Surface Water and Energy Budgets over the Mississippi and Columbia River Basins as Simulated by Two Generations of the Canadian Regional Climate Model

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ABSTRACT *This paper aims to compare and evaluate the surface energy and water budgets of simulations with the operational version of the Canadian Regional Climate Model (CRCM op) and the developmental version (CRCM dev). The CRCM op and CRCM dev differ in their use of second- and third-generation physical parametrization packages of the Canadian General Circulation Model (CGCM) II and III, respectively. The improvements to the physics of CGCM III include the use of the Canadian LAnd Surface Scheme (CLASS), a three-layer soil model with explicit treatment of snow and canopy layers; it replaces the so-called Bucket hydrological scheme and one-layer force-restore surface energy budget in the CGCM II.*

The common experimental configuration for this comparison is taken from the Project to Intercompare Regional Climate Simulations (PIRCS-1c) over the continental United States between 1987 and 1994. The analysis focuses on two major river basins with substantial differences in atmospheric forcings, vegetation and topography: the Mississippi and the Columbia river basins. The evaluation is made using observation-based data for monthly means of screen temperature, diurnal temperature range, precipitation, run-off estimated from streamflow, and snow depth. Some surface fluxes are also compared with the reanalyses from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) and the European Centre for Medium-range Weather Forecasts (ECMWF).

Results show that CRCM dev constitutes an improvement over CRCM op, particularly for summer evapotranspiration, precipitation and diurnal temperature range; a remaining cold bias in screen temperature, however, is associated with an excessive amount of snow in winter and a high run-off peak in spring. CRCM op underestimates the snow cover at the expense of the frozen water in the soil.

RÉSUMÉ *Cette étude a pour but de comparer et d'évaluer les bilans énergétique et hydrique de surface simulés par les versions en exploitation (MRCC op) et en développement (MRCC dev) du Modèle Régional Canadien du Climat (MRCC). Les MRCC op et MRCC dev se distinguent par l'emploi du module de paramétrage des processus physiques du Modèle de Circulation Générale Canadien (MCGC) de deuxième et troisième génération, respectivement. Parmi les améliorations apportées à la physique du MCGC III, on note l'implantation d'un nouveau schéma de surface appelé CLASS (Canadian LAnd Surface Scheme), un modèle à trois couches de sol avec traitement explicite des couverts végétal et nival; il remplace le modèle hydrologique Bucket et le régime thermique de force de rappel à une couche de sol utilisés dans la version en exploitation du MRCC.*

Les simulations sont issues de la phase 1c du Projet d'inter-comparaison des simulations de climat régional (PIRCS-1c) couvrant l'ensemble des États-Unis entre 1987 et 1994. L'analyse est réalisée sur deux bassins-versants dotés d'une végétation, d'une topographie et de forçages atmosphériques fort différents : les bassins-versants des fleuves Mississippi et Columbia. La température à l'abri, l'écart diurne, la précipitation, le ruissellement et la profondeur de neige sont comparés avec des climatologies d'observations. Les estimés mensuels de ruissellement proviennent de mesures de débits fluviaux sur les deux bassins-versants. Certains flux de surface sont aussi comparés avec les ré-analyses du National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) et du European Centre for Medium-range Weather Forecasts (ECMWF).

Les résultats montrent que le MRCC dev tend à simuler une meilleure climatologie que la version en exploitation, particulièrement en ce qui concerne l'évapotranspiration, l'écart diurne et la précipitation estivale. Cependant, un biais froid persistant de température à l'abri sur les deux bassins est associé à un couvert de neige excessif suivi d'une importante crête de ruissellement au printemps. Le MRCC op favorise la formation de glace dans le sol aux dépens de la couverture de neige.

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1 Introduction

Over the last decade substantial improvements to climate models have resulted from the progress made on subgrid-scale physical parametrizations in general and to land-surface schemes (LSSs) in particular (Wilson and Hendersen-Sellers, 1985). The main function of an LSS is to provide a lower boundary condition for the model atmosphere, handling surface fluxes of radiative, sensible and latent heat, as well as moisture. The first-generation LSS that appeared in the late 1960s had only one layer, with one prognostic thermal variable for surface temperature and usually three prognostic hydrological variables: snow amount, liquid and frozen soil moisture. Vegetation canopy was not considered as a separate layer and few (if any) of its properties were considered as having an influence on surface parameters. Snow mass was handled explicitly in the surface water and energy balance, but through a bulk formulation. The simplicity of the first-generation LSS induced significant biases in the hydrological processes. Increasing computer power and interest in accurate climate simulations promoted the development of second-generation LSSs including explicit treatment of vegetation canopy and snow layers, with several soil layers and more detailed representation of hydrological processes.

The Canadian Regional Climate Model (CRCM) exists in two versions, operational (CRCM op) and developmental (CRCM dev), differing in their use of the second- and third-generation physical parametrization packages of the Canadian General Circulation Model (CGCM), respectively. Among the several differences CRCM op uses the so-called Bucket hydrological scheme and a one-layer Force-Restore surface energy budget (BFR) while CRCM dev uses the Canadian LAnd Surface Scheme (CLASS; Verseghy, 1991; Verseghy et al., 1993), with three soil layers and explicit treatment of snow and vegetation.

CLASS has already been compared to BFR in a stand-alone mode (Verseghy, 1991) and coupled within the CGCM (Verseghy et al., 1993; Verseghy, 1996). These studies have established that CLASS corrects a wet and cold surface bias present with the BFR scheme, in particular during summer months. Overall, the simulations of CGCM III using CLASS have a climate closer to observations, but retain similar biases to CGCM using the BFR scheme in screen temperature and precipitation rate.

CRCM op has been compared with other regional models (Takle et al., 1999; Anderson et al., 2003), and with global models, reanalyses or climatological observations (Laprise et al., 1998; Caya and Laprise, 1999; Feng et al., 2000; Laprise et al., 2003). Interim versions of CRCM dev have also been the focus of some evaluations (Lorant et al., 2002; Feng et al., 2003; MacKay et al., 2003). No study has yet compared the overall skill of the two versions of CRCM.

Model intercomparison projects (MIPs) are widely used by the modelling community, e.g., the Project to Intercompare Regional Climate Simulations (PIRCS; Takle et al., 1999), the Atmospheric Model Intercomparison Project (AMIP; Gates, 1992), the Coupled Model Intercomparison Project (CMIP; Lambert and Boer, 2001), to name a few. This study is a simple MIP, aiming to compare and assess the surface energy (SEB) and water (SWB) budgets over the Mississippi and Columbia river basins, in simulations of CRCM op and CRCM dev, and to compare these with available surface observations and atmospheric reanalyses (a discussion of the limitation of the atmospheric reanalyses in general and the National Centers for Environmental Prediction (NCEP) reanalyses in particular can be found in Kalnay et al. (1996)). The river-basin approach enables the comparison of simulated run-off with streamflow observations. The study of two contrasting river basins reinforces the analysis by revealing possibly differing biases. The CRCM op simulation was carried out as part of PIRCS, phase 1c (PIRCS-1c; Anderson et al., 2003). Except for the spin-up time that was increased from six months to one year, the same experimental configuration has been used for CRCM dev.

This paper is divided in five sections. In Section 2, the main components of the two CRCM versions and the experimental configuration are described. The SWB and SEB are presented in Sections 3 and 4, respectively. Section 5 presents the concluding remarks.

2 Description of models and experimental configuration

a Model Descriptions

The CRCM is a high-resolution limited-area model driven by lower resolution General Circulation Models (GCMs) or reanalyses (Caya and Laprise, 1999; Laprise et al., 2003). The differences between CRCM op and CRCM dev physical parametrizations are listed in Table 1. Most components of CRCM op come from CGCM II (McFarlane et al., 1992) except for moist convection, which is taken from Bechtold et al. (2001). CRCM dev uses the CGCM III parametrization package, which includes the moist convection of Zhang and McFarlane (1995) and the land-surface scheme CLASS (Verseghy, 1991; Verseghy et al., 1993).

Briefly, CLASS uses three soil layers with thicknesses of 0.1, 0.25 and 3.75 m from top to bottom, corresponding approximately to the depth influenced by the diurnal cycle, the rooting zone and the annual variations of temperature, respectively. The hydrological component of CLASS considers three soil water reservoirs as well as additional reservoirs when snow, ponded water or water over the canopy (liquid and solid phases) are present. Ponded water appears at the surface over saturated soil when snow melts or when the rainfall rate exceeds the infiltration rate; its maximum depth is prescribed as a function of the type of composite vegetation. In CLASS, as in the BFR scheme, reservoir overflow is instantaneously routed to the ocean as run-off (R). However the BFR scheme considers only surface run-off while CLASS considers both surface run-off and bottom vertical drainage.

In order to account for fractional surface types coverage, CLASS divides each grid cell into a maximum of four sub-areas: bare soil, vegetation, snow over bare soil and snow with vegetation. The energy and water budget equations are first solved for each sub-area separately and then averaged over the grid cell.

TABLE 1. CRCM op and CRCM dev physics formulation.

