407	−78	121	−143		−4	−30	−74	−105
	4		736	510	226	−349	−74	135	−157		−30	169	17	186
	5		586	457	129	−486	−110	183	−288		−84	−51	−164	−215
	6		927	587	340	−384	−144	283	−441		−25	70	−86	−17
	7		654	507	147	−482	−117	174	−354		−58	−98	−143	−241

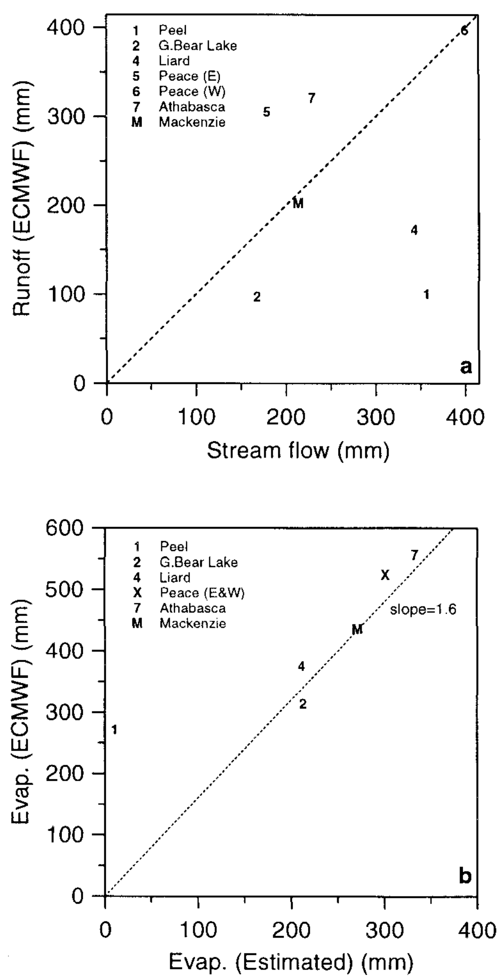

FIG. 6. (a) Comparison of ECMWF runoff and observed stream flow for Mackenzie River and six subbasins for 1997 water year. (b) Comparison of total ECMWF evaporation and evaporation estimated from observed precipitation and stream flow for 1997 water year.

discussed previously, although there is a secondary maximum in fall for some basins (not shown). There is no change in SWE_{anal} on an annual basis, so this term is omitted.

a. Basin comparison of ECMWF runoff and evaporation with annual stream flow and estimated evaporation

A detailed monthly comparison between the ECMWF runoff and the observed stream flow is not worthwhile, because the current model has only drainage from the lowest model layer and no river routing scheme. Figure 6a compares annual runoff and stream flow (both plotted as positive) for the first water year, September 1996/August 1997. It is clear that the variability in model runoff on an annual basis across the basins bears no relationship to the stream flow differences, even though for the Mackenzie as a whole (point M), model runoff and observed stream flow are close. In the Mississippi studies, model runoff was less than observed stream flow by a factor of roughly 2 (Betts et al. 1998a, 1999a). However, Fig. 6a suggests that the large liquid residuals of opposite sign in Table 4 may be associated with model runoff errors. Basins 5 and 7, with runoff higher than stream flow, have negative liquid residuals, which is consistent with having nudging supply water to the liquid budget. Basins 2 and 4, with less runoff than stream flow, have roughly compensating positive residuals, consistent with having nudging remove water. Basin 1 is an outlier in Fig. 6a (and Fig. 6b), perhaps because the high observed stream flow per unit area represents only the mountainous area of basin 1.

