Evaluation of the Hydrological Cycle over the Mississippi River Basin as Simulated by the Canadian Regional Climate Model (CRCM)

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ABSTRACT

The water cycle over a given region is governed by many complex multiscale interactions and feedbacks, and their representation in climate models can vary in complexity. To understand which of the key processes require better representation, evaluation and validation of all components of the simulated water cycle are required. Adequate assessing of the simulated hydrological cycle over a given region is not trivial because observations for various water cycle components are seldom available at the regional scale.

In this paper, a comprehensive validation method of the water budget components over a river basin is presented. In addition, the sensitivity of the hydrological cycle in the Canadian Regional Climate Model (CRCM) to a more realistic representation of the land surface processes, as well as radiation, cloud cover, and atmospheric boundary layer mixing is investigated. The changes to the physical parameterizations are assessed by evaluating the CRCM hydrological cycle over the Mississippi River basin. The first part of the evaluation looks at the basin annual means. The second part consists of the analysis and validation of the annual cycle of all water budget components. Finally, the third part is directed toward the spatial distribution of the annual mean precipitation, evapotranspiration, and runoff.

Results indicate a strong response of the CRCM evapotranspiration and precipitation biases to the physical parameterization changes. Noticeable improvement was obtained in the simulated annual cycles of precipitation, evapotranspiration, moisture flux convergence, and terrestrial water storage tendency when more sophisticated physical parameterizations were used. Some improvements are also observed for the simulated spatial distribution of precipitation and evapotranspiration. The simulated runoff is less sensitive to changes in the CRCM physical parameterizations.

1. Introduction

The hydrological cycle controls and regulates climate in a fundamental way through many complex interactions (Peixoto and Oort 1992). Inadequate understanding of the hydrological cycle and limited ability to model and predict the various hydrological cycle processes and their associated feedbacks contribute to many of the uncertainties associated with our understanding of long-term changes in the climate system (Watson et al. 2001). An international effort focusing on the understanding, measurement, and modeling of water and energy cycles within the climate system at the continental scale has been undertaken within the framework of Continental-Scale Experiments (CSEs) of the Global Energy and Water Cycle Experiment (GEWEX) Hydrometeorological Panel (HP).

GEWEX initiated the Continental-Scale International Project (GCIP) in the early 1990s. The goals of GCIP were to understand the hydrology and water balance of the Mississippi River basin (Robock 2003). GCIP has recently transitioned into the GEWEX America Prediction Project, which aims to demonstrate skill in predicting changes in water resources at seasonal and annual time scales, as an integral part of the climate system. Many studies realized during GCIP have relied on global, regional mesoscale, land surface, and hydrological models. Roads et al. (2003) provide a comprehensive description of GCIP water and energy
budget synthesis (WEBS) by summarizing the estimates of several models as well as data of global and regional reanalyses. The models in their study include global circulation, regional climate, and macroscale hydrologic models. They concluded that despite some agreement between the modeled and observed water budget components, there is still much quantitative uncertainty. Many other authors have undertaken water and energy budget studies over the region (e.g., Berbery and Rasmusson 1999; Berbery et al. 1999; Yarosh et al. 1999; Roads and Betts 2000; Maurer et al. 2001; Roads et al. 2002; Berbery et al. 2003; Ek et al. 2003).

Effort is being carried out in these studies to understand improvements that are necessary in the models and reanalyses as well as observation products to better describe and eventually predict water and energy cycles.

Regional climate models (RCMs) can be powerful tools in quantitative studies of the hydrological cycle at the continental and subcontinental scales. These models, based on the fundamental laws of physics, can reproduce many of the complex processes in the hydrological cycle and can generate information about hydrological cycle components that are difficult to measure. Unfortunately, deficiencies in hydrological cycle modeling induce errors in RCM simulations. These errors depend on the skill of the RCM itself, but also on the quality of the data used to drive the RCM at its boundaries. Model validation is therefore required to evaluate the magnitude of these errors. A thorough evaluation is also useful to identify errors in the model formulation and eventually correct them. Usually, only precipitation and river streamflow long-term observations are available at the regional scale. Surface flux measurements of latent and sensible heat that are very useful in model validations are extremely rare. Soil moisture and snow water equivalent, whose tendencies are important components of the water budget, are sporadically available in some regions. Therefore, we need to develop methodologies for carry out the validation of hydrological cycle components, which take into account the available observations.

In the present study, we investigate the influence of changes in the physical parameterization on the hydrological cycle of the Canadian Regional Climate Model (CRCM) by validating its water budget components using observations over the Mississippi River basin. Two model versions referred to here as CRCM_V3.6 and CRCM_V4.0 are used in this investigation. We combine atmospheric and terrestrial water budgets to estimate components of the hydrological cycle that are not directly observed. These components are hence referred to as “quasi-observed” components and serve to validate the corresponding simulated fields. The paper is structured as follows: the water budget analysis and the validation approach are presented in section 2. Section 3 describes the CRCM and the experimental configuration. The datasets used for the validation of the CRCM hydrological cycle are presented in section 4. Section 5 presents the validation of annual means of all water budget components for the 10-yr period (1988–97), the annual cycle validation, and a comparison of the spatial distribution of some hydrological cycle components with the corresponding reference fields. The paper concludes in section 6.

2. Water budget analysis

The application of water mass conservation in a given control volume results in the water budget analysis. In this section, the atmospheric, terrestrial, and combined water budget equations are presented as well as their application in the evaluation of the CRCM hydrological cycle.

a. Water budget equations

The water budget equation for an atmospheric column (per unit area) may be written as

$$\frac{\partial W}{\partial t} = -\nabla_H \cdot \mathbf{Q} - (P - E),$$  \hspace{1cm} (1)

where \(W\) (kg m\(^{-2}\)) is the precipitable water in the atmosphere, which represents the amount of water that would precipitate if all the water vapor in a column of the atmosphere were condensed (note that the contribution of cloud water in the column is neglected). \(E\) (kg m\(^{-2}\) s\(^{-1}\)) is evapotranspiration, and \(P\) (kg m\(^{-2}\) s\(^{-1}\)) is precipitation. The operator “\(\nabla_H\)” represents the horizontal divergence and \(\mathbf{Q}\) is the vertically integrated horizontal water vapor flux:

$$\mathbf{Q} = \int_{p_s}^{p_{top}} q \nabla \frac{dp}{g},$$  \hspace{1cm} (2)

where \(q\), \(\nabla\), and \(g\) represent specific humidity, horizontal velocity vector, and gravitational acceleration, respectively. The lower limit in the integral \((p_s)\) is the surface pressure and \(p_{top}\) is the pressure at the model lid.