Characteristics	CRCM op (version 3.6.1)	CRCM dev
Parametrizations	CGCM II (McFarlane et al., 1992)	CGCM III
Solar radiation	Fouquart and Bonnel (1980)	Improvements in atmospheric solar radiation absorption by Barker and Li (1995)
Terrestrial radiation	Morcrette (1984)	Morcrette (1984)
Surface fluxes	Bulk transfer coefficient formulation and Monin-Obukhov similarity theory	New stability functions in stable conditions by Abdella and McFarlane (1996)
Large-scale precipitation	Supersaturation-based condensation scheme (McFarlane and Laprise, 1985)	Supersaturation-based condensation scheme (McFarlane and Laprise, 1985)
Moist convection	Deep and shallow mass-flux by Bechtold-Kain-Fritsch (Bechtold et al., 2001)	Deep and shallow mass-flux by Zhang and McFarlane (1995)
Clouds	Diagnostic cloud scheme and fixed convective cloud percentages in layers where convection is activated	Modified diagnostic cloud scheme of Lorant et al. (2002)
Land surface scheme	Bucket and Force-Restore (BFR) (McFarlane et al., 1992)	CLASS version 2.7 (Verseghy, 1991; Verseghy et al., 1993)

b Experimental Configuration

Figure 1 shows the PIRCS-1c computational domain comprising 150 by 120 grid points including a nine grid-point sponge zone where horizontal winds are relaxed towards the values of the driving data. The diagnostic zone covers the conterminous United States, the southern part of Canada and most of Mexico. The projection is polar-stereographic with a grid-point spacing of 45 km (true at 60°N). In the vertical, 18 unequally spaced Gal-Chen levels are used with the thermodynamic layer thicknesses increasing from approximately 170 m above the surface up to 4 km below the top of the model located at 29 km. The time step is 15 minutes and diagnostic fields are archived at 6-hour intervals. CRCM op and CRCM dev were run from January 1987 to December 1994, with a spin-up prior to this date of six months and one year, respectively. Initial and lateral boundary conditions were taken from the first version of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalyses (NRA1; Kistler et al., 2001). Monthly values of sea surface temperature and sea-ice cover were taken from AMIP, phase II (AMIP II; Taylor et al., 2000). For CRCM op, although recommended otherwise by Taylor et al. (2000), the Great Lakes surface temperatures and ice cover were also prescribed by AMIP II. For CRCM dev, the grid points falling over the Great Lakes were considered as land points with properties similar to adjacent land points. Initial values of surface variables for CRCM op (CRCM dev) came from CGCM II (CGCM III) monthly mean climatologies. Vegetation and soil properties were defined from the global archive of Wilson and Hendersen-Sellers (1985).

Figure 2 shows the regions covered by the Mississippi and Columbia river basins over the PIRCS-1c diagnostic zone. The very high resolution (5′ × 5′ latitude-longitude) database of Graham et al. (1999) was used for the delineation of both catchments. However, based on the redelineation of Comanor et al. (2000), endorheic and areic regions of the Columbia River basin were removed as well as the region downstream of The Dalles (Oregon) where the last stream gauge station before the outlet is located, in order to increase the similarity between the CRCM and the observed drainage areas. This database was interpolated on the CRCM polar-stereographic grid. Over the Mississippi basin, monthly estimates of run-off are taken from Maurer and Lettenmaier (2001; hereinafter M&L) who extrapolated the values in the database from the U.S. Geological Survey (USGS) Water Resources (2005) restricted to affluents upstream of Vicksburg (Mississippi) to the entire Mississippi basin with the help of the hydrological and river routing Variable Infiltration Capacity (VIC) scheme. Over the Columbia River basin, monthly estimated run-offs are taken from the USGS between 1987 and 1994 and the historical data of the River Discharge version 1.1 (Vörösmarty et al., 1998; hereinafter RivDis1.1), naturalized by the A.G. Crook Company (Nijssen et al., 2001) to remove some of the anthropogenic biases (regulation at the dam, irrigation, water deviation, etc.). The differences between the CRCM drainage areas and those calculated by M&L over the Mississippi or RivDis1.1 over the Columbia are small, –0.7% and 0.3%, respectively.

The Mississippi River basin is a large catchment (approximately 3 219 000 km^2) with spatial heterogeneities in terms of mean climate and topography. In comparison, the Columbia River basin (without the coastal region) is five times smaller (approximately 616 000 km^2) with more homogeneous characteristics. Based on the classification of Verseghy et al. (1993), the Mississippi catchment is covered by 78% short vegetation (crops and grass) whereas the Columbia catchment is 45% trees (coniferous forest essentially) and 46% short vegetation. These differences between the two basins can have a profound influence on surface forcing and responses. Indeed, composite vegetation albedo averaged over each river basin decreases by 5% from the Mississippi (31%) to the Columbia (26%) catchment.

3 Surface water budget

a Total Water Budget over the Mississippi and Columbia River Basins

The terrestrial branch of the SWB can be written as (Peixoto and Oort, 1992):

$$\partial_t w = P - E - R \tag{1}$$

where w is the total surface water (liquid and frozen soil moisture and snow), and P, E and R are the total precipitation,

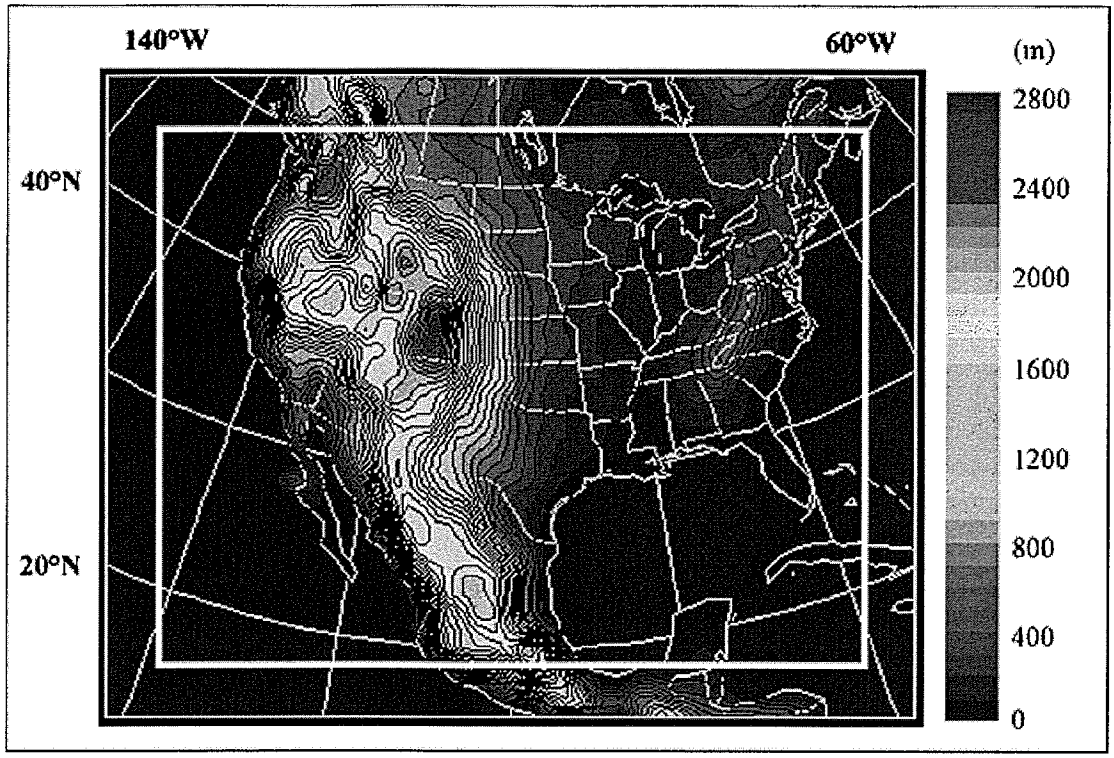

Fig. 1 PIRCS-1c computational domain and topographic height contours at the resolution of the CRCM. The diagnostic zone is delimited from the 9 grid-point sponge zone by the white rectangle.

evaporation and run-off rates, respectively. When averaged over several years, it is fair to assume that $\partial_t w \approx 0$ so that:

$$E \approx P - R. \tag{2}$$

In this study, averaged values over two drainage basins will be considered. The proper comparison of R with streamflow requires the use of a river routing scheme to calculate the travel time of run-off water from its origin to the drainage basin outlet. Betts et al. (2003) argued that river routing is particularly important for weak uneven basins containing lakes; over the Mackenzie basin, this delay time is about one month. On the other hand, when further averaged over an annual cycle, R can be directly related to streamflow at the outlet of a drainage basin.

Table 2 summarizes the eight-year mean SWB averaged over the Mississippi and Columbia river basins as simulated by the two versions of the CRCM. These are compared with the first version of the NCEP reanalyses (NRA1) and the European Centre for Medium-range Weather Forecasts (ECMWF) 40-year reanalyses (ERA40; ECMWF Data server, 2003), as well as with climatological gridded analyses of observations by the Climatic Research Unit, second version (CRU2; Mitchell et al., 2003) and Wilmott and Matsuura, version 1.02 (WM1.02; Wilmott and Matsuura, 2001), and naturalized estimated run-off by M&L, USGS and RivDis1.1. We have also added our "best estimate", based on a combination

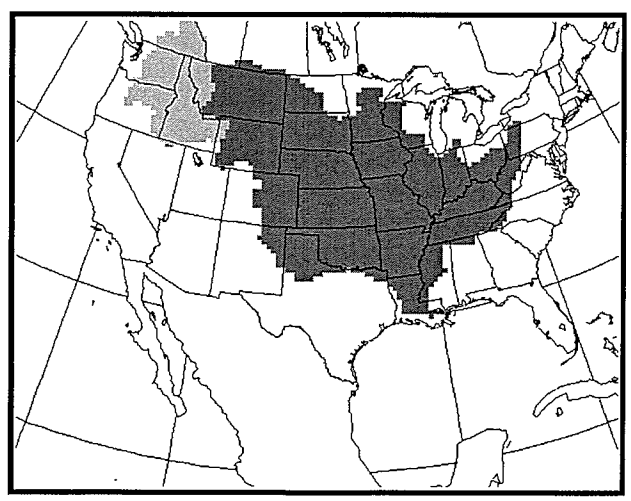

Fig. 2 Mississippi (dark blue) and Columbia (light blue) river basins on the CRCM grid over the PIRCS-1c diagnostic zone.

of observed and observation-based calculated values. Values written in normal font come directly from models, reanalyses or observation diagnostics. Values written in italics were calculated as residuals from other diagnosed fluxes, following Eqs (1) and (2). For example, our "best estimate" of the evaporation rate over the Mississippi catchment is based on Eq. (2) using the observed precipitation from CRU2 or WM1.02

TABLE 2. 1987-94 mean surface water budget (SWB) over the Mississippi/Columbia* river basins. See text for explanation of specific fonts.