On an annual basis, basin evaporation can be estimated from the observed precipitation and stream flow data as

$$\text{Evap (Estimated)} = \text{Precip}_{obs} - \text{Streamflow}_{obs}, \quad (5)$$

by ignoring basin-scale storage changes of water. Figure 6b compares Evap (Estimated) with the annual model total evaporation:

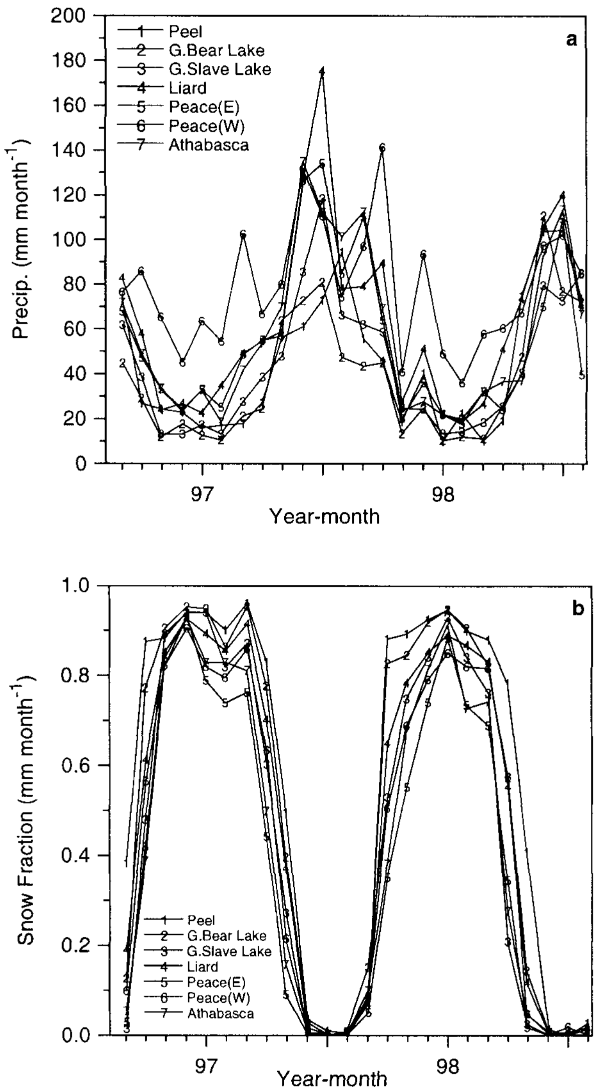

FIG. 7. (a) Monthly distribution of model precipitation for the seven subbasins. (b) As in (a) for the fraction of precipitation that falls as snow.

$$\text{Evap (ECMWF)} = \text{Evap}_{\text{liq}} + \text{Evap}_{\text{snow}}. \qquad (6)$$

The dotted line has a slope of 1.6, showing that, on an annual basis, the model evaporation exceeds the observed estimate from (5) by about 60%. For basin 1, which lies far off the line, it is clear that the evaporation estimate from (5) is too low, perhaps because the catchment area for the stream flow estimate is smaller (and more mountainous) than the total area of basin 1 (which includes the Mackenzie delta), for which mean precipitation is available.

b. *Monthly surface hydrological budget by basin*

Figure 7a shows monthly precipitation for the seven subbasins from the model. Basin 6, the western section of the Peace River, which originates in the Rocky Mountains, has the most winter precipitation; the northern and eastern basins (basins 1–3) have the least. Summer rainfall is high in all the southern basins (basins 4–7) and is lower in the north. The winter precipitation in the model is dominated completely by large-scale processes. Convective processes play an important role in summer, providing 30% of the June–August rainfall for basins 3, 5, and 7 and less (17%) for the mountain basins 4 and 6. Figure 5b showed that, although the model precipitation is positively biased, it is well correlated with the observations.

Figure 7b shows that the fraction of precipitation that falls as snow generally decreases from northwest to southeast. It is over 90% in winter in the north (on a monthly basis) and near zero from June to August, showing the very strong seasonal cycle for the northern basins. Note that, in the warmer spring of 1998, less precipitation fell as snow in all basins. The model may be the best estimate of the fraction of precipitation that falls as snow that is available on this basin scale. However, model and climatological means may not agree. Mekis and Hogg (1999) estimate that precipitation over the basin is divided evenly between rain and snow. Table 4 shows that only 30% of the annual precipitation falls as snow.