Let us now consider the water balance requirement for the terrestrial branch of the hydrological cycle. Applying the water conservation law to a land column, the terrestrial water budget can be expressed as
where $M + S$ (kg m$^{-2}$) represents the storage of soil moisture ($M$) and the accumulated snowpack ($S$), and $R$ (kg m$^{-2}$ s$^{-1}$) is the total runoff, which includes the surface runoff and recharge from the groundwater reservoir (subsurface runoff).

The term ($P$) is common for Eqs. (1) and (3), and it establishes the connection between the terrestrial and atmospheric branches of the hydrological cycle. Elimination of ($P$) between these two equations yields a combined budget equation:

$$\frac{\partial (M + S)}{\partial t} = (P - E) - R,$$

where $\bar{X}$ represents the time average of component $X$, and $[X]$ is the spatial average (over the entire Mississippi River basin). Annual mean tendencies of atmospheric and terrestrial water storage ($\frac{\partial (M + S)}{\partial t}$) can safely be neglected because they tend toward zero when averaged over long period of time.

To validate the various components of Eqs. (5) and (6) from the simulation, the corresponding observed values must be known. An estimation of annual mean precipitation for the basin ($[P]_{OBS}$) can be obtained from existing gridded precipitation analysis datasets. River streamflows observed at gauging stations are available for many river basins, so a fairly good accuracy can be obtained for the annual mean runoff for the Mississippi River basin ($[R]_{OBS}$).

Evapotranspiration observations are seldom available at the regional scale and evapotranspiration must be estimated as a residual using the water budget analysis. We used the time- and space-averaged terrestrial water budget Eq. (6) to obtain the quasi-observed evapotranspiration:

$$[E]_{OBS} = [P]_{OBS} - [R]_{OBS}.$$

The model-simulated atmospheric water vapor convergence over the basin can be compared with the convergence computed from reanalysis data ($[C]_{REAN}$). It must be emphasized that the characteristics of reanalysis data, such as spatial and temporal sampling, vertical resolution, and treatment of the lower boundary layer in the computation, limit the accuracy of estimated water vapor convergence.

b. Validation methodology

An integrative analysis approach is used in the validation of the CRCM hydrological cycle. This approach links both the terrestrial and atmospheric branches and involves a long-term time mean of the hydrological cycle components, spatially averaged over a large area: in our case, the Mississippi River basin.

1) ANNUAL MEANS ANALYSIS APPROACH

Taking time and spatial averages of the atmospheric and terrestrial water budget Eqs. (1) and (3) over a multiyear period and over the whole basin leads to the following equations:

$$[C] = [P] - [E],$$

and

$$[R] = [P] - [E].$$

where $\bar{X}$ represents the time average of component $X$, and $[X]$ is the spatial average (over the entire Mississippi River basin). Annual mean tendencies of atmospheric and terrestrial water storage ($\frac{\partial (M + S)}{\partial t}$) can safely be neglected because they tend toward zero when averaged over long period of time.

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2) ANNUAL CYCLE ANALYSIS APPROACH

The validation of the annual cycle of water budget components is more complex and involves larger uncertainties. While terrestrial and atmospheric water storage components can be neglected for multiyear means, they cannot be neglected for monthly means, as these terms can be particularly large during spring and fall (Rasmusson 1968). For the annual cycle analysis, the averaged water budget equations becomes

$$\frac{\partial (M + S)}{\partial t} = (P - E) - R,$$

where $\bar{X}$ represents the time average of component $X$, and $[X]$ is the spatial average (over the entire Mississippi River basin). Annual mean tendencies of atmospheric and terrestrial water storage ($\frac{\partial (M + S)}{\partial t}$) can safely be neglected because they tend toward zero when averaged over long period of time.
The terms \( \overline{[\mathcal{W}_i]} \), \( \overline{[\mathcal{E}_i]} \), \( \overline{[\mathcal{P}_i]} \), \( \overline{[\mathcal{J}_i]} \), and \( \overline{[\mathcal{R}_i]} \) can be obtained from one of the existing datasets based on in situ observations (first two terms) and from re-analysis (last two terms). Finally, monthly values of quasi-observed terrestrial water storage tendencies can be computed as residuals from the averaged combined water budget Eq. (4):

\[
\frac{\partial \overline{[\mathcal{S}_i]}}{\partial t} = \overline{[\mathcal{E}_i]} \text{REAN} - \overline{[\mathcal{P}_i]} \text{REAN} - \overline{[\mathcal{J}_i]} \text{REAN} + \overline{[\mathcal{R}_i]} \text{OBS}.
\]

The accuracy of atmospheric water balance estimations depends on the investigated domain area. Seneviratne et al. (2004) have shown that the critical domain size for the water balance estimation for terrestrial water storage using water vapor flux convergence from high-resolution 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) is \( 2 \times 10^5 \text{ km}^2 \). Earlier studies (Rasmusson 1968, 1977) based on raw radiosonde data over North America recommended even larger regions—larger than \( 10^6 \text{ km}^2 \). The surface of the Mississippi River basin is approximately \( 3.2 \times 10^6 \text{ km}^2 \), thus satisfying both criteria.

3. CRCM description and experimental configuration

\( a. \) Model description

The CRCM is a limited-area nested model, originally developed at Université du Québec à Montréal, based on the fully elastic nonhydrostatic Euler equations. These equations are solved by noncentered semi-implicit and semi-Lagrangian numerical algorithm (Caya 1996; Laprise et al. 1998; Caya and Laprise 1999). The CRCM horizontal grid is uniform in a polar stereographic projection, with a typical 45-km grid mesh (true at 60°N), and its vertical resolution is variable using a Gal-Chen scaled height terrain-following coordinate. In this study, two versions of the CRCM referred to as CRCM_V3.6 and CRCM_V4.0 are used. In the following paragraphs, some model characteristics, which pertain to the hydrological cycle, are described.

The CRCM_V3.6 shares most of the subgrid-scale physical parameterization package of the second generation Canadian Coupled General Circulation Model (CGCM2; Flato and Boer 2001; McFarlane et al. 1992). The stratiform precipitation is parameterized as a simple supersaturation-based condensation scheme, while the convective processes are described by the Bechtold–Kain–Fritsch (BKF) mass flux scheme (Bechtold et al. 2001), adapted to the CRCM resolution.