	SWB (mm d^{-1})			
Models/Reanalyses/Obs	P	E	R	$\partial_t w$
CRCM op	3.3 / 4.0	2.7 / 2.6	0.5 / 1.4	*0.0 / 0.0*
CRCM dev	2.4 / 2.7	2.0 / 1.3	0.4 / 1.4	*0.0 / 0.0*
ERA40	1.9 / 1.5	1.9 / 1.2	0.2 / 0.7	*(-0.2) / (-0.4)*
NRA1	2.5 / 2.0	2.4 / 1.6	0.4 / 0.7	*(-0.3) / (-0.3)*
CRU2	2.2 / 1.4	–	–	–
WM1.02	2.2 / 1.2	–	–	–
M&L / RivDis1.1 naturalized	–	–	0.6 / 0.7	–
USGS	–	–	0.5** / 0.6	–
"Best estimate"	2.2 / 1.4	*1.6 / 0.7*	0.6 / 0.7	*0.0 / 0.0*

* Restricted to affluents upstream of The Dalles (Oregon).
** Restricted to affluents upstream of Vicksburg (Mississippi).

minus the estimated run-off from M&L; since it was calculated as a residual, this number is in italics. It should be noted that in the reanalyses, the SWB is closed only with the addition of the nudging term in Eq. (1). Consequently, the reanalyses $\partial_t w$ term, which is not equal to zero, is in fact equal to the negative of the nudging term; as a reminder of this, the value of $\partial_t w$ has been placed in parentheses for the reanalyses. Over the Mississippi basin, ERA40 and NRA1 nudging terms contribute +0.2 and +0.3 mm d^{-1} respectively on an annual basis. According to Betts et al. (2003), with ERA40 reanalyses over the same basin, this term is highly positive in summer and slightly negative during the thawing period (subtraction of melted water). Annually, the nudging terms of both reanalyses are of the same order of magnitude as the run-off terms, meaning that their influence on the SWB cannot be ignored.

The mean CRCM dev simulated precipitation over the Mississippi River basin (2.4 mm d^{-1}) is the closest to our best estimate (2.2 mm d^{-1}), with a 10% overestimation of 0.2 mm d^{-1}. The mean evaporation rate is overestimated by the two CRCM versions and the reanalyses when compared with our best estimate of 1.6 mm d^{-1} which is obtained as a residual between observed P and R, with ERA40 being the closest one (1.9 mm d^{-1}) followed by CRCM dev (2.0 mm d^{-1}). This excessive evaporation depletes surface water, thus contributing to a reduced R which is underestimated by the two versions of CRCM and the reanalyses. By choosing the precipitation of CRU2 and run-off rates of RivDis1.1 naturalized as our best estimate over the Columbia River basin, the observation-based mean evaporation can be estimated as 0.7 mm d^{-1}. This value is less than half that estimated over the Mississippi basin; there may be many reasons to explain this behaviour, including the length of the snow season, the soil water holding capacity and the vegetation cover. Over the Columbia River basin, E is largely overestimated by all models and reanalyses. CRCM op grossly overestimates P (by about 2.6 mm d^{-1}) compared to CRU2 data; this bias is reduced by half with CRCM dev. Generally, all terms in the SWB over the Columbia catchment are overestimated in both versions of CRCM.

It should be noted that most differences between models, models and observations, or observations alone are larger over the Columbia catchment than over the Mississippi. This behaviour could be due, in part, to the Columbia basin complex topography and the length of the cold season. Topography induces biases in climatological observations of temperature and precipitation depending on the location of the measurement sites and on the interpolation algorithm used to grid these data. Model parametrizations are not specifically designed for complex topography. As we will show in Section 3c, frozen water budgets differ widely among models, pointing to inadequacies in the handling of soil and frozen surface water processes in the climate models.

Figure 3 shows the eight-year mean CRCM-simulated annual cycle of the SWB (Eq. (1)). Over both basins the summer extremes of E and P using CRCM op were reduced using CRCM dev. Over the Mississippi catchment, the annual cycles of E and P seem to be intimately related, which indicates that precipitation recycling (defined as the fraction of evaporation from a specified control area that falls back as precipitation within the same control area) is very efficient over this region in CRCM simulations. Brubaker et al. (1993) reached the same conclusion, estimating that the summer precipitation recycling is approximately 30% over an appreciable portion of the Mississippi watershed. Over the Columbia catchment the connection between E and P is not as strong, particularly from October to March, indicating that large-scale atmospheric transport of moisture plays an important role for this basin. It is noteworthy that the evaporation over the Columbia basin at the end of fall and in winter is much reduced in CRCM dev compared to CRCM op. At this time of the year, screen temperatures (ST) are below freezing during most of the day, so that canopy stomatas in CLASS are closed and evapotranspiration is almost nil (monthly-mean STs are discussed in Section 4). As shall be shown later in Fig. 10, the Columbia basin is snow covered in CRCM dev, limiting the surface evaporation to snow sublimation which is very weak. With CRCM dev, variations in total surface water over the Columbia catchment are large, and probably overestimated.

Figure 4 shows the eight-year mean annual cycles of the SWB biases, defined with respect to gridded analyses of observations for P, local measurements for R, and ERA40 reanalyses for E and $\partial_t w$. A positive (negative) flux bias represents an overestimation (underestimation) by the models

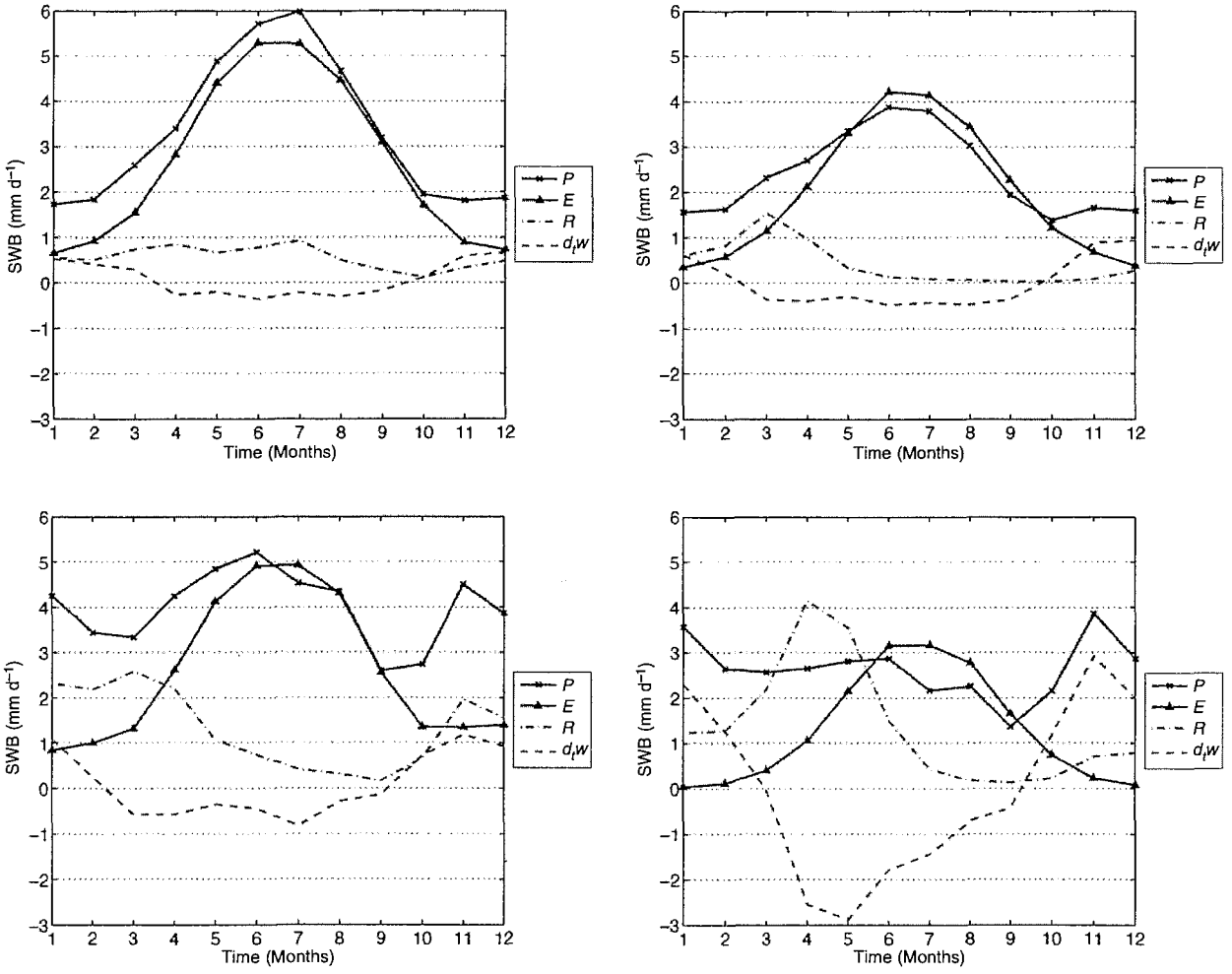

Fig. 3 1987–94 mean annual cycles of the surface water budget (SWB) for CRCM op (left) and CRCM dev (right) over the Mississippi (top) and Columbia (bottom) river basins.

against observations or reanalyses. Note, however, that because the ERA40 annual mean $\partial_t w$ is negatively biased for both basins due to the nudging term, the integral under the CRCM $\partial_t w$ bias curves over the year is not equal to zero. There is a substantial reduction in the evaporation and precipitation biases over both basins with CRCM dev. In summer, over the Columbia basin, P and E biases decreased by more than 60% compared to CRCM op. This, however, did not translate into an improvement for run-off and total surface water variations. By-and-large in summer, over both basins, the CRCM dev biases in P are balanced by biases in E, and biases in run-off are balanced by biases in soil moisture tendency. Compared to ERA40 reanalyses, the winter E appears too low with CRCM dev, whereas with CRCM op it seems better. However, Betts et al. (2003) have pointed out that the ERA40 reanalyses probably have excess evaporation in winter because the assimilation model has no seasonal cycle of vegetation; consequently, the CRCM dev winter evaporation deficit may not be as significant as the figure suggests.

