New Approaches to Hydrological Prediction in Data-sparse Regions (Proc. of Symposium HS.2 at the Joint IAHS & IAH Convention, Hyderabad, India, September 2009). IAHS Publ. 333, 2009.

Runoff modelling within the Canadian Regional Climate Model (CRCM): analysis over the Quebec/Labrador watersheds

BILJANA MUSIC[1], ANNE FRIGON[1], MICHEL SLIVITZKY[1], ANDRE MUSY[1], DANIEL CAYA[1] & RENÉ ROY[2,1]

1 *Ouranos, Consortium sur la climatologie régionale et l'adaptation aux changements climatiques, 550 Sherbrooke Street West, 19th Floor, Montréal, Québec H3A 1B9, Canada*
music.biljana@ouranos.ca

2 *Hydro-Québec (IREQ), 1800 montée L. Boulet, Varennes, Québec J3X 1S1, Canada*

Abstract This study focuses on evaluation of the hydrological performance of the Canadian Regional Climate Model (CRCM) coupled to the Canadian Land Surface Scheme (CLASS). The CRCM's ability to adequately simulate annual mean runoff over 21 small watersheds in the Quebec/Labrador peninsula is assessed over the period 1961–1999. Since runoff is a spatial and temporal integrator of weather events, it represents a very useful variable for climate model validation, especially in areas where conventional surface weather observations are scarce. In addition, the sensitivity of simulated runoff to domain size and lateral boundary conditions is investigated. Results of the analysis indicate that CRCM tends to systematically underestimate observed annual mean runoff over most of the investigated watersheds. It was found that choice of simulation domain has a considerable effect on the simulated hydrological regime at the watershed scale. Different re-analyses used as driving data have less influence than domain size. However it may be important (larger than CRCM's internal variability) when simulations are performed over a relatively small domain.

Key words runoff; watershed; land-surface processes; internal variability; Canadian RCM; CLASS

INTRODUCTION

Regional Climate Models (RCMs), now widely used for providing regional climate projections at relatively high spatial resolution (10–50 km), may reproduce many complex processes involved in the hydrological cycle. They can therefore be powerful tools for generating quantitative information of runoff in data-sparse regions, where application of traditional hydrological models (HMs) is limited. In contrast to the traditional HMs, which are usually calibrated by jointly optimizing the numerous parameters in order to achieve specific objectives, the RCMs are designed to be run over any region of the globe without parameter calibration. The RCM parameters should therefore be physically relevant. An important problem stemming from this is that land-surface and ground characteristics, described within the RCM land-surface scheme (LSS), may be quite heterogeneous, while the climate simulation usually assigns a single value within each grid cell. This could be partly addressed, either by using a subgrid mosaic approach or by reducing grid cell size, but both of those measures lead to an increase in computational requirements.

Another important characteristic and advantage of RCMs is the fact that they are based on an energy and water balance concept. Conservation of water and energy allows an internal consistency of simulated hydrological cycle components. However, most of the LSSs designed for use in RCMs do not adequately address many aspects of land-surface and groundwater processes. In addition, the complex and nonlinear nature of hydrological processes and associated feedbacks limit their ability to accurately reproduce observed regional hydrological regimes. Furthermore, RCMs simulate climate only over a specific area of interest and, hence, require nesting information at their lateral boundaries. Thus, the hydrological performance of an RCM depends not only on the skill of the RCM itself, but also on the quality of nesting meteorological variables. The RCM can be nested within a global re-analysis of atmospheric observations for present climate simulations, or within a general circulation model (GCM), for present and future climate simulations.

The Canadian Regional Climate Model (CRCM) developed at UQAM/Ouranos is one of the most sophisticated state-of-the-art RCMs based on high-performance numerical integration techniques (Laprise *et al*., 1998; Caya & Laprise, 1999). The CRCM horizontal grid is uniform in a polar stereographic projection, presently used operationally at a 45-km grid mesh. This spatial resolution is much higher than the resolution of a typical GCM (usually in the order of 200 km) and allows a relatively good representation of land-surface forcing, which has an important effect on the regulation of hydrological regimes at regional scale. Recently, a set of more realistic physical parameterizations was implemented into the CRCM. It includes changes to the radiative scheme, treatment of cloud cover, atmospheric boundary mixing scheme and land-surface parameterization scheme. For more details related to these modifications, the reader is referred to Music & Caya (2007, 2009). The authors have investigated their effects on both atmospheric and terrestrial water cycle components over three large North-American river basins: the Mississippi, the Mackenzie and the St Lawrence basins, whose drainage areas are about 2 868 900, 1 680 000 and 774 000 km^2, respectively. It was found that most of the water cycle components simulated by the updated model version (referred to as CRCM_V4.0.0) are in better agreement with observations. Noticeable improvement was obtained in simulated annual cycles of precipitation, evapotranspiration, moisture flux convergence, and terrestrial water storage tendency. However, simulated runoff was less sensitive to the changes in the CRCM physical parameterization.