The land surface processes in the CRCM_V3.6 are described by the Manabe (1969)-based land surface scheme originally presented in McFarlane and Laprise (1985) and McFarlane et al. (1992). This scheme treats soil moisture as a single layer, with gains and losses occurring only at the surface via infiltration and evapotranspiration (drainage from the bottom of the layer is neglected). Infiltration is assumed to equal rainfall until the soil moisture exceeds the soil water-holding capacity; the excess water is assigned to runoff. The surface evapotranspiration rate is defined as a product of potential evapotranspiration and the factor of moisture availability (\( \beta \)-function), which is a simple function of the total soil moisture amount and soil water-holding capacity. As discussed by McFarlane et al. (1992), the use of the \( \beta \) function is appropriate when dealing with bare soil alone. To take into account—to some extent—the effects of vegetation on surface evaporation (the canopy is not modeled explicitly), the soil water-holding capacity is made to vary with both vegetation and bare soil characteristics of the surface. The Wilson and Henderson-Sellers (1985) land surface global dataset is used to specify soil properties and to determine the most frequently occurring primary and secondary vegetation classes.

The updated version of the model (CRCM_V4.0) is an important evolution from the previous version. The parameterization package of the CRCM_V4.0 includes changes to the radiation scheme, treatment of cloud cover, boundary layer mixing scheme, and land surface parameterization scheme.

A new radiation scheme uses four bands in the visible and near-infrared region, replacing an earlier two-band parameterization, to describe solar radiation heating. The treatment of the terrestrial radiation uses broadband emissivities and a more detailed vapor continuum (Puckrin et al. 2004). A new cloud scheme adds layer...
stability to relative humidity as a parameter for triggering cloud formation (Paquin and Harvey 2003). The boundary layer mixing scheme has been modified to include nonlocal mixing of heat and moisture. Instead of mixing surface fluxes only with the lowest model layer, the new mixing scheme evenly adds fluxes to whole boundary layers so as to mimic the vertical profiles of water vapor and potential temperature in a well-mixed planetary boundary layer (Jiao and Caya 2006). The Manabe-based formulation of the land surface processes is replaced by a state-of-the-art land surface scheme [Canadian Land Surface Scheme (CLASS_2.7; Verseghy 1991; Verseghy et al. 1993)] in order to provide a more realistic description of water and energy exchange between the land surface and atmosphere. The soil column in CLASS comprises a 10-cm surface layer, a 25-cm vegetation root zone, and a 3.75-m-deep soil layer. The layers’ liquid and frozen moisture contents as well as temperature are prognostic variables. They evolve following energy and moisture fluxes at the top and bottom of each layer. CLASS uses Darcy’s equations to evaluate water fluxes between the layers. Water infiltration into the upper soil layer is treated as a downward propagation square wave (Mein and Larson 1973). When the infiltration capacity is exceeded, water is allowed to pond on the surface up to a maximum surface retention capacity, which varies according to the land cover. The overflow of the surface retention capacity is assumed to be surface runoff. The subsurface runoff refers to the drainage of water from the deep soil column and is parameterized as \( Q_d = k_{sat}(w_d/w_{sat})^{2b+3} \), where \( w_d \) is the volumetric water content (\( m^3/m^3 \)) in the deep soil layer, \( w_{sat} \) is the saturation soil water content, and \( k_{sat} \) is the saturation hydraulic conductivity. The \( b \), \( w_{sat} \), and \( k_{sat} \) depend on soil type. Vegetation canopy in CLASS is treated explicitly. The vegetation properties are determined based on the following vegetation types: coniferous tree, deciduous trees, crops, and grass. The leaf area index, roughness length, area mass, and rooting depth of each of those groups are considered as varying over the seasonal time scale. Evapotranspiration over land originates from the following sources: bare soil evaporation from the top-soil layer, potential evaporation of the canopy intercepted water, and transpiration from the root zone. The canopy interception capacity is a function of the leaf area index and varies for liquid or solid precipitation. Transpiration is controlled by the bulk canopy stomatal resistance, which is a function of leaf area index, incoming solar radiation, atmospheric vapor pressure deficit, temperature, and soil moisture tension.

As mentioned above, the CRCM uses the semi-Lagrangian numerical scheme, which induces slight nonconservation of prognostic variables. A corrective factor, which takes into account this inaccuracy, is introduced in the CRCM_V4.0 and is applied to the specific humidity values at each grid point. The calculation of the corrective factor is presented in Paquin and Laprise (2003).

Finally, it should be noted that in both the CRCM_V3.6 and the CRCM_V4.0, the atmospheric moisture flux is calculated on each model level (Gal-Chen) and vertically integrated at each time step. Moisture flux convergence is derived from accumulated (during 6 h) vertically integrated atmospheric moisture flux.

b. Experimental setup

Two model simulations will be analyzed in this study; one performed using CRCM_V3.6, while the other one uses CRCM_V4.0. The computational domain for both models covers the whole of North America [Amérique du Nord (AMNO) domain], and parts of the adjacent Pacific, Atlantic, and Arctic Oceans. The simulations were driven by 6-hourly National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses over the 1959–99 period, linearly interpolated in time to the model’s 15-min time step. The sea surface temperature and sea ice are taken from the Atmospheric Model Intercomparison Project II (AMIP-II) database (Fiorino et al. 1997). In addition to the nesting method of Davies (1976) used in most regional climate models to specify their lateral boundaries and to assure coherence between the large-scale circulations of the driving and driven models over the large AMNO domain, the large-scale (waves longer than 1400 km) horizontal wind field from the CRCM was nudged toward the large-scale wind of the driving data (Riette and Caya 2002). The nudging coefficient increases linearly above 500 hPa to reach 0.05 at the top level. The simulations have been performed at a 45-km horizontal resolution using 29 unequally spaced Gal-Chen levels. The lowest thermodynamic level is at about 170 m above the surface, and the computational lid is near 29 km. Most of the vertical levels are assigned to the lower troposphere in order to allow the planetary boundary layer and lower troposphere to be well resolved. Figure 2 presents the domain where the analyzed region over the Mississippi River basin is indicated. A discretization of major river basins at 5’ resolution by Graham et al. (1999) is used as a template to define the Mississippi basin.

4. Validation datasets

The components derived directly from observations or closely connected to them can be used as reference
fields in the validation of model-simulated hydrological cycle components. In this section, we describe the datasets used to supply some of the observations to validate the hydrological cycle components.

a. Precipitation dataset

For climate model evaluation, using a gridded dataset of precipitation is preferred. The gridding is a necessary preliminary step, which helps to reduce biases arising from the irregular station distribution. Several gridded datasets of monthly precipitation have been developed in recent years by groups such as the Climatic Research Unit (CRU; Hulme 1994; New et al. 2000; Mitchell and Jones 2005), Global Precipitation Climatology Project/Centre (GPCP; Adler et al. 2003), Center for Climatic Research (CCR; Willmott and Matsuura 2001), and Global Historical Climatology Network (Peterson and Vose 1997). New et al. (2000) specify that the major sources of difference in gridded precipitation datasets are due to insufficient station coverage as well as by using a different interpolation method. The Mississippi River basin has good station coverage (see Fig. 2c in Roads et al. 2003); as such, there should not be significant differences between existing precipitation gridded datasets for this region.