We speculate whether the remaining excessive summertime evaporation bias with CRCM dev could be related to the treatment of ponded water (also called "skin reservoir" or "interception reservoir") in CLASS. Ponded water greatly enhances evaporation by inhibiting soil resistance. As mentioned in Section 2, CLASS ponded water maximum depth depends on the type of composite vegetation. For example, on a CRCM grid cell entirely covered with low vegetation, CLASS allows a maximum ponded water depth of 3 mm. For comparison, in the ERA40 Tiled ECMWF Scheme for Surface Exchanges over Land (TESSEL), the interception reservoir over one layer of leaves or over bare soil is restricted to 0.2 mm (ECMWF Data server, 2003). An overly large maximum ponded water depth could contribute to evaporation excess.

Figure 5 presents mean annual cycles of precipitation rates for both versions of CRCM and available observations and reanalyses. Over the Mississippi River basin the two gridded datasets, CRU2 and WM1.02, agree very well. The ERA40

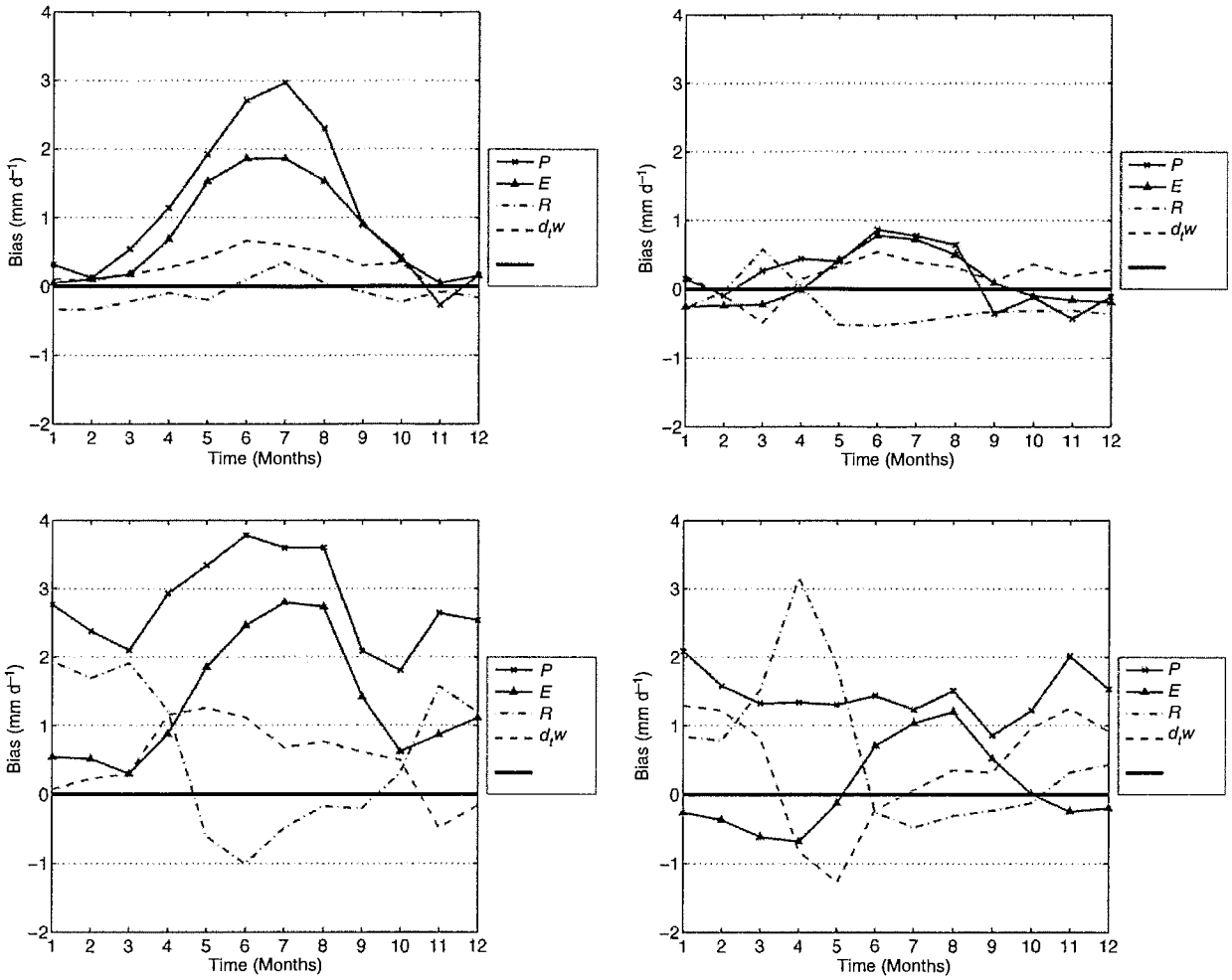

Fig. 4 1987–94 mean annual cycles of the surface water budget (SWB) biases, defined with respect to available observations or ERA40 reanalyses, for CRCM op (left) and CRCM dev (right) over the Mississippi (top) and Columbia (bottom) river basins.

dataset exhibits a systematic small underestimation while the NRA1 bias varies from an underestimation in winter to a large overestimation in summer. Note that reanalyses precipitation are the zero to six-hour segment of the data assimilation cycle, which may suffer from spin-up problems. The value of P from the CRCM op exceeds the observed P throughout the year except in November. The large positive summer P bias of CRCM op is greatly reduced when using CRCM dev. For both versions of the CRCM, the overestimation of P is located over the western part of the Mississippi basin (not shown), a region that should be mostly dry and semi-arid.

The annual cycle of P over the Columbia River basin is markedly different, with semi-annual and smaller amplitude variations, with an absolute minimum (maximum) in September (November). Overall, both versions of the CRCM capture the semi-annual variation but with excessive precipitation amounts. The biases are substantially reduced with CRCM dev; it is plausible that the implementation of more complex physical processes, such as the canopy resistance which limits the warm season evaporation over dry canopy, may reduce the evaporation leading to reduced precipitation.

Over both basins, NRA1 reanalyses exhibit rather pronounced biases. Kistler et al. (2001) show that NRA1 specific humidity and longitudinal winds, which are intimately connected to precipitation, have noticeable uncertainties over oceans where few observations are available. Since 70% of the PIRCS-1c domain boundaries are located over oceans, the potential exists for contamination of the CRCM simulation by NRA1 errors. Paquin et al. (2002) have compared summer precipitation of two identical four-month simulations with CRCM op over the PIRCS-1c computational domain, driven by two sets of lateral boundary conditions: NRA1 and ECMWF 15-year reanalyses (ERA15). Considering land grid-points only, they found an overestimation of nearly 0.2 mm d^{-1} in the simulation driven by NRA1. With the

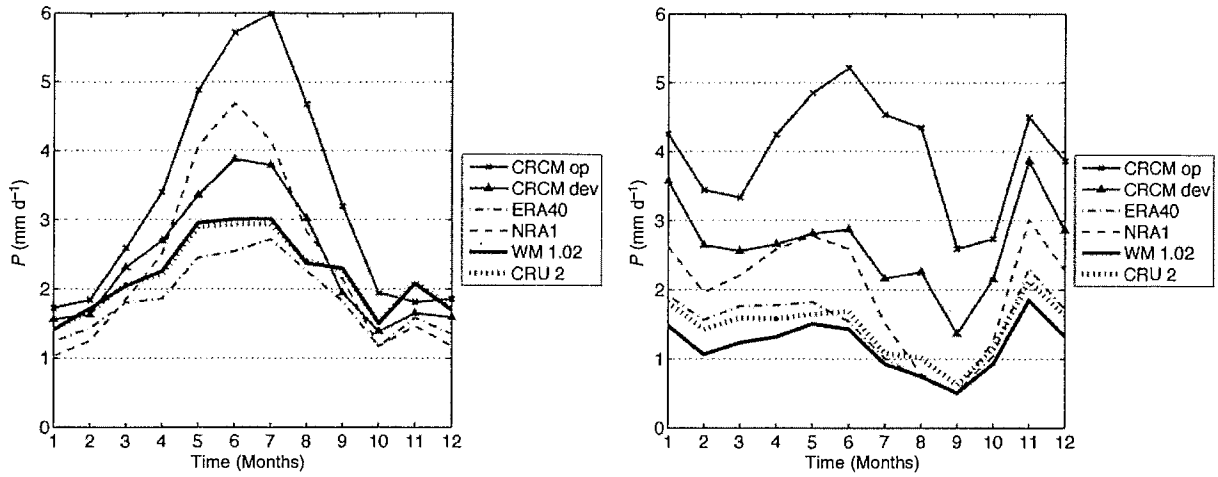

Fig. 5 1987–94 mean annual cycle of the precipitation rate for both versions of the CRCM and available reanalyses and observations over the Mississippi (left) and Columbia (right) river basins.

fifth-generation NCAR mesoscale model nested by the same two reanalyses over the western part of the United States, Leung et al. (2003) found some profound localized overestimations in winter P, amplified by high topography, of about 0.6 mm d^{-1} in the simulation driven by NRA1.

b Run-off

Figure 6 presents the mean annual cycle of run-off rates. None of the models or the reanalyses succeed in capturing the details of the annual cycle of R over either catchment. The excessive spring run-off with CRCM dev is related to the excessive snow cover: 254% (182%) annually over the Mississippi (Columbia) River basin, compared to the analyses of Brown et al. (2003). On the other hand there is a run-off deficit in summer and autumn with CRCM dev. The same deficit is also noted in ERA40 data; in their study over the Mississippi River basin, Betts et al. (2003) concluded that the nesting term in ERA40 contributed to a significant underestimation of R. Because CRCM op employs a very simple formulation of surface run-off, its run-off responds overly strongly to specific events such as rapid snowmelt or intense precipitation.