In this study, runoff simulated by the CRCM_V4.2.0 over 21 small watersheds in the Quebec/Labrador peninsula is analysed and compared with available observations. In addition, the sensitivity of simulated runoff to domain size and driving data is investigated. The CRCM_V4.2.0 actually includes the same physical parameterizations package as CRCM_V4.0.0, with some minor coding error corrections mainly related to the LSS. The Canadian Land Surface Scheme (CLASS, Verseghy, 1991; Verseghy *et al*., 1993) is used to describe land-surface–atmosphere interaction. An integrated analysis of the CRCM_V4.0.0 hydrological performance over the Québec/Labrador region has already been conducted by Frigon *et al*. (2007a,b). Their analysis was focused on water budget components averaged over a ten-river basin subset covering a relatively large area (406 000 km^2). Since there is an increasing demand from water resource management authorities for quantitative information of hydrological cycle components at the smaller scale, an evaluation of the CRCM hydrological performance at the scale of small watersheds is of great interest. Drainage areas of watersheds considered in this study range from 13 000 to 177 000 km^2. It should be mentioned that some of these watersheds, such as Churchill Falls and La Grande, are very important to Quebec's hydropower industry.

OVERVIEW OF THE CANADIAN LAND SURFACE SCHEME IN THE CRCM

Runoff is a variable produced by a LSS, which is an important component of any climate model. The importance of land-surface processes formulation on climate simulated by a GCM has been commonly recognized in the 1980s. Since then, land surface parameterizations have evolved from a quite simple first generation LSS (based on Manabe, 1969) to very sophisticated second and third generation schemes. Most of these so-called "state-of-the-art" LSS involve very sophisticated explicit formulation of canopy processes and allow vegetation to determine the way in which the land surface interacts with the atmosphere (e.g. Dickinson 1984; Sellers *et al*., 1986, 1996; Verseghy, 1991; Verseghy *et al*., 1993; Dickinson *et al*., 1998). Some authors described canopy processes in a rather simple way, but paid more attention to effects of subgrid-scale soil moisture variability on surface and subsurface runoff generation (e.g. Entekhabi & Eagleson, 1989; Wood *et al*., 1992; Hageman & Gates, 2003). The main objective of any LSS designed for use in a climate model is to supply accurate water, energy and momentum fluxes across the land-surface–atmosphere interface. One of the main challenges is an adequate partitioning of precipitation into surface runoff and evapotranspiration.

Among the wide spectrum of land-surface parameterizations designed for climate models, a rational choice for CRCM is the Canadian Land Surface Scheme (CLASS; Verseghy, 1991; Verseghy *et al*., 1993). This scheme is also implemented in the third generation of the Canadian Climate Centre for Climate Modelling and Analysis (CCCma) Coupled Global Climate Model (CGCM3, Scinocca *et al*., 2008; Flato & Boer, 2001), which participated in the IPCC (2007) global warming projections. The version 2.7 of CLASS implemented in the CRCM_V4.0 and later (CLASS V2.7) is a second generation LSS and hence involves conventional surface water and energy balance calculations. Carbon budget calculation is not included. At every time step, CLASS receives the following information from the atmospheric model: the precipitation rate, the incoming short-wave and long-wave radiative fluxes, air temperature, humidity and wind speed. Each land surface grid cell can have up to four sub-areas: bare soil, vegetation-covered soil, snow-covered soil, and soil covered by both vegetation and snow. There are four vegetation types in CLASS: coniferous trees, deciduous trees, crops, and grass. Snow in CLASS is modelled as a separate layer for both thermal and hydrological processes. The moisture and energy budgets are calculated separately for each land-surface sub-area, then the surface fluxes are averaged over the grid cell and passed back to the atmospheric model.