Figure 8 shows four components of the model hydrological budget. Figure 8a is the model runoff (with the sign reversed in this figure). The western branch of the Peace River (basin 6), which has the deepest winter snowpack (see Figs. 9 and 10 below) has the highest spring runoff peak in the model. All basins have a spring peak; basins 5, 6, and 7 also have a secondary maximum in the model in the fall. The stream flow measurements for the Athabasca and Peace Rivers do not indicate a fall maximum (not shown); however, the Peace River is regulated heavily by the Bennett Dam. Figure 8b shows the melt term in the model. Basins 1, 2, 4, and 6 have a May peak in 1997, a month later than basins 3, 5, and 7 in the east. In 1998, melt is earlier, and only basin 6 has a May peak.

Figure 8c shows the model liquid evaporation, which increases from northwest to southeast in summer and is zero when the ground is covered with snow. Like rainfall, summer evaporation is also larger in the model than in climatological estimates. Stewart et al. (1998) estimate summer (May–October) climatological evaporation to be 230 mm for the Mackenzie, while the corresponding model value in 1997 is 350 mm, 52% more than the Stewart et al. climatological estimates and slightly less than the 60% estimate of the annual evaporation bias for 1996/97 in Fig. 6b. Figure 8d shows the snow evaporation. This term is smaller and peaks later in spring in the far northwest and is larger and peaks earlier in the south (basin 6, which has the greatest snowfall, has the largest snow evaporation). The spring peak in snow evaporation is much higher than the fall peak, because the net radiation is higher in spring. Snow