The difference in the magnitude of summer R over the Columbia River basin between estimated values from the USGS and that of the RivDis1.1 naturalized data is appreciable. This demonstrates that streamflow measurements in rivers modified by human activity cannot be used for validation of meteorological models. In spite of good agreement between the RivDis1.1 naturalized data and the ERA40 reanalyses, large uncertainties remain because regulated streamflows are difficult to naturalize. The spring flood occurs with a time shift of approximately two months for the CRCM op and ERA40, and one month for the CRCM dev compared to RivDis1.1 naturalized data. The study of Betts et al. (2003) on another basin noted a similar phase shift between observed and reanalysed R. They argued that accounting for refreezing of melted snow on the snowpack delays the disappearance of snow in spring and retards the flood period. CLASS takes this aspect of surface modelling into account in CRCM dev. The absence of a river routing scheme to process the CRCM and ERA40 data likely explains most of the run-off phase shift over the Columbia River basin.

Questions remain concerning the low summer R simulated by CRCM dev. As noted earlier in discussing Fig. 4, the summer R deficit is balanced by soil that is not losing moisture at a high enough rate. Since only about 20% of the Mississippi basin annual soil moisture is either being recycled as precipitation, suctioned by canopy roots or evacuated by bottom drainage (not shown), the remaining 80% should be subject to lateral movements following the ground slope and drainage to rivers. Soulis et al. (2000) proposed an approach consisting of coupling the hydrological model WATFLOOD with CLASS (WATCLASS) for experiments over small watersheds. WATFLOOD considers three horizontal run-off mechanisms: overland run-off routed into a microdrainage system, bottom drainage that later appears as base flow in streams and a subsurface interflow occurring through the soil matrix. These authors argue that this latter type of flow can be as important as bottom drainage, leading to a 17% reduction in summer evaporation over bare soil. To the best of our knowledge, the new linked model, WATCLASS, has not yet been used in long-term climate simulations.

c Frozen Surface Water Budget (FSWB) over the Columbia River Basin

Total surface water can be subdivided into its three components, namely liquid water, w_L; frozen water, w_F, and snow, n, in the SWB Eq. (1):

$$\partial_t w_L = P_L - E_L + M_F + M_n - R, \tag{3}$$

$$\partial_t w_F = -E_F - M_F, \tag{4}$$

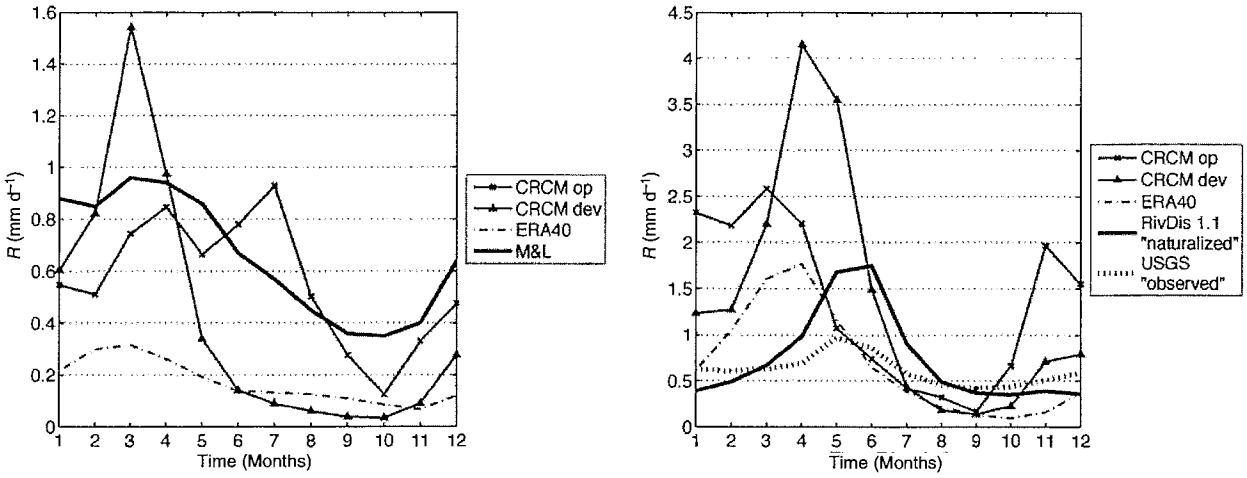

Fig. 6 1987–94 mean annual cycle of the run-off rate for both versions of the CRCM, ERA40 reanalyses and available observations over the Mississippi (left) and Columbia (right) river basins (note the use of different scales for the two basins).

$$\partial_t n = P_n - E_n - M_n. \tag{5}$$

The terms M_F and M_n represent the melting rates of frozen ground water and snow, respectively; a negative M_F indicates freezing of liquid water and M_n is always positive. The terms P_L and P_n refer to rain and snow fall rates, respectively. The terms E_L, E_F and E_n refer to evaporation rates of liquid ground water and sublimation of frozen ground water and snow, respectively. Equation (1) follows from summing Eqs (3), (4) and (5), using the definitions:

$$w = w_L + w_F + n, \tag{6}$$

$$P = P_L + P_n, \tag{7}$$

$$E = E_L + E_F + E_n. \tag{8}$$

Both versions of the CRCM solve Eqs (4) and (5) subject to different assumptions. The archived monthly-mean variables are w_L, w_F, n, P, P_n, E, E_n and R. Most other variables can be recovered from these using Eqs (1) to (8). But there remain five unknowns: $\partial_t w_F$, $\partial_t n$, E_F, M_F and M_n. In order to avoid returning to the entire six-hourly archive of the model, a methodology has been adopted to estimate the missing terms as explained in the Appendix. ERA40 snow fluxes were also available, as was snow depth in the ERA40 reanalyses and the Brown et al. (2003) analyses.

Table 3 presents the eight-year mean FSWB over the Columbia River basin for both versions of the CRCM and ERA40 reanalyses. All terms written in normal style come from models or reanalyses diagnostics, while those in italics were calculated as the residual following Eq. (5) for ERA40 or as explained in the Appendix for both versions of the CRCM. Since the ERA40 budget is only closed with the addition of a nudging term, its $\partial_t n$ value was written in parentheses; this nudging term adds 0.3 mm d^{-1} of water into the soil on average, which is of the same order of magnitude as snowfall and snowmelt rates and one order of magnitude larger than snow sublimation. In Table 3, the negative value of M_F in CRCM op indicates that there is more ground water freezing than melting; the difference is made up by the sublimation of frozen ground water so that, on a multi-year basis, $\partial_t w_F \approx 0$. Similarly, snowfall is perfectly compensated for by the sum of snowmelt and snow sublimation, so that $\partial_t n \approx 0$, on average.

Snow budgets are very different in the two versions of the CRCM. In CRCM op, 40% of the fallen snow is sublimated and 60% is thawed. The high percentage of snow sublimation, four times larger than ERA40, is mostly due to the warm surface temperature bias in late fall and early winter. In CRCM dev, 98% of the annual snowfall melts and only 2% is sublimated.

In CRCM op, 250 mm of the frozen ground water is formed during the cold season, 7% of which sublimates and the balance thaws and returns to liquid ground water during the warm season (not shown). In contrast, in CRCM dev, 17 mm of frozen ground water returns to liquid ground water because CLASS does not allow sublimation of frozen ground water and ponded water that freezes is considered part of the snowpack. Processes related to frozen ground water and snow remain poorly understood and their representation in climate models constitutes a significant source of uncertainty.

Figure 7 presents the average annual cycle of the FSWB. It is quite striking that CRCM op has much larger contributions from frozen ground water while in CRCM dev it is snow that contributes the most. The spring thawing peak occurs nearly one month later in CRCM dev than in CRCM op, as was noted earlier in discussing run-off.

TABLE 3. 1987–94 mean frozen surface water budget (FSWB) over the Columbia River basin. See text for explanation of specific fonts.

Models/ Reanalyses	FSWB ($\times 10^{-2}$ mm d^{-1})						
	P_n	E_n	E_F	M_n	M_F	$\partial_t n$	$\partial_t w_F$
CRCM op	61	25	*5*	*36*	*–5*	*0*	*0*
CRCM dev	123	3	*0*	*120*	*0*	*0*	*0*
ERA40	40	7	–	63	–	*(-30)*	–

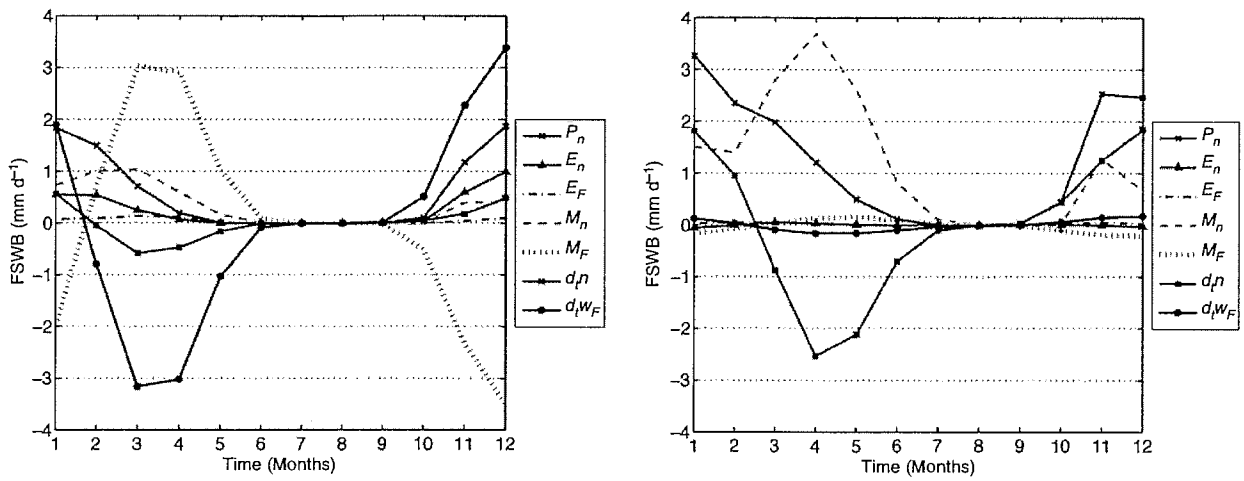

Fig. 7 1987–94 mean annual cycle of the frozen surface water budget (FSWB) for CRCM op (left) and CRCM dev (right) over the Columbia River basin.