The data of three available gridded monthly precipitation datasets were used in this study: CRU (Mitchell and Jones 2005), CCR (Willmott and Matsuura 2001), and GPCP (Adler et al. 2003). The CRU gridded dataset, already available for 1901–95 (New et al. 2000), has been recently extended to 2000 by Mitchell and Jones (2005). The primary variables (precipitation, mean temperature, and diurnal temperature range) were interpolated directly from station observations to a regular 0.5° latitude × 0.5° longitude grid following a method adapted from Piper and Stewart (1996). The correction for undercatch of precipitation was not carried out. The CCR (Willmott and Matsuura 2001) precipitation dataset covers the 1950–99 period. Surface station observations were interpolated to a 0.5° latitude × 0.5° longitude grid using a spherical version of Shepard’s method (Shepard 1968; Willmott et al. 1985). As CRU, CCR precipitation data did not correct for undercatch of precipitation. The approach used by Adler et al. (2003) in the production of GPCP dataset (for the 1979–2003 period) involved combining the precipitation information available from different sources into a final merged product. The surface rain gauge data were corrected for undercatch of precipitation using Legates’ (1987) method. The station data were first interpolated using Willmott et al. (1985) method to a regular 0.5° latitude × 0.5° longitude grid and then av-
eraged to provide area mean precipitation on 2.5° grid cells. A gauge analysis is merged to precipitation data obtained from low-orbit microwave and geosynchronous orbit satellite infrared measurements. The higher accuracy of the low-orbit microwave observations is used to calibrate the more frequent geosynchronous infrared observations.

b. Runoff datasets

For the Mississippi River basin, the observed data can be obtained from the U.S. Geological Survey (USGS) measurements (http://waterdata.usgs.gov/nwis/sw), which routinely collect streamflow data at numerous gauging stations (see Fig. 2d in Roads et al. 2003). Since the Mississippi River basin is affected by water management practices, the so-called naturalized runoff (removing the effect of water management) is preferred for model validation purposes. Maurer and Lettenmaier (2001) estimated naturalized runoff using streamflow data at Vicksburg, Mississippi, and extrapolated this value to the entire Mississippi River basin. The dataset contains monthly and annual series for the period 1988–2000. We used this dataset for validation of the CRCM runoff averaged over the basin. This is also used for estimations of mean annual evapotranspiration over the basin and monthly tendencies of terrestrial water storage [see Eqs. (7) and (11)].

To validate the spatial distribution of simulated runoff (section 5c), the composite gridded runoff dataset, developed by the Global Runoff Data Center (GRDC) can be used. It has a high resolution (0.5° latitude × 0.5° longitude), however the water management effect is neglected. The dataset is constructed using USGS observation data and data from other National Hydrological Services, along with the GRDC climate-driven water balance model (Fekete et al. 2000). The observation data cover the mid-1960s to the mid-1980s. We also use the Variable Infiltration Capacity (VIC) model runoff data at 1/8 degree resolution (Maurer et al. 2002). As suggested by Roads et al. (2003), VIC may actually provide a realistic geographic distribution of Mississippi runoff. It must be emphasized however, that the VIC model is tuned to reproduce observed runoff at the outlet of major tributaries of the Mississippi and its pattern is not realistic in the central northern part of the basin (Roads et al. 2003).

c. Reanalyses datasets

The global and regional reanalysis products, such as those from the NCEP–NCAR, NCEP/U.S. Department of Energy (DOE), and ECMWF, as well as the North American Regional Reanalysis (NARR), provide long time series of optimal estimations of the four-dimensional state of the atmosphere. The motivation for the reanalysis projects was the apparent “climate change” detected in the standard analysis data resulting from many changes introduced into data assimilation systems in order to improve the forecasts. The basis of these projects was to use a frozen version of a numerical weather prediction model retrospectively and perform data assimilation using an observed database as completely as possible. In this regard, the reanalyses can provide an excellent source for the estimation of variables that are closely linked to assimilated variables.

In the present study, we use the vertical integrated moisture convergences and precipitable water tendencies computed from NCEP–NCAR and ERA-40. The NCEP–NCAR system is based on a numerical weather prediction model with T62 spectral resolution (~200 km) and 28 sigma levels in the vertical with five of those levels in the atmospheric boundary layer. The monthly series of vertical integrated moisture convergence and precipitable water tendencies, derived from NCEP–NCAR full-resolution data, are obtained from University Corporation for Atmospheric Research (UCAR) Climate and Global Dynamics Division (http://www.cgd.ucar.edu/cas/catalog/newbudgets/index.html).

The ERA-40 model has a T159 spherical harmonic representation of the atmospheric dynamical and thermodynamical fields, and a gridpoint representation of humidity and cloud variables (Hortal and Simmons 1991). In the horizontal, the so-called reduced Gaussian grid is used with a grid spacing of about 112 km. A vertical coordinate is a hybrid sigma-pressure coordinate with 60 vertical levels (15 of those levels are in the first 2000 m). The monthly series of moisture flux convergence and precipitable water tendency, derived from ERA-40 full resolution, has been provided by ECMWF. For a detailed description of the computation of moisture flux convergence, the reader is referred to Seneviratne et al. (2004).

5. Results and discussion

The annual and monthly means of the CRCM-simulated hydrological cycle components over the Mississippi River basin are analyzed and compared with the available reference fields. The analysis is restricted to the 1988–97 period for which monthly series of the naturalized runoff, ERA-40 moisture flux convergence, and precipitable water tendency were available.

a. Analysis of the CRCM V3.6 simulation: Annual means of water budget components

Water mass conservation, when applied to the annual scale over the basin, requires that the atmospheric
moisture flux convergence balances the difference between precipitation and evapotranspiration \((P - E)\) and therefore the runoff [see Eqs. (5) and (6)]. As can be seen from Fig. 3, where the summary of the annual-mean analysis is presented, the CRCM_V3.6 moisture flux convergence \(C_{CRCM\text{V3.6}} = 0.28 \text{ mm day}^{-1}\) does not exactly balance the simulated \((P - E)\) \(P_{CRCM\text{V3.6}} - E_{CRCM\text{V3.6}} = 0.39 \text{ mm day}^{-1}\) and runoff \(R_{CRCM\text{V3.6}} = 0.39 \text{ mm day}^{-1}\), that is, the model hydrological cycle is closed with an error of about 0.1 mm day\(^{-1}\). Because the moisture flux convergence is calculated within the model using all levels and time steps, a fair part of this error in the atmospheric budget is related to the semi-Lagrangian numerical scheme, which induces a slight nonconservation of the prognostic variables (Paquin and Laprise 2003).