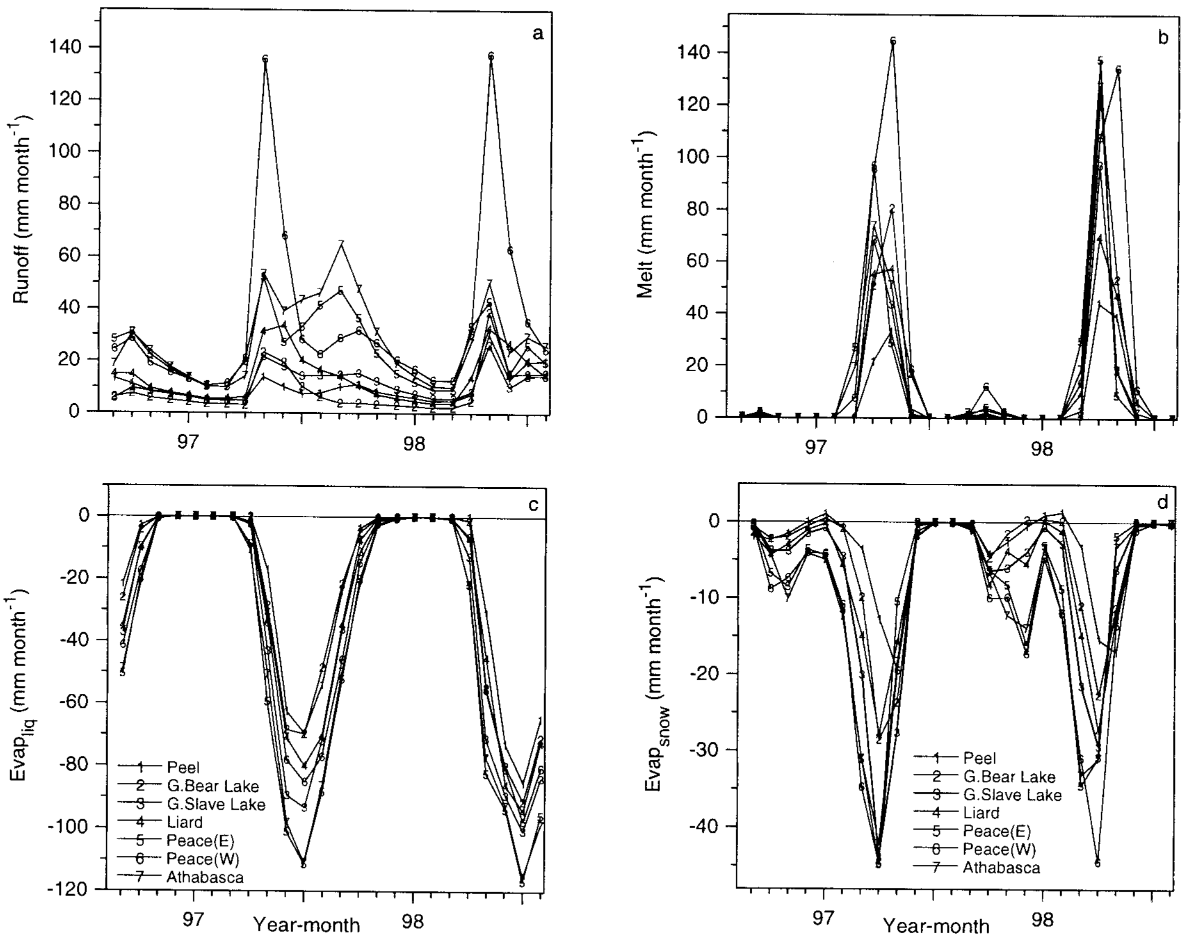

FIG. 8. Monthly distribution of model (a) runoff, (b) snowmelt, (c) liquid evaporation, and (d) snow evaporation for the seven subbasins.

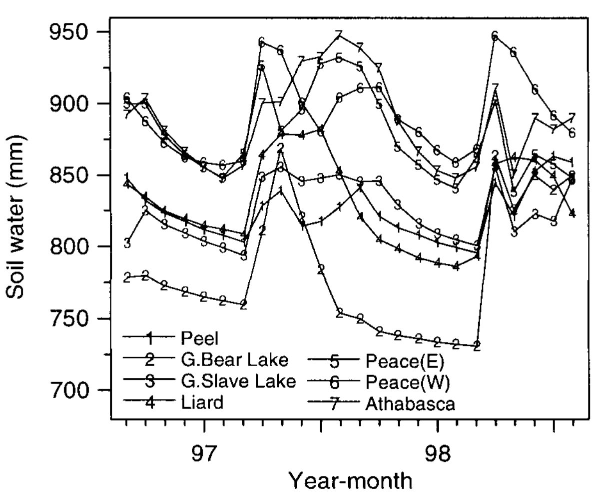

FIG. 9. Monthly distribution of column soil water for the seven subbasins.

evaporation probably is positively biased, as is discussed in the next section.

c. *Water storage terms*

Figure 9 shows the interbasin variation of integrated column soil water, which increases from a minimum for basin 2 to a maximum for basins 5, 6, and 7. The annual patterns are very similar for all basins. Soil water decreases unrealistically in winter as deep drainage continues, even when the soil is frozen, as discussed in section 1a. This decrease leads to a minimum soil water in the spring just before a rapid recharge on the order of 100 mm, with the melting of snow in April and May. Soil water is more variable in summer, as is rainfall.

Figure 10a shows the variation of the snowpack water storage in the analysis for each basin, ranging from a winter peak of over 150 mm for the mountain basins 4 and 6 to only 70 mm for the northern basins. Figure 10b is a corresponding SWE_{calc} from (3). During the winter accumulation phase, the variation between basins is similar to that seen in Fig. 10a. This result is shown more clearly in Fig. 11, which compares the maximum