Water and energy fluxes at the land surface, and therefore runoff generation, are closely linked to the amount of available soil moisture. Soil in CLASS is divided into three horizontal layers: 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 are prognostic variables and evolve following moisture fluxes at the top and bottom of each layer. The classic Darcy theory of drainage and capillary rise is used to evaluate fluxes between the soil layers. Infiltration into the upper soil layer is calculated following the Mein & Larson (1973) method. Total runoff in CLASS is composed of surface runoff and water drainage from the deep soil column (subsurface runoff). Surface runoff is generated if the surface infiltration capacity is exceeded, then water is allowed to pond on the surface up to the surface retention capacity. The overflow of the surface retention capacity is assumed to be surface runoff. The subsurface runoff is calculated as $Q_d = k_{sat}(w_d w_{sat}^{-1})^{2b+3}$, 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, k_{sat} is the saturation hydraulic conductivity, and b is soil texture parameter. The surface retention capacity varies with land cover type, while the hydraulic properties of the soil layers as well as the parameters b, w_{sat}, and k_{sat} depend on soil texture. The Webb *et al.* (1993) global data set is used to derive each soil layer texture and the overall depth to bedrock, while the land cover data are obtained from Bartholomé & Belward (2005).

EXPERIMENTAL SET-UP, OBSERVATION DATA SET AND ANALYSIS METHOD

As mentioned in the previous section, the simulations used in the present investigation were generated using the CRCM_V4.2.0. The experimental design is summarized in Table 1. All simulations were performed over the period 1 January 1958–31 December 1999 with a 45-km horizontal resolution using 29 unequally-spaced vertical levels. Most of the vertical levels are assigned within the lower troposphere, thus allowing better representation of the land-surface–atmosphere interaction. The simulations were driven either by the National Center for Environmental Prediction–National Center for Atmospheric global atmospheric re-analysis (hereafter referred to as NRA; Kalnay *et al*., 1996) or the 40-year European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA40; Uppala *et al*., 2005), both at a 2.5° × 2.5° resolution. Two simulations were performed over a large domain covering North America (AMNO; 201 × 193 grid points) and are referred to as AMNO_ERA and AMNO_NRA. The other two (QC_ERA and QC_NRA) were generated over a smaller domain centred over Québec (QC; 112 × 88 grid points).

Figure 1 shows both the AMNO and QC domain of integration. It is important to mention that the large-scale (wavelength greater than 1400 km) horizontal wind and temperature fields from the CRCM are weakly nudged (Riette & Caya, 2002) toward the large-scale fields of the driving data. Boundary conditions over the ocean and the Great Lakes grid points (sea-surface temperature and sea-ice amount) were taken from the Atmospheric Model Intercomparison Project II (AMIP II) observation data set (Fiorino, 1997).

As runoff is a variable that is not directly observed, an appropriate estimation of total runoff over a river basin is required for model validation. As discussed by Roads *et al.* (2003), flow discharge, which is routinely measured at many streamgauge stations, can be considered as runoff lagged and routed through a basin channel network. Total runoff of a basin of

Table 1 Experimental configuration of the CRCM_V4.2.0 simulations.

Name	Domain	Driving data	Period
AMNO_ERA	AMNO	ERA40	1 Jan 1958–31 Dec 1999
QC_ERA	QC	ERA40	1 Jan 1958–31 Dec 1999
AMNO_NRA	AMNO	NRA	1 Jan 1958–31 Dec 1999
QC_NRA	QC	NRA	1 Jan 1958–31 Dec 1999

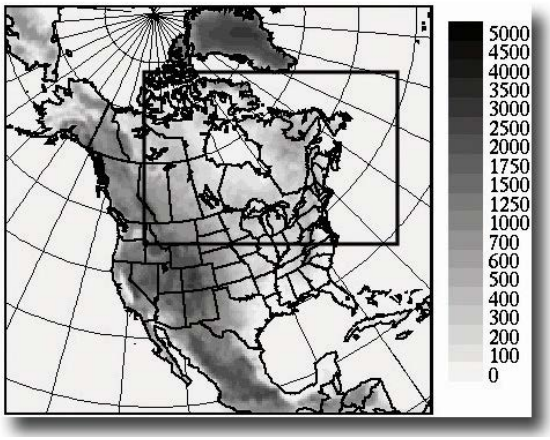

Fig. 1 The large AMNO and the smaller QC domains used in CRCM simulations. Topography is shown in colour shades (in metres).