Comparing the moisture flux convergence calculated from the NCEP/NCAR reanalysis \(C_{NCEP} = 0.50 \text{ mm day}^{-1}\) to the naturalized runoff \(R_{\text{NAT}} = 0.66 \text{ mm day}^{-1}\), an error in the closure of the quasi-observed water budget of \(\epsilon_{\text{QOBS}} = 0.16 \text{ mm day}^{-1}\) is also seen in our analysis. This lack of balance could be related to inaccuracies in the atmospheric moisture flux convergence calculated from NCEP–NCAR reanalysis data, or in the runoff data, and gives an approximation of the error bars on our observations. The coarse horizontal and vertical resolutions and the time sampling for calculating the fluxes of NCEP–NCAR reanalysis as well as NCEP model physics can introduce errors in atmospheric moisture and wind vertical profiles. As well, the estimation of water management effects can introduce errors to the naturalized runoff value. In addition, the streamflow measurements at the outlet of streams are an imperfect measure of complete runoff. An evaluation of the uncertainties in the moisture flux convergence calculated from the reanalysis data could be undertaken by comparing the NCEP–NCAR convergence to those calculated from ERA-40. The difference between annually averaged moisture flux convergences from the ERA-40 and NCEP–NCAR reanalyses for the Mississippi River basin is 0.2 mm day\(^{-1}\). The ERA-40 moisture flux convergence \(C_{\text{ERA40}} = 0.70 \text{ mm day}^{-1}\) balances much better than the naturalized runoff, while the NCEP–NCAR convergence is closer to the observed runoff, derived from streamflow observations at Vicksburg \(R_{\text{OBS}} = 0.57 \text{ mm day}^{-1}\).

Mean annual precipitation over the basin simulated by the CRCM is compared to precipitation observed from three observation datasets (CRU2, GPCP, and CCR). The uncertainty of observed precipitation, which is annually averaged over the basin, is much smaller than the uncertainty associated with the reanalysis moisture convergence; the maximum difference between precipitation datasets is 0.08 mm day\(^{-1}\) (see Fig. 3).

The CRCM_V3.6 annual mean precipitation \(P_{\text{CRCM\text{V3.6}}} = 2.63 \text{ mm day}^{-1}\) is higher than observed by about 0.4 mm day\(^{-1}\) (+17%). The comparison of the CRCM_V3.6 simulated evapotranspiration \(E_{\text{CRCM\text{V3.6}}} = 2.24 \text{ mm day}^{-1}\) to quasi-observed evapotranspiration \(E_{\text{QOBS}} = 1.58 \text{ mm day}^{-1}\) indicates a positive bias in the model of about 0.7 mm day\(^{-1}\) (+42%). Since the quasi-observed evapotranspiration is estimated from the multiyear observed precipitation (average of three datasets) and from the naturalized runoff [see Eq. (7)], it should be relatively realistic. The simulated annual mean runoff \(R_{\text{CRCM\text{V3.6}}} = 0.39 \text{ mm day}^{-1}\) is smaller than the naturalized runoff by about 0.3 mm day\(^{-1}\) (41%). This discrepancy is related to the excess in evapotranspiration bias with respect to the precipitation bias. When the simulated atmospheric moisture flux convergence \(C_{\text{CRCM\text{V3.6}}} = 0.28 \text{ mm day}^{-1}\) is compared to the NCEP–NCAR and ERA-40 convergences, the model biases of -0.2 (-44%) and -0.4 mm day\(^{-1}\) (-60%) are obtained.

The results presented above show that the hydrological cycle over the Mississippi River basin as simulated by the CRCM_V3.6 basin is characterized by a relatively large deficit of moisture convergence and by ex-
cess evapotranspiration. Hence, the simulated moisture convergence cannot be the cause of the excess of the mean annual precipitation over the basin. Therefore, the excessive evapotranspiration could be a major source of the error in the precipitation.

The CRCM_V3.6 evapotranspiration is conditioned by its simple single-layer surface scheme. The prescribed soil water-holding capacity in this model version seems to be very large (average value over the basin is 528 kg m$^{-2}$). The soil water-holding capacity is an important parameter affecting evapotranspiration: a too-small water-holding capacity will favor more runoff (the soil rapidly reaching its saturated value), thus reducing the water available for evaporation; a too-large value allows for a larger fraction of precipitation to be stored and later released for evaporation, therefore reducing the runoff. As such, the large CRCM_V3.6 water-holding capacity can be linked to the excessive evapotranspiration and inadequate runoff. An additional reason for the excessive evapotranspiration rate is the lack of vegetation stomatal resistance, which could reduce the evapotranspiration considerably.

b. Analysis of the CRCM_V3.6 simulation: Annual cycle of water budget components

Figure 4 presents the mean annual cycles for all components of the monthly averaged atmospheric water budget equations [Eqs. (8) and (9)]. In Fig. 4a, the observed and simulated annual cycles of precipitation are compared. Since the uncertainty of observed monthly mean precipitation is small, we can safely take average of our three precipitation datasets to represent observed precipitation over the basin. The CRCM_V3.6 slightly underestimates observed precipitation during November to March but largely overestimates it during summertime. The positive precipitation bias (BIAS_P) of the CRCM_V3.6 on the annual time scale is therefore caused mainly by an extensive overestimation of the precipitation from June to August.

The simulated annual cycles of evapotranspiration are compared to the quasi-observed values in Fig. 4b. The monthly mean of quasi-observed evapotranspirations are derived as a residual from the atmospheric water budget using mean observed precipitation and NCEP–NCAR (ERA-40) moisture convergences and precipitable water tendencies [see Eq. (10)]. An estimation of the uncertainty in the quasi-observed evapotranspiration derived from the atmospheric water budget could be obtained by comparing its annual mean to the one derived from the land water budget using Eq. (7). The annual mean evapotranspiration derived from the atmospheric water budget using NCEP–NCAR (ERA-40) data is higher (smaller) by 0.2 mm day$^{-1}$ (0.02 mm day$^{-1}$) than residual evapotranspiration derived from the terrestrial water budget. The major differences in the quasi-observed evapotranspiration derived from the atmospheric water budget appear during spring (see Fig. 4b).