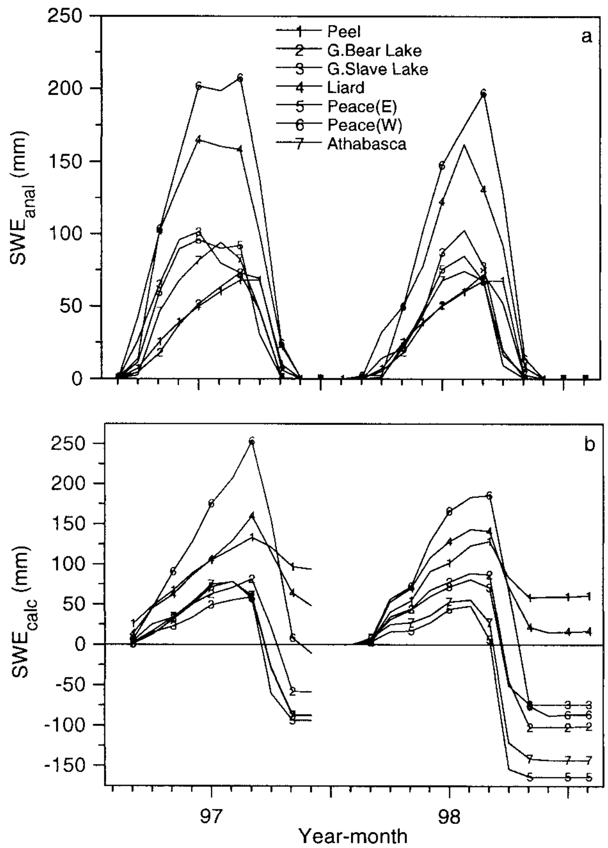

FIG. 10. Snowpack water equivalent in (a) the model analysis, and (b) calculated from the model snow budget terms.

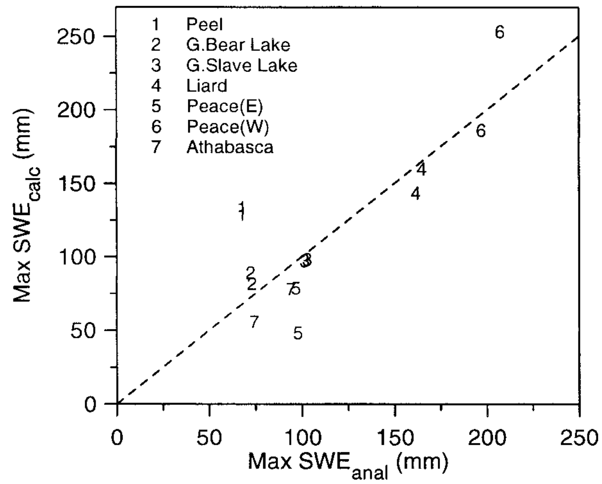

FIG. 11. Comparison of maximum winter snowpack in the analysis with that calculated from the model snow budget. Each number represents a value for that basin for one winter.

SWE$_{anal}$ from the analysis with the maximum model SWF$_{calc}$. The analysis snowpack is much smaller for basin 1 but a little greater for some basins, such as basins 5 and 7. However, Fig. 10b shows that, during the spring melt phase, except for basins 1 and 4 [which have the lowest net radiation (not shown)], the spring melt and evaporation of snow exceed the water stored in the snowpack, whether analyzed or the model-accumulated value. Note that, for basins 2, 4, 5, and 6, the interannual variability of SWE$_{calc}$ exceeds that of SWE$_{anal}$. This result reflects the fact that, in data-sparse areas, the snow analysis is dominated by a climatological value (Mahfouf and Viterbo 1996).

This result again suggests that the model must overestimate either the evaporation of snow, or the melting, or both. One probable reason for this overestimation is that most of the southern two-thirds of the basin is forested, and the snow lies under the trees. The energy balance in boreal canopies in winter is complex (Pomeroy and Dion 1996). The forest canopy intercepts much of the incoming solar radiation and ''returns'' most of it back to the atmosphere as sensible heat (Betts et al. 1998b, 1999b). The model, however, has only a single surface energy balance, and the snow evaporation algorithm responds directly to the net radiation above the canopy. The northwestern basins 1 and 4 have a lower net radiation (presumably because of greater cloud cover), and, consequently, snow evaporation is less for these basins. In addition, there is no separate snow temperature field in the model: the snow has the temperature of the first soil layer. Consequently, snowmelt and groundmelt are coupled, and they both again respond to the single surface net radiation balance, even for forested areas. As the ground melts, the fluxes into the ground are very large, absorbing almost all the net radiation, while the fluxes to the atmosphere are small. Clearly, in northern forested areas (which include much of the Mackenzie) the model needs separate energy balances for the snow-covered ground surface and the forest canopy. This change has been made in the tiled land surface and snow model under development for ERA-40.