The excessive ground water in CRCM op has repercussions on surface temperature in early winter, as discussed by Verseghy (1996). In the BFR scheme, land surface temperature is not allowed to fall below freezing as long as some liquid ground water remains; the delay in freezing the ground in the fall is largely due to the large values of soil water holding capacity in CRCM op (for a one layer LSS). Precipitation is not considered snow till rather late in autumn when the ground finally freezes. With the three soil layers of CLASS, ground surface temperatures can fall below freezing after the water contained in the first soil layer has frozen; this layer has a small water holding capacity, less than 0.1 m compared to 0.5 m for the BFR scheme when averaged over the Columbia River basin.

Figure 8 shows the average annual cycle of snow depth for both versions of the CRCM compared with ERA40 reanalyses and the Brown et al. (2003) analyses. In CRCM op and CRCM dev, snow depths are, respectively, about one-third and twice that of the Brown et al. (2003) analyses. As we will see in Section 4, this is related to surface temperature biases, warm in CRCM op and cold in CRCM dev. As a result, the ratio, P_n/P, for winter months is 45% in CRCM op and 90% in CRCM dev. In ERA40 a warm bias also contributes to the underestimation of snow depth. The noted biases in snow depth and temperature are also consistent with the time of snow disappearance that occurs about one month earlier in CRCM op and ERA40 and one month later in CRCM dev. A similar bias of late snow disappearance has been noted and studied by Slater et al. (2001) with CLASS. A new version of CLASS (version 3.0) has been developed, which addresses this shortcoming.

Figure 9 shows maps of averaged winter snow depth for both versions of the CRCM and the Brown et al. (2003) analyses. The biases in snow depth are accompanied by corresponding biases in snow cover extent. CRCM op underestimates snow cover on the Cascade and Sierra Nevada mountains, but reproduces it well over the Mississippi basin where there is little snow cover; CRCM dev overestimates depth and the snow cover extent almost everywhere in the domain.

4 Surface energy budget

The SEB over land takes the following form:

$$G = Q_* + Q_T - H_S - H_L - H_M \tag{9}$$

where G is the interfacial flux, Q_* and Q_T are the net solar and terrestrial radiative fluxes at the surface, and H_S, H_L and H_M are the sensible heat, the latent heat of evaporation and the latent heat of fusion fluxes, respectively. Q_T can also be expressed as the sum of the incoming ($Q_{T\,in}$) and outgoing ($Q_{T\,out}$) terrestrial radiative fluxes at the surface:

$$Q_T = Q_{T\,in} - Q_{T\,out}. \tag{10}$$

All fluxes in Eqs (9) and (10) are part of the standard CRCM diagnostics except for G, H_L and H_M. These three fluxes were

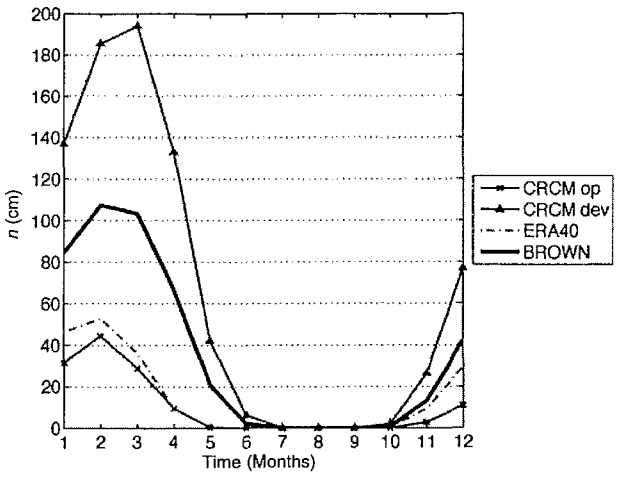

Fig. 8 1987–94 mean annual cycle of snow depth for both versions of the CRCM, ERA40 reanalyses and Brown et al. (2003) analyses over the Columbia River basin.

estimated using the procedure detailed in the Appendix. For convenience an additional quantity, Q_g, is calculated in the CRCM as the sum of the first four terms of the right hand-side of Eq. (9):

$$Q_g = Q_* + Q_T - H_S - H_L = G + H_M. \tag{11}$$

For the ERA40 and NRA1 reanalyses, H_L and Q_g were available; for ERA40, the G and H_M values were estimated using the strategy described in the Appendix. We note in passing that the time mean of G should vanish.

Table 4 presents the mean SEB. All fluxes written in normal font come from models or reanalysis diagnostics while fluxes written in italics were calculated as the residual following the methodology explained in the Appendix. CRCM dev has the smallest annual mean net solar flux, Q_*, over both basins, in part due to an overestimated surface albedo during the snow season, as we shall see in Table 6.

The release of latent heat of fusion, H_M, is quite small in the Mississippi basin. As seen in Fig. 10, the absorption of the latent heat of fusion by the surface (negative H_M) due to the freezing of liquid ground water in autumn is compensated for by the release of latent heat of fusion (positive H_M) in melting frozen ground water and snow in spring. Because snow accumulations are smaller in CRCM op than in CRCM dev, the compensating effect of H_M is almost perfect in CRCM op. The small positive H_M annual mean over the Columbia basin reflects the more substantial snowpack there, particularly with CRCM dev. The annual mean interfacial flux, G, is small but non-vanishing, probably as a result of approximations made in estimating some quantities to close the budget (see the Appendix).

Figure 10 shows the mean annual cycle of the SEB. The winter-average value of Q_* is lower by approximately 25 W m^{-2} over the Columbia basin than over the Mississippi basin, as a result of more clouds (13% more, see Table 5) and more snow (particularly for CRCM dev and ERA40) resulting in a higher surface albedo (see Table 6). Over the Columbia basin, the wintertime Q_* is approximately 25 W m^{-2} smaller in CRCM dev than in CRCM op. Table 6 shows that in CRCM dev winter-average surface albedo is 20% higher than in CRCM op and 14% higher than in ERA40. While ERA40 and CRU2 indicate similar cloud cover over both basins in summer, both versions of the CRCM, however, give more clouds and lower values of Q_* over the Columbia basin than over the Mississippi. Despite the fact that CRCM dev average summer cloud covers are 11% (18%) lower than the CRCM op ones over the Mississippi (Columbia) catchments, the values of Q_* are smaller in CRCM dev than in CRCM op. This may, in part, result from the modified solar radiative scheme of Barker and Li (1995) implemented in CRCM dev. According to these authors, the new scheme increases the solar radiation absorption by the atmosphere to the detriment of the surface. Overall CRCM dev average cloud cover values are closest to CRU2 data.

Table 7 and Fig. 11 show the eight-year average of ST and diurnal screen temperature range (DSTR). The NRA1 reanalyses exhibit a cold bias compared to CRU2, WM1.02 and ERA40 reanalyses. On an annual mean basis, CRCM dev has the largest cold ST bias with an annual mean ST of 9.9°C (3.6°C) over the Mississippi (Columbia) basin compared to 11.1°C (6.2°C) in CRU2. The CRCM op ST biases during the freezing and thawing periods were mentioned earlier: during freezing months the biases reach +3°C (+4.5°C) over the Mississippi (Columbia) basin compared to CRU2. In CRCM dev a cold bias is present from October to April over the Mississippi basin and throughout the year for the Columbia basin.

Owing to the continental nature of the climate of both basins, the DSTR values are large throughout the year, with two maxima in April and October over the Mississippi basin corresponding to warm days and cold nights, and a single maximum in September over the Columbia basin. CRCM op largely underestimates the amplitude of DSTR; this bias relates to aspects discussed earlier, namely the use of the BFR scheme with a deep bucket, resulting in excessive H_L in summer and excessive H_M in autumn and spring, as well as somewhat excessive cloud cover in summer. Despite its persistent cold ST bias, CRCM dev captures the magnitude and seasonal variations of DSTR well.

Figure 12 illustrates the eight-year mean annual cycle of the SEB biases computed using the ERA40 reanalyses as reference. A positive (negative) bias represents an overestimation (underestimation) by the models against reanalyses. As can be seen at a glance, most biases are reduced in CRCM dev compared to CRCM op. The previously mentioned biases of CRCM op clearly stand out in summer, with a large positive bias of H_L and an almost compensating large negative bias of H_S. In CRCM dev the excess snow results in a negative bias of Q_* during the cold season; this bias is probably

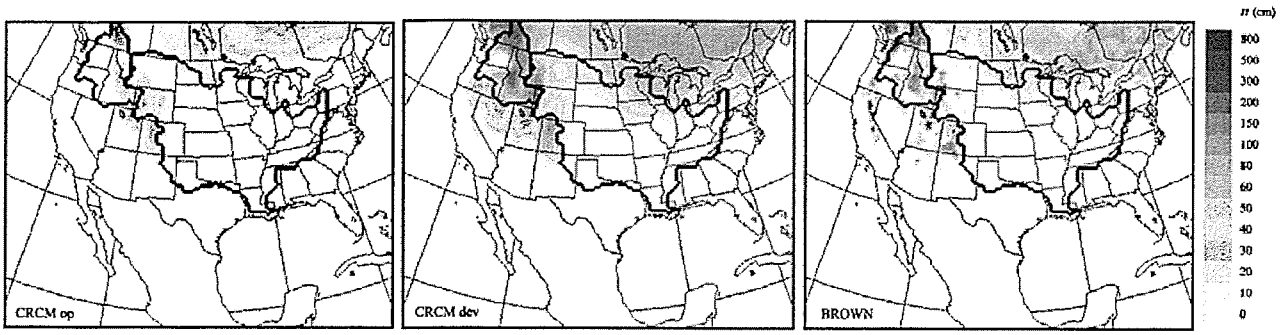

Fig. 9 1987–94 mean maps of winter (December–January–February) snow depth for CRCM op (left), CRCM dev (middle) and Brown et al. (2003) analyses (right) over the PIRCS-1c diagnostic zone.