any size can therefore be estimated from streamflow discharge data by dividing observed streamflow at a basin outlet with the drainage area. However, not all runoff leaves a river basin through the surface river network (Roads *et al.*, 2003). Moreover, water management activity may greatly affect streamflow observations. An appropriate correction for the effect of upstream water storage and diversion is therefore required for some river basins to obtain an estimation of so-called naturalized (water management effects removed) basin mean runoff, which is preferred for model validation. For this study, monthly series of observed or naturalized (for several man-affected basins) streamflow data over the period 1961–1999 for 21 rivers in the northern Québec/Labrador peninsula were obtained from three different sources: Hydro-Québec (HQ), Hydrometric Service of the Québec Ministry of Environment (HSQME) and Alcan Inc. Table 2 indicates drainage areas and streamflow data sources, as well as the number of the CRCM grid points and the length of observation time series for each of the investigated watersheds.

Geographical positions and outlines of the watersheds are displayed in Fig. 2(a). The Quebec/Labrador peninsula sits mostly on the Canadian Shield, which is covered by a thin layer of soil. The northernmost watersheds located in the subarctic and tundra shields are covered with numerous rock outcrops, with discontinuous and some sporadic permafrost, and sparse coniferous vegetation. The southern watersheds located in the boreal shield are covered in the northern part with needle-leaf evergreen forest and a mix of coniferous and broad-leaved trees in the southern-most part. Maximum altitude in the peninsula of 1015 m is observed in the Reservoir Manic5 watershed. A distinguishing feature of the Quebec/Labrador territory is its numerous lakes, which cover from 5% to 30% of watershed areas. The physics of the lakes and their storage are not considered in CLASS_V2.7. It should also be noted that information on land surface and ground characteristics required for runoff modelling is of a relatively poor quality in the Quebec/Labrador region, especially in the central and the northern parts of the Labrador peninsula.

The CRCM skill in simulating runoff at the basin scale is evaluated by comparing simulated runoff spatially averaged over a given watershed (obtained by aggregating data from all grid points located within the watershed) with the watershed runoff computed from streamflow observations (hereafter referred to as observed runoff: R_{OBS}). A comparison of the AMNO_ERA and AMNO_NRA

Table 2 Drainage area and corresponding number of CRCM grid tiles at 45-km resolution (true at 60°N) for each of the 21 watersheds of interest. Reference to Fig. 2 helps locate the watersheds.

Watershed name	Data sources	Drainage area (km^2)	Number of CRCM 45 km grid cells	Length of observation time series (years)
Rivière Arnaud (ARN)	HSQME	26 900	14	20
Rivière à la Baleine (BAL)	Hydro-Québec	29 000	17	36
Rivière Bell (BEL)	HSQME	22 200	15	36
Bersimis-Outardes-Manic (BOM)	Hydro-Québec	87 000	47	39
Réservoir Caniapiscau (CAN)	Hydro-Québec	37 870	23	39
Réservoir Churchill Falls (CHU)	Hydro-Québec	69 300	34	39
Rivière aux Feuilles (FEU)	HSQME	41 700	22	23
Rivière Georges (GEO)	HSQME	24 200	11	30
Grande rivière de la Baleine (GRB)	Hydro-Québec	36 300	18	39
La Grande Rivière (LGR)	HSQME	177 000	91	39
Réservoir Manic5 (MAN)	Hydro-Québec	29 240	17	39
Rivière aux Mélèzes (MEL)	HSQME	42 700	22	29
Rivière Moisie (MOI)	HSQME	19 000	12	33
Rivière Natashquan (NAT)	HSQME	15 600	9	37
Rivière Caniapiscau (Pyrite) (PYR)	HSQME	48 500	24	17
Rivière des Outaouais (RDO)	Hydro-Québec	143 000	80	31
Rivière Romaine (ROM)	HSQME	13 000	9	39
Rivière Rupert (RUP)	HSQME	40 900	22	37
Lac Saint-Jean (SAG)	Alcan Inc.	73 000	43	39
Rivière Saint-Maurice (STM)	Hydro-Québec	47 200	28	28
Rivière Waswanipi (WAS)	HSQME	31 900	16	32