4. Energy balance

The surface energy balance in the model can be written

$$R_{\rm net} + {\rm SH} + {\rm LH} + {\rm LH}_{\rm snow} - Q_{\rm melt} - G = 0, \quad (7)$$

where the surface net radiation $R_{\rm net}$ is partitioned into fluxes to the atmosphere of sensible heat SH and latent heat (LH from the evaporation of water and LH$_{\rm snow}$ from the sublimation of snow), a snowmelt energy term $Q_{\rm melt}$, and a residual flux G into the ground. The sign convention used here is that downward fluxes are positive and upward fluxes to the atmosphere are negative. Figure 12 summarizes the surface energy balance of the whole Mackenzie basin for the two years. All values are monthly averages (W m^{-2}). At these high latitudes, $R_{\rm net}$ has a strong annual cycle. Following the sign convention above, $R_{\rm net}$, G, and $Q_{\rm melt}$ are positive in spring and summer, while the balancing (upward) sensible and

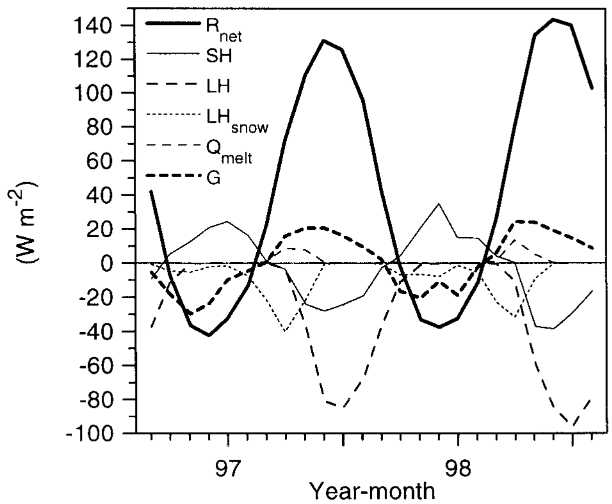

FIG. 12. Model surface energy budget for the Mackenzie. Symbols are defined in the text.

latent heat fluxes are shown as negative. The energy taken by the melting of snow is smaller than that for the sublimation of snow (although more water is involved), since the latent heat of melting is much less than that of sublimation. The SH flux almost certainly is too small in April, when the model snow evaporation peaks. Over the boreal forest black spruce site in Betts et al. (1999b), the measured SH flux actually has two peaks, one in April because evaporation is very low in spring and a second in June when net radiation is largest. This model error, as discussed in the previous section, is caused primarily by the lack of proper energy balance for the snow, which mostly is shaded by the forest canopy.

The two years are summarized in Table 5, together with the annual averages. The annual average net radiation and latent heat flux are considerably higher in 1997/98. The net ground heat flux is downward in 1997/98 but is upward in 1996/97 when R_{net} is less. Although no validation data are available on the basin scale for R_{net}, Betts et al. (1998b) found no systematic bias in the model R_{net} versus data in a point comparison over the boreal forest after snowmelt. The annual average of the sensible heat flux is very small. Tables 3 and 4 show evaporation terms in millimeters from the surface hydrological budget, while Table 5 shows the latent heat flux to the atmosphere. In the same units, the latent heat flux (from evaporation of water) is about 2% larger in summer than the liquid evaporation is. Betts et al. (1998a) found a similar but larger error (about 7%) for the Arkansas–Red River basin, resulting from an unsatisfactory approximation in the calculation of the evaporation of water intercepted by the canopy that remained from an earlier version of the model.

Figure 13 shows a 1200–0000 UTC (''daytime'') energy partition from April to September by basin (an average for the two years). The solid lines are the fraction of R_{net} going into ground storage and snowmelt, defined as $(G + Q_{melt})/R_{net}$. In April it is very large, as much as 50%–75% of the daytime net radiation, and it is largest for the most northern basins. Although the

TABLE 5. Energy balance terms for the Mackenzie basin. Terms are defined in the text.