The CRCM_V3.6 evapotranspiration is larger than both quasi-observed evapotranspirations throughout the year. The positive evapotranspiration bias (BIAS_E) increases during spring and reaches its maximum in June, which is related to the warm air temperature and large soil moisture available for evapotranspiration during this period of the year.

The NCEP–NCAR, ERA-40 and CRCM_V3.6 annual cycles of the atmospheric moisture flux convergence are compared in Fig. 4c. The NCEP–NCAR...
shows atmospheric moisture flux convergence during October to May, reaching a maximum in January, and moisture flux divergence during June to September, with a maximum in July. As discussed by Roads et al. (2002), the large summertime divergence seen in the reanalysis is disconcerting since it occurs at a time when the low-level jet is usually active and thought to be a strong contributor to moisture convergence in the region. However, ERA–40 also shows a moisture flux divergence in summer, which is even slightly higher than that of NCEP–NCAR. On the other hand, NCEP–NCAR moisture flux convergence from October to May is smaller than the ERA–40. The most significant difference between the two reanalyses appears during March to May, reaching a maximum of 0.54 mm day$^{-1}$ in May. Despite this uncertainty, it can be seen that the increasing observed precipitation during spring over the Mississippi River basin is related only to the increasing evapotranspiration because moisture flux convergence derived from NCEP–NCAR (ERA–40) slightly decreases (remains similar) from March to May.

Similar to the reanalyses, the CRCM_V3.6 shows atmospheric moisture flux divergence over the Mississippi River basin during the summer and at the beginning of the fall, and a moisture flux convergence during the rest of the year. However, the simulated annual cycle amplitude is smaller compared to those from the reanalyses: while the moisture flux divergences from the reanalyses are strong during July to August and drop in September, the CRCM_V3.6 moisture divergence keeps a similar magnitude from July to September. In addition, the simulated atmospheric moisture convergence, which appears over the basin in October and lasts until May, is smaller than those from the reanalyses.

The quasi-observed monthly tendencies of the atmospheric water storage (Fig. 4d) are relatively small and CRCM_V3.6 captures them well.

To better understand the model behavior, we compared the CRCM_V3.6 simulation biases of the atmospheric water budget components to each other in Fig. 5a. Since precipitation removes moisture from the atmosphere and evapotranspiration represents a source of atmospheric humidity, the negative difference between BIAS_P and BIAS_E from September to May
could generate a positive bias of simulated atmospheric specific humidity, which in turn could be compensated by the decreasing moisture flux convergence over the basin. It is interesting to note that the underestimation of the moisture flux divergence (with respect to the one computed from NCEP–NCAR and ERA-40), from July to August, is linked to the excess in precipitation bias with respect to the evapotranspiration bias. The error in closure of the simulated atmospheric water budget is also shown in Fig. 5a and has a maximum value in summer.

Figures 6 and 7 present mean annual cycles of the terrestrial water budget components and corresponding CRCM biases. The naturalized, the observed, and the CRCM_V3.6 runoff are compared in Fig. 6a: runoff is underestimated by the model, throughout the year, particularly in the first three months, when the negative bias reaches 0.4 mm day$^{-1}$. There are two sources of runoff underestimation by this model version. The first is related to the deficiencies in the “bucket” surface scheme: runoff is generated only when soil moisture content exceeds the prescribed water-holding capacity, which is too large. The second one is related to the biases of simulated precipitation and evapotranspiration. The negative bias in the difference between precipitation and evapotranspiration, that is, the underestimation of the (P – E) term [simulated and quasi-observed (P – E) are compared in Fig. 6b], which moistens the soil during September to May, contributes to the runoff underestimation by the model.
The annual cycle of the CRCM terrestrial water storage tendency and the quasi-observed one [derived from naturalized runoff and moisture convergences and precipitable water tendencies of the reanalyses; see Eq. (11)] are compared in Fig. 6c. It should be emphasized that the quasi-observed monthly tendencies of the terrestrial water storage are not free from errors. Rough error estimation by calculating quasi-observed annual mean tendency gives \(-0.2 \text{ mm day}^{-1}\) (with NCEP–NCAR moisture flux convergence) and \(0.08 \text{ mm day}^{-1}\) (with ERA-40 moisture flux convergence). These errors are linked to the error in the closure of quasi-observed water balance. Unfortunately, the seasonal error distribution in water balance estimates is unknown.

The terrestrial water tendencies simulated by the CRCM_V3.6 are relatively close to the quasi observed, except during summer, when the evapotranspiration exceeds precipitation and hence the soil dries. In summer, the positive bias in precipitation exceeds bias in evapotranspiration, which is consistent with the summer soil drying underestimation. In addition, the negative runoff bias contributes to the summer soil drying underestimation.

c. Analysis of the CRCM_V4.0 simulation: Annual mean of water budget components

The changes in the physical parameterization between model versions 3.6 and 4.0, described in section 3a, result in a significant decrease of 0.50 mm day\(^{-1}\) in the annual mean evapotranspiration over the Mississippi River basin. As can be seen in Fig. 3, the annual mean of simulated evapotranspiration by the updated model version \(E_{\text{CRCM,V4.0}} = 1.74 \text{ mm day}^{-1}\) is closer to the quasi observed. Implementation of CLASS in the CRCM provides a more realistic parameterization of the evapotranspiration including the stomatal resistance effect in its vegetation. This resistance restricts transpiration of water extracted from the soil by vegetation roots. Modifications of the radiative scheme and treatment of the cloud cover result in an increased atmospheric absorption of the incoming solar radiation and an increased planetary albedo. As a consequence, the net radiative energy at the surface \(R_{\text{net}}\), which is

![Fig. 7. The CRCM biases of the terrestrial hydrological cycle branch: (a) CRCM V3.6 simulation, and (b) CRCM V4.0 simulation.](image-url)
mainly partitioned between latent and sensible heat fluxes, is decreased. This can be seen in Fig. 8, which also shows how $R_{\text{net}}$ is partitioned between latent and sensible heat in both model versions: latent heat of the CRCM V 4.0 is smaller than the one from the CRCM V3.6, while the sensible heat is larger.