TABLE 4. 1987–94 mean surface energy budget (SEB) over the Mississippi/Columbia river basins. See text for explanation of specific fonts.

Models/ Reanalyses	SEB (W m^{-2})						
	Q_*	$Q_{T\,in}$	$Q_{T\,out}$	H_L	H_S	H_M	G
CRCM op	160 / 138	311 / 302	375 / 350	*78 / 75*	13 / 11	*0 / 1*	*5 / 3*
CRCM dev	143 / 109	294 / 272	364 / 331	*58 / 38*	12 / 7	*1 / 5*	*3 / 0*
ERA40	154 / 140	310 / 280	376 / 347	55 / 36	27 / 35	*1 / 2*	*5 / 0*
NRA1	161 / 143	295 / 263	368 / 337	71 / 47	13 / 9	–	–

overestimated, however, due to the underestimated snow in ERA40 compared to the Brown et al. (2003) analyses.

5 Conclusions

An evaluation and comparison of the skill of the operational (CRCM op) and developmental (CRCM dev) versions of the CRCM to simulate the climate over the Mississippi and Columbia River basins has been performed, focusing on the surface water and energy budgets. The two CRCM versions differ in their physical parametrization packages: CRCM op uses most of the modules of the second-generation CGCM package including a simple LSS based on the BFR method, while CRCM dev uses the third-generation CGCM package including the more advanced CLASS. Simulations were performed following the PIRCS-1c experimental framework for the period 1987 to 1994. Simulated results were compared with several sources of observation-based data, including reanalyses (ERA40 and NRA1), gridded analyses of climatological observations (CRU2 and WM1.02), snow depth analyses (Brown et al., 2003) and run-off measurements (M&L, USGS and RivDis1.1 naturalized). To close the surface budgets some terms were estimated using the methodology described in the Appendix.

CRCM op simulated climate at the surface is constantly too wet but with a small annual-mean bias in ST owing to the partial compensation of a warm bias in winter, resulting from excessive latent heat of fusion for the ground water, and a cold bias in summer, resulting from excessive latent heat of evaporation and cloud cover. Over the Mississippi River basin, precipitation is greatly overestimated from April until September, which is related to the excessive evaporation, resulting in a fair annual-mean run-off. Over the Columbia basin, frozen water fluxes largely dominate over snow fluxes, giving an annual snow cover one-third that normally observed. Over both catchments, simulated DSTR is considerably underestimated, due to many different factors, including excessive latent heat of evaporation and fusion in the BFR scheme, and excessive cloud cover in summer.

The simulation of the climate at the surface by CRCM dev is an improvement over CRCM op. It is far less humid at the surface but exhibits a systematic cold bias and excessive snow depth: these two biases feed back on each other, the cold bias extending the length of the snow season, with the snow reducing the net solar flux at the surface. The excess snow generates an excessive run-off peak in spring. Summer precipitation bias is much smaller with CRCM dev, particularly over the Mississippi basin as a result of a reduction in summer evaporation excess. The DSTR magnitude and seasonal variation are relatively well simulated over both catchments.

Acknowledgements

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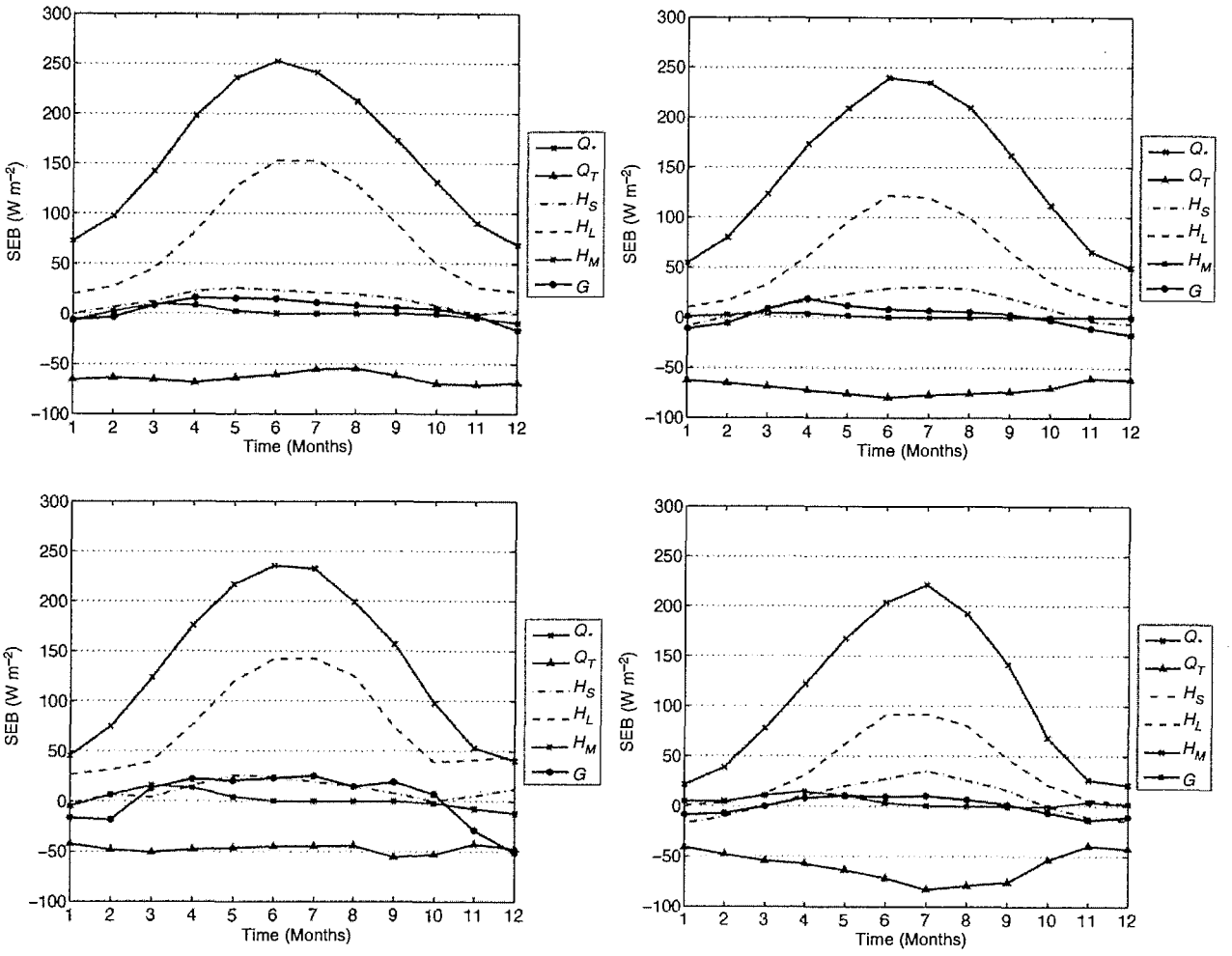

Fig. 10 1987–94 mean annual cycle of the surface energy budget (SEB) for CRCM op (left) and CRCM dev (right) over the Mississippi (top) and Columbia (bottom) river basins.

TABLE 5. 1987–94 seasonal-mean vertically integrated cloud cover (%) over the Mississippi/Columbia river basins.

	Summer	Winter
Models	%	%
CRCM op	64 / 74	50 / 77
CRCM dev	53 / 56	58 / 78
ERA40	42 / 42	54 / 72
CRU2*	53 / 50	63 / 76

* Constructed using a combination of observed data (screen temperature and precipitation rate) and empirical relationships.

TABLE 6. 1987–94 seasonal-mean average surface albedo* (%) over the Mississippi/Columbia river basins.

	Summer	Winter
Models	%	%
CRCM op	19 / 18	29 / 22
CRCM dev	17 / 15	32 / 42
ERA40	15 / 16	25 / 28

* Defined as the ratio of the outgoing to the incoming surface solar fluxes.

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TABLE 7. 1987–94 mean of screen temperature (ST) and diurnal screen temperature range (DSTR) over the Mississippi/Columbia river basins.