Year	Month	R_{net}	SH	LH	LH_{snow}	Q_{melt}	G
1996	9	42.0	−9.3	−37.4	−0.8	0.0	−5.6
1996	10	−6.8	5.2	−11.6	−4.8	0.1	−18.0
1996	11	−36.6	12.6	−0.3	−5.5	0.0	−29.8
1996	12	−42.5	20.8	0.0	−2.2	0.0	−23.8
1997	1	−32.5	24.4	0.0	−1.8	0.0	−9.9
1997	2	−13.2	16.2	0.0	−7.5	0.0	−4.5
1997	3	22.6	1.0	−0.1	−22.0	0.9	0.6
1997	4	72.1	−3.8	−3.6	−40.1	8.7	15.9
1997	5	110.8	−24.2	−37.2	−21.3	7.6	20.6
1997	6	131.2	−28.1	−81.0	−0.7	0.6	20.6
1997	7	125.7	−24.4	−85.1	0.0	0.0	16.1
1997	8	95.9	−19.2	−67.2	0.0	0.0	9.4
1996/97		39.1	−2.4	−27.0	−8.9	1.5	−0.7
1997	9	42.2	−2.9	−36.6	−0.6	0.1	2.0
1997	10	−1.9	4.0	−11.3	−7.0	0.4	−16.6
1997	11	−33.2	20.6	−1.1	−6.7	0.1	−20.5
1997	12	−37.7	35.1	−0.2	−7.9	0.0	−10.8
1998	1	−32.5	15.1	0.0	−1.4	0.0	−18.9
1998	2	−11.3	14.6	0.0	−5.5	0.0	−2.1
1998	3	26.2	4.1	−0.3	−22.9	1.3	5.7
1998	4	79.9	0.4	−10.6	−31.6	13.6	24.5
1998	5	134.5	−37.1	−59.3	−9.0	5.1	24.0
1998	6	143.7	−38.5	−85.4	−0.3	0.3	19.1
1998	7	140.4	−29.5	−96.1	0.0	0.0	14.7
1998	8	103.1	−16.4	−77.9	−0.1	0.0	8.8
1997/98		46.1	−2.5	−31.6	−7.8	1.7	2.5

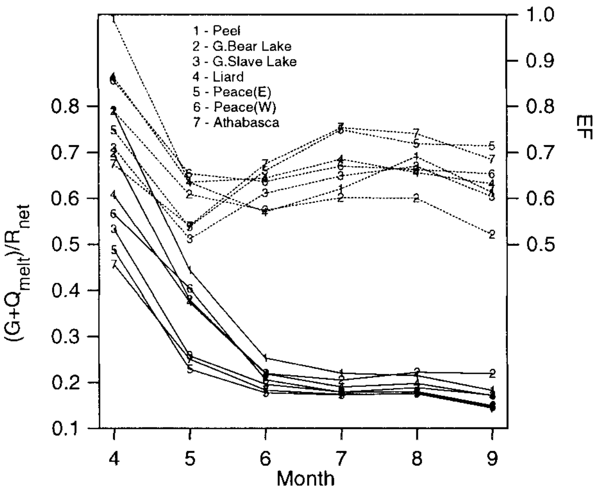

FIG. 13. Surface energy balance partition for the seven subbasins from Apr to Sep, showing ratio of ground heat flux and melt to net radiation (solid) and evaporative fraction (dashed) during the daytime (1200–0000 UTC).

ground and snow are melting in spring, we believe this ratio is too large, because in forested areas the canopy shades the surface and effectively returns a significant proportion of R_{net} directly back to the atmosphere as a SH flux. The dashed lines show the partition of the remaining surface available energy (SH + LH + LH_{snow}) = $-(R_{net} - G - Q_{melt})$ from (7) as an evaporative fraction EF for the 1200–0000 UTC daytime period, defined as

$$\mathrm{EF} = (\mathrm{LH} + \mathrm{LH}_{snow})/(\mathrm{SH} + \mathrm{LH} + \mathrm{LH}_{snow}). \quad (8)$$

Daytime EF is high in April when snow is evaporating—probably too high, as mentioned in section 3c. One important consequence of the large fraction of R_{net} going into storage and melting of snow and this large EF is that the modeled SH flux in spring is unrealistically small when compared with observations over a boreal spruce forest (Betts et al. 1999b).