The only other water budget component that has changed significantly is the annual mean precipitation: the decrease of the annual mean evapotranspiration of 0.50 mm day$^{-1}$ over the basin is associated with a decrease of annual mean precipitation of 0.47 mm day$^{-1}$. Simulated precipitation is now much closer to the observed: precipitation bias is reduced from 0.4 to $-0.1$ mm day$^{-1}$. Changes in the annual mean moisture flux convergence and runoff are smaller than the error in closure of the annual mean water budget of the CRCM 3.6 (0.1 mm day$^{-1}$). The annual mean of the CRCM_V4.0 moisture flux convergence ($C_{\text{CRCM_V4.0}} = 0.36$ mm day$^{-1}$) exactly balances the difference between precipitation and evapotranspiration $[(P - E)_{\text{CRCM_V4.0}} = 0.36$ mm day$^{-1}]$ as well as runoff ($R_{\text{CRCM_V4.0}} = 0.36$ mm day$^{-1}$). Elimination of the water budget closure error is provided by introducing a small correction to the specific humidity values at each grid point (see section 3a).

d. Analysis of the CRCM V4.0 simulation: Annual cycle of water budget components

Figure 5b shows the CRCM V4.0 biases of the monthly averaged atmospheric water budget components. These biases are noticeably smaller compared to those of CRCM V3.6. Although the simulated annual cycle of precipitation by the updated model version matches the observed precipitation better, it is now underestimated throughout most of the year (July to March), especially from July to October. The negative bias in precipitation is mainly related to the underestimation of evapotranspiration (see also Fig. 4).

As discussed in the previous section, the significant change in the simulated annual mean evapotranspiration does not noticeably affect the annual mean simulated moisture flux convergence, the change being smaller than the error in closure of the CRCM V3.6 annual water budget. However, in Fig. 9 (where the difference between the atmospheric water budget components of the CRCM V4.0 and CRCM V3.6 is shown) it can be seen that the moisture flux convergence (as well as precipitation) actually responds to the evapotranspiration change: a decrease of the evapotranspiration is associated with an increase in the moisture flux convergence from September to May. Despite this change, the moisture flux convergence over this period remains smaller than those from the reanalyses. Summer moisture flux divergence from the CRCM V4.0 is larger than the one from CRCM V3.6 and matches those of the reanalyses better. The bias in the precipitation is now almost equal to the bias in evapotranspiration because of the larger decrease in precipitation than in evapotranspiration. Such a large decrease in summer precipitation is related to the combined effects of the evapotranspiration reduction and stronger mixing in the CRCM V4.0 boundary layer water vapor.

The new vertical diffusion scheme distributes the water vapor on more levels within the boundary layer and therefore avoids the excessive accumulation of moisture in the near-surface boundary layer. Jiao and Caya (2006) demonstrated how the accumulation of moisture in the lower boundary layers with the old scheme provides favorable conditions for triggering the convection. The new vertical diffusion scheme implemented in CRCM V4.0 together with the reduced evapotranspiration result in less favorable conditions for convection, therefore reducing condensation and precipitation.

Figure 7b shows the CRCM V4.0 biases of the monthly averaged terrestrial water budget components. Despite some improvement in the simulated annual cycle of the moisture storage tendency as well as the $(P - E)$ term (see also Fig. 6), the CRCM V4.0 runoff remains underestimated throughout most of the year. The negative runoff bias (BIAS_R) of the CRCM V4.0 is even larger than the one of the CRCM V3.6, from May to December.

e. Spatial distribution: Validation of the CRCM V3.6 simulated fields

In the previous sections, the hydrological cycle components averaged in time (1988–97) and in space (over the entire Mississippi River basin) have been discussed.
The spatial distribution of precipitation, runoff, and evapotranspiration over the basin is now investigated when averaged over the same period.

The precipitation fields simulated by the CRCM are compared to those of CRU, CCR, and GPCP in Fig. 10. There is generally good agreement between the observed precipitation patterns: precipitation is largest at the mouth of the basin and decreases northwestward. Note that CRU and CCR precipitation fields are better spatially correlated to each other than with GPCP. Both CRU and CCR datasets have not been corrected for gauge biases by undercatch of solid precipitation. The GPCP precipitation dataset is a merged product of the surface gauge, low-orbit microwave, and geosynchronous infrared measurements.

The CRCM_V3.6 precipitation, which is largely influenced by the abundant summertime precipitation, does not reproduce the observed dry area west of the basin. Precipitation is overestimated almost everywhere over the basin with the exception of the southern part of the basin where it is underestimated.

As discussed in section 4b, a relatively good estimate of the spatial distribution of the Mississippi runoff can be obtained from the VIC model, which is tuned to reproduce the observed Mississippi runoff. Therefore, the VIC monthly data series provided by Maurer et al. (2002) are used to calculate a runoff field representative of the 1988–97 period. Additional information on the spatial distribution of the Mississippi runoff based on observations can be obtained from the GRDC gridded composite runoff dataset. It should be kept in mind that the GRDC dataset is climatology from the mid-1960s to the mid-1980s, which does not match the 1988–97 period analyzed in our study. In Fig. 11, the two runoff fields are used to validate runoff simulated by the CRCM. As can be seen, runoff is largely underestimated by the CRCM_V3.6 in the southeast part of the basin and overestimated in the mountainous region to the west.

Figure 12 shows the simulated evapotranspiration fields together with two quasi-observed fields. The first is derived as the difference between averaged precipitation (average of all three datasets) and the VIC runoff, while the second is the difference between averaged precipitation and the GRDC runoff. Despite some discrepancies between the two quasi-observed fields, which are more apparent in the southeast region of the basin, they provide useful information on the evapotranspiration pattern over the Mississippi River basin. Similar to the observed precipitation, the northwest–southeast gradient in the quasi-observed evapotranspiration fields is simulated, but it is weaker. The simulated evapotranspiration by the CRCM_V3.6 is overestimated throughout the basin except at its mouth, which is consistent with the precipitation overestimation.

f. Spatial distribution: Validation of the CRCM_V4.0 simulated fields

As can be seen in Fig. 10, the CRCM_V4.0 shows a noticeable improvement in the simulated precipitation
pattern. Although slightly weaker, the northwest–southeast gradient is well captured by CRCM_V4.0. However, the precipitation is still underestimated in the southeast basin region and overestimated in the mountainous region to the northwest. Some improvement is obtained also in the spatial distribution of the simulated evapotranspiration over the basin (see Fig. 12). However, the simulated runoff by the updated model version (see Fig. 11) is relatively similar to the runoff simulated by the CRCM_V3.6, despite the important changes in the simulated evapotranspiration and precipitation.