	ST	DSTR
Models/Reanalyses/Obs	°C	°C
CRCM op	11.4 / 6.8	6.7 / 4.4
CRCM dev	9.9 / 3.6	11.5 / 10.3
ERA40	11.4 / 7.0	–
NRA1	10.0 / 4.4	–
CRU2	11.1 / 6.2	13.6 / 12.8
WM1.02	10.9 / 5.4	–

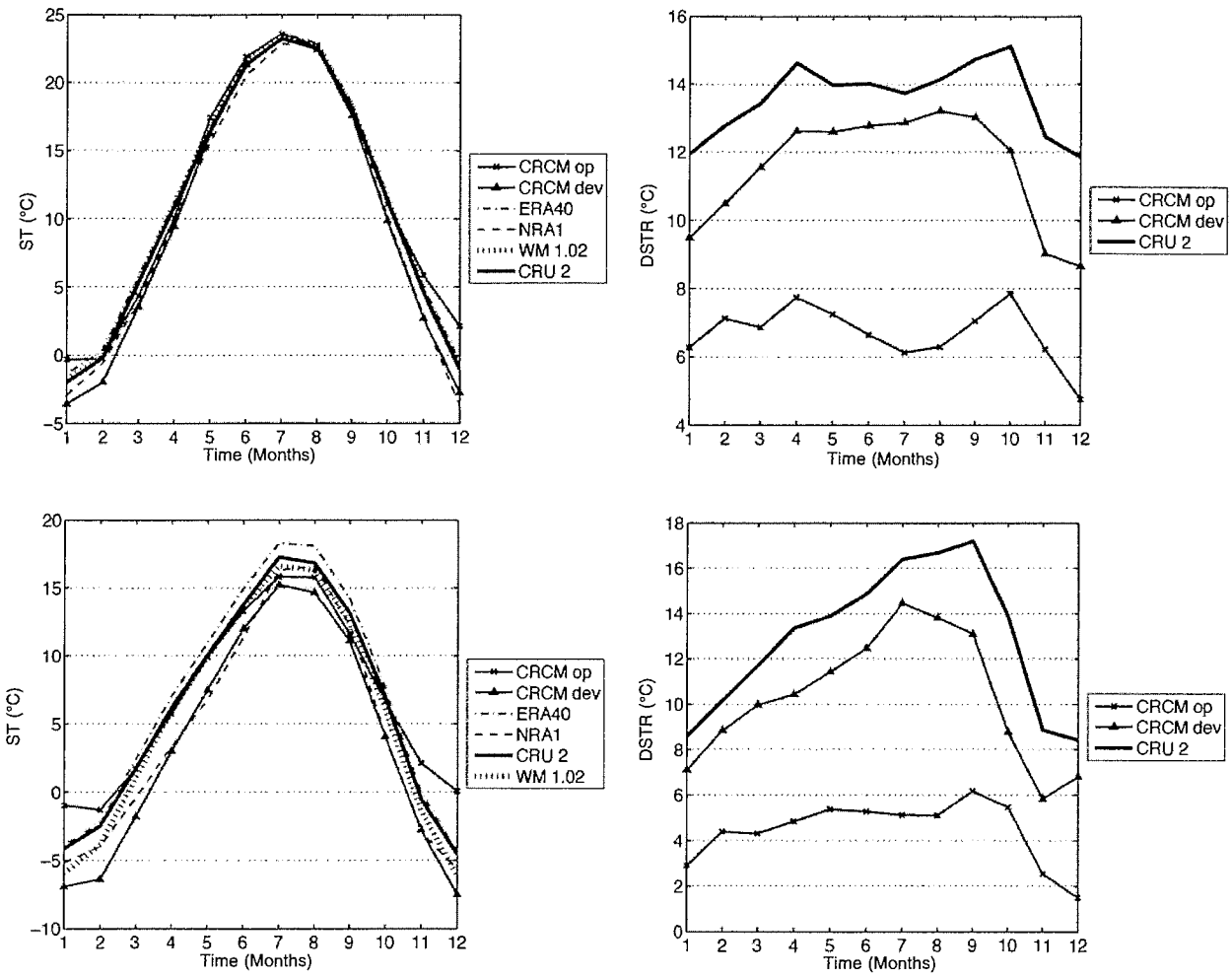

Fig. 11 1987–94 mean annual cycle of the screen temperature (ST, left) and diurnal screen temperature range (DSTR, right) for both versions of the CRCM and available reanalyses and observations over the Mississippi (top) and Columbia (bottom) river basins.

Appendix: Calculation of the latent heat flux of fusion

The latent heat of fusion, H_M, is not archived by CRCM. The purpose of this section is to develop a methodology to estimate H_M from the available diagnostic fields. In addition, other unavailable fields will be derived: M_n, M_F, E_F, $\partial_t n$, $\partial_t w_F$, H_L and G.

The heat flux due to the latent heat of fusion is obtained as the sum of the melting of both snow and frozen ground water, multiplied by the latent heat of fusion, L_f:

$$H_M = L_f(M_F + M_n). \tag{12}$$

The melting fluxes can be obtained as a residual by combining Eqs (4) and (5) of the FSWB:

$$(M_F + M_n) = P_n - (E_n + E_F) - \partial_t(n + w_F). \tag{13}$$

The monthly means of $\partial_t w_F$ and $\partial_t n$ are crudely approximated by taking the centred time difference of monthly-mean values of w_F and n. The only remaining unknown on the right-hand side of Eq. (13) is E_F, the sublimation of frozen ground water. Recalling the definition of H_L and making use of Eq. (8) gives

$$H_L = L_V E + L_f(E_F + E_n) \tag{14}$$

where L_V is the latent heat of vaporisation, L_S is the latent heat of sublimation, and $L_S = L_V + L_f$. However, H_L is not archived by the CRCM. Combining Eqs (11) and (14) gives:

$$E_F = \frac{Q_g - (Q_* + Q_T - H_S) - L_V E - L_f E_n}{L_f}. \tag{15}$$

All terms on the right-hand side of Eq. (15) are archived by the CRCM. Combining Eqs (12), (13) and (15) gives a useful relation to estimate H_M. The interfacial flux, G, and melting fluxes, M_F and M_n, can then be estimated using Eqs (11), (4) and (5), respectively.

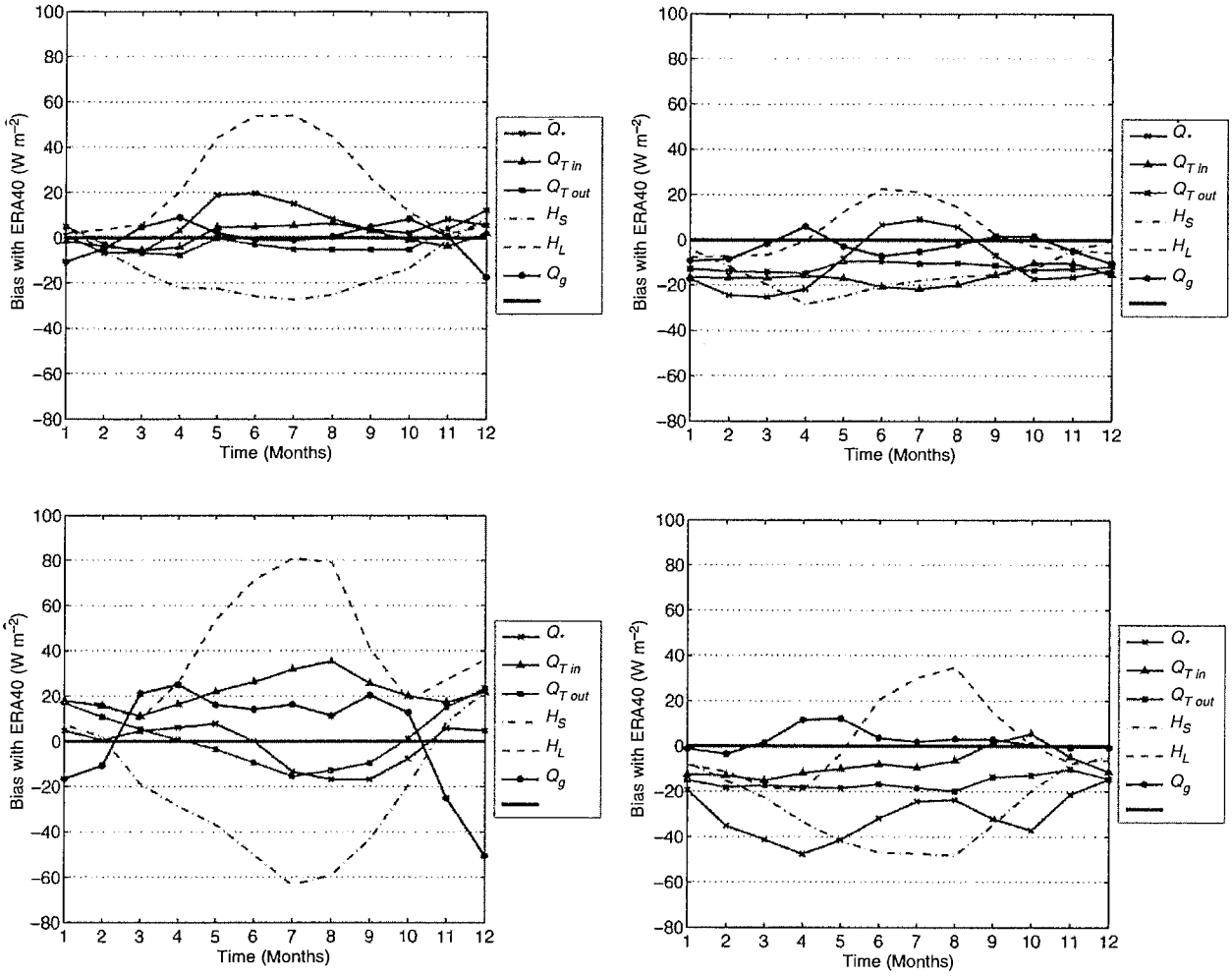

Fig. 12 1987–94 mean annual cycle of the surface energy budget (SEB) biases (defined with respect to ERA40 reanalyses) for CRCM op (left) and CRCM dev (right) over the Mississippi (top) and Columbia (bottom) river basins.

Unfortunately, there was an error in the definition of Q_g archived by CRCM op. A solution to this problem is to estimate E_F as a proportion of the monthly-mean fraction of frozen water into the bucket:

$$E_F = \delta_F(E - E_n) \tag{16}$$

where δ_F is also a diagnostic output from the CRCM. Combining Eqs (12), (13) and (16) gives a useful relation to estimate the CRCM op H_M.

None of the fluxes in Eq. (4) were available to us for the ERA40 reanalyses; it is then impossible to estimate the annual cycle of H_M for ERA40. However, M_N was available. For a long-term average $\partial_t w_F \approx 0$, this implies that $E_F \approx M_F$. Recognizing that sublimation of frozen ground water is very small in multi-layer LSSs (such as those of ERA40 or CRCM dev), we can therefore state that $E_F \approx M_F \approx 0$. In other words, the ERA40 annual latent heat of fusion flux can be estimated as $H_M \approx L_f M_n$.

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