The evaporative fraction is relatively low after snowmelt when the temperature is low and then increases during the summer as temperature rises. There is a general increase of modeled EF in summer from the northwest basins to the southeast. For the forested areas, these daytime summer values are too high, since the model evapotranspiration algorithm, which was developed using grassland data (Viterbo and Beljaars 1995), does not recognize different vegetation types (such as the coniferous forests). The ERA-40 land surface model under development has separate tiles for short and tall (forest) vegetation, with different parameters. Betts et al. (1998b), in a comparison over the boreal forest in Manitoba, found that the ECMWF model daytime evaporative fraction, which had a summer range of 0.5–0.8, similar to that seen in Fig. 13, was significantly higher than measurements from a representative black spruce site for which summer daytime EF was typically in the range 0.3–0.4 (Betts et al. 1999b). This result is entirely consistent with the 60% positive evaporation bias shown in Fig. 6b. Reducing summer LH in the model by 60%, with a corresponding increase in SH (but no change in $R_{net} - G$), would reduce mean summer EF by a factor 1/1.6, or from about 0.64 to 0.4.

5. Conclusions

The monthly surface energy and water balance terms from the operational ECMWF analysis have been presented for seven subbasins of the Mackenzie River for a two-year period from September 1996 to August 1998. Other model and observational studies are under way as part of the MAGS program, and, at this point, precipitation and stream flow data are available for comparison with the model results only up to December 1997, but these data are sufficient to indicate some of the model biases. The value of model studies is that they provide representative area averages in regions of sparse data and show the spatial and temporal variability. In particular, the model estimates of snowfall, and the fraction of cold season precipitation that falls as snow, might be superior to measurements on the basin scale. The model precipitation is significantly higher (by about 40%) than the corrected precipitation observations for the Mackenzie (Hogg et al. 1996), although model and observed monthly precipitation are well correlated on the basin scale. This bias seems to be uniform across the basins, although it is higher during spring melt. An earlier study, based on observations over the boreal forest (Betts et al. 1998b), showed that the ECMWF model evaporation is positively biased in summer and in spring when the evaporation of snow is overestimated. Using observed precipitation and stream flow data to estimate annual evaporation, we concluded that the model evaporation is positively biased by 60% on an annual basis.

The model annual runoff, which is parameterized as deep drainage and not routed through stream flow channels, is nonetheless comparable with the observed annual stream flow, unlike that for the Mississippi basins, for which an earlier study showed that the ECMWF model runoff was less than half the value of the observed stream flow (Betts et al. 1999a). The spring runoff peak in the model occurs, however, about a month earlier than the stream flow peak observed for the Mackenzie, and the probable reason is the lack of routing in the model. However, the variability in model runoff on an annual basis across the basins bears no relationship to the stream flow differences.

Neither the model liquid or frozen hydrological budgets are closed at the surface, albeit for different reasons. In the liquid budget, soil water nudging can add or subtract a large amount of water to the model. Earlier studies for the Mississippi basin (Betts et al. 1998a, 1999a) have explored the projection of model errors in precipitation, evaporation, and runoff onto this nudging term. However, the Mackenzie dataset, based on 11–35-

h model forecasts, does not include the analysis cycle fluxes, so the nudging term cannot be calculated explicitly, although some of its impact is visible as a residual in summer. Nudging is compensating for basin runoff errors in summer. The frozen hydrological budget is not closed, because a new snow analysis based on observations and climatological means is introduced at each analysis time. It was found that, during the winter accumulation phase, the sum of the model snowfall, snow evaporation, and melt terms agrees reasonably well with the analysis snowpack, but, in spring, the model melt and snow evaporation terms are too large: in total they exceed the amount of the snowpack, except in the northwestern basins, which have the lowest net radiation. The model soil water continues to drain (unrealistically) in winter when the ground is frozen but is recharged by the spring melt.

In this analysis, only monthly values were shown. The model data are hourly and so show considerable detail associated with shorter timescales, such as the passage of synoptic weather events. These hourly datasets for the seven MAGS basins are available from the first author for further studies. An improved soil moisture initialization scheme has been developed (Douville et al. 2000), and a new tiled land surface model is under development for ERA-40, which will correct some of the errors of the current model in winter and over the northern forests. We plan to reexamine the Mackenzie basin budgets for a longer time period when this reanalysis becomes available.

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