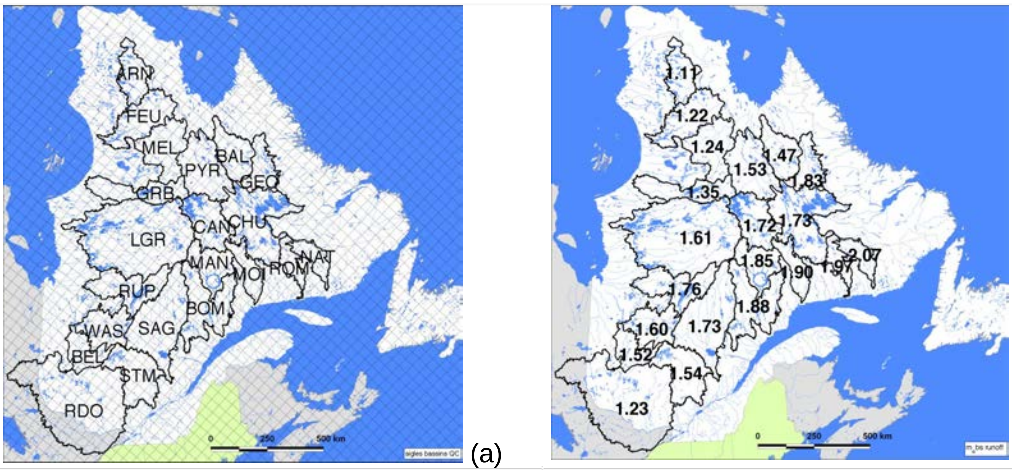

Fig. 2 (a) Geographical positions and outlines of the 21 watersheds of interest, along with 45-km CRCM grid. (b) Annual mean runoff ($\overline{R}_{OBS}$) in mm day^{-1} derived from streamflow observations over the period 1961–1999.

simulations allows an analysis of the sensitivity of the simulated runoff to the driving data. The pairs QC_ERA-AMNO_ERA and QC_NRA-AMNO_NRA are used to estimate simulated runoff sensitivity to domain size. The analyses were carried out over the 1961–1999 period, thus providing a three-year spin-up period needed for an adequate adjustment of simulated fields.

The analysis in this study is restricted to annual mean runoff computed over the January–December period of each year. Several statistics can be used to quantify differences between the two annual time series. One of the most often used is the root mean square difference, *E*, defined as:

$$E = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \tag{1}$$

where x_i and y_i are elements of the two time series and *n* is the length of the time series. This statistic is in fact a combined measure of bias and covariance between the two time series (Wilks, 2006). Following Taylor (2001) and Murphy (1988), *E* is separated into two components to isolate the difference in the pattern from the difference in the means. The first component is the overall "bias" (difference in the means) given as:

$$\overline{E} = \overline{x} - \overline{y} \tag{2}$$

where $\overline{x}$ and $\overline{y}$ are the time mean values of the time series. The second component is the centred pattern RMSD defined by:

$$E' = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[(x_i - \overline{x}) - (y_i - \overline{y})\right]^2} \tag{3}$$

The square of E' can be written as:

$$E'^2 = \sigma_x^2 + \sigma_y^2 - 2\sigma_x\sigma_y R \tag{4}$$

where *R* is the correlation coefficient, and σ_x and σ_y are the standard deviations. Note that all of these statistics are useful in the comparison of patterns in the time series. As E' approaches zero, the compared variables will have more similar patterns. The squares of the two components from equations (2) and (3) add to yield the full mean square difference: $E^2 = \overline{E}^2 + E'^2$.

RESULTS AND DISCUSSION

Annual means of observed runoff ($\overline{R}_{OBS}$) for 21 investigated watersheds over the period 1961–1999 are shown in Fig. 3, which gives an idea of runoff spatial distribution over the Québec/ Labrador region. The values of $\overline{R}_{OBS}$ vary from 1.11 mm day^{-1} for Arnaud River Basin (ARN) to 2.07 mm day^{-1} for Natashquan River Basin (NAT). The largest values appear along the Saint-Lawrence River, which may be related to the orographic effects. Runoff in the central watersheds of the Québec/Labrador region is characterized by intermediate values and decreases toward the north mainly due to smaller annual precipitation and despite a decrease in annual evapotranspiration. An analysis shows that about half of the annual runoff over the watersheds comes from spring snowmelt (Frigon *et al*., 2007a).

Figures 3 and 4 compare annual mean runoff (over the period 1961–1999) of the watersheds computed from the QC_ERA, QC_NRA, AMNO_ERA and AMNO_NRA simulations with $\overline{R}_{OBS}$. As errors are also inherent to observations, an arbitrary confidence interval of ±10% is assigned to $\overline{R}_{OBS}$ in Fig. 3. It can be seen that the CRCM tends to systematically underestimate $\overline{R}_{OBS}$. In general, simulations carried out over the smaller QC domain (QC_