6. Summary and conclusions

Current inability of climate models to adequately simulate many of the complex multiscale processes involved in the water cycle is a major source of uncertainty in long-term climate projection. Model evaluation and development are therefore crucial for improvement of the reliability of climate projection. Once models are capable of successfully simulating present water cycle behavior, they can more accurately assess potential change due to changes in greenhouse gas concentration in the atmosphere. Various studies performed with different climate models have demonstrated better agreement of simulated and observed hydrological variables when more realistic physical parameterizations are used (e.g., Viterbo and Beljaars 1995; Beljaars et al. 1996; Ducharne et al. 2000; Ek et al. 2003; Hagemann et al. 2004; GFDL Global Atmospheric Model Development Team 2004; Hagemann et al. 2006). The incentive to create a model that real-
isticallly represents many of the complex subgrid-scale processes involved in the water cycle has to comply with the need to have a computationally fast enough model so that an ensemble of multiyear integrations can be performed. The optimal level of complexity in physical parameterizations designed for use in climate models is still an unresolved issue. The only way to address this question is evaluation of simulated water cycle by comparison with observations wherever possible. The high complexity of the multiscale processes involved in the hydrological cycle and their associated feedbacks as well as scarcity of observations for some water cycle components contribute to the problem of assessing simulated hydrological cycle over a given region. Usually, for regional-scale studies, only simulated precipitation and runoff are evaluated.

In this paper, a comprehensive validation of all water budget components over the Mississippi River basin as simulated by the Canadian Regional Climate Model (CRCM) has been performed. In addition, the sensitivity of a simulated hydrological cycle to a more realistic representation of the land surface processes, as well as radiation, cloud cover, and atmospheric boundary layer mixing, is investigated. Two simulations using different model versions (CRCM_V3.6 and CRCM_V4.0) were analyzed and compared with the corresponding values derived from observations or quasi observations. The analysis was first performed for the annual means where the contributions of water budget components were integrated in space over the entire basin, and in time over the 1988–97 period. The analysis has shown an error in closure of the CRCM_V3.6 simulated water budget: the simulated annual mean atmospheric moisture flux convergence does not balance the simulated runoff exactly. Since the moisture flux convergence is calculated within the model using all levels and time steps, a fair part of this error in the atmospheric budget is related to the semi-Lagrangian numerical scheme, which induces a slight nonconservation of the prognostic variables (Paquin and Laprise 2003).

Comparing the annual mean observed to the simulated precipitation over the Mississippi River basin, a large positive bias is found in the CRCM_V3.6. It is thought that the positive precipitation bias is mainly caused by an overestimation of the annual mean evapotranspiration. The CRCM_V3.6 has a single-layer Manabe-based land surface scheme, which cannot adequately represent many of the effects of vegetative control on evapotranspiration. The prescribed water-holding capacity appears to be too high and results in an excessive evapotranspiration. On the other hand, the annual means of the runoff and atmospheric moisture flux convergence are underestimated, which is linked to
the excess in evapotranspiration bias with respect to the precipitation bias.

Implementation of the Canadian Land Surface Scheme (CLASS) in the CRCM_V4.0 as well as changes to the radiation, cloud cover, and boundary layer mixing treatments have resulted in significant improvements to the simulated annual mean evapotranspiration over the basin. As a consequence, the annual mean bias of the CRCM_V4.0 precipitation is strongly reduced. The simulated annual mean of the atmospheric moisture flux convergence is slightly increased and now exactly balances annual mean runoff. Elimination of the water budget closure error is obtained by introducing a small correction to the specific humidity values at each grid point, which takes into account the inaccuracy related to the semi-Lagrangian numerical scheme.

The annual cycle analysis shows that the annual positive precipitation bias of the CRCM_V3.6 is caused mainly by an excessive overestimation of the precipitation during summer. Such a large positive precipitation bias is related to the combined effects of an excessive summer evapotranspiration and inadequate moisture distribution in the CRCM_V3.6 lower boundary layer. Similarly to the NCEP–NCAR and ERA-40 reanalyses, the CRCM_V3.6 shows a moisture flux convergence (divergence) over the Mississippi River basin from October to May (in summer), but the model underestimates this. The CRCM_V3.6 underestimates runoff throughout the year and underestimates soil drying in summer. As well, the absolute value of the difference between precipitation and evapotranspiration, \(|P - E|\), is underestimated by the CRCM_V3.6 throughout the year. This is consistent with the underestimation of summer soil drying and summer moisture flux divergence: the \((P - E)\) term dries the soil in summer but moistens the atmosphere, because during this time evapotranspiration exceeds precipitation. Similarly, the negative bias in the difference between precipitation and evapotranspiration is linked to the underestimation of the atmospheric moisture flux convergence and runoff from September to May when the \((P - E)\) term dries the atmosphere and moistens the soil.

The comparison of the annual cycles of the water budget components simulated by the CRCM_V3.6 and CRCM_V4.0 has demonstrated that the atmospheric moisture flux convergence (as well as precipitation) responds to changes in the evapotranspiration. A decrease in the evapotranspiration is associated with an increase in the atmospheric moisture flux convergence from September to May. Inversely, precipitation is decreased throughout most of the year. In summer, the decrease in precipitation is larger than the decrease in

![Image](image_url)
evapotranspiration because of the combined effect of the evapotranspiration reduction and stronger mixing of the water vapor in the CRCM_V4.0 boundary layer, which means less favorable conditions for triggering convection. As a consequence, summer moisture flux divergence is increased and matches those of reanalyses more accurately.

Analysis of the spatial distribution has shown that the CRCM_V4.0 captures observed precipitation patterns better than the CRCM_V3.6. As well, some improvement is obtained in simulated spatial distribution of evapotranspiration. However, the simulated runoff in the updated model version is relatively similar to the runoff simulated by the CRCM_V3.6, despite the important changes in the simulated evapotranspiration and precipitation.

In summary, implementation of a four-band instead of the two-band radiation scheme in the CRCM and an improved treatment of cloud cover results in diminution of the net radiation at the surface and therefore in decreased latent and sensible heat fluxes. Replacing the Manabe-based parameterization with a state-of-the-art land surface scheme, which provides more realistic land surface processes by taking into account stomatal resistance of vegetation, results in an important reduction of simulated evapotranspiration. Finally, stronger mixing of the water vapor in the new boundary layer scheme results in less favorable conditions for convection, therefore reducing condensation and precipitation. The overall effect of the changes to the physical parameterization of the CRCM is an improved annual cycle (and annual mean) of simulated precipitation, evapotranspiration, moisture flux convergence, and terrestrial water storage tendency. Despite these improvements, simulated runoff remains underestimated throughout the year (except for March).

In a continuing effort to improve parameterization of subgrid processes in the CRCM, work is underway to improve runoff generation and water transfer in soil.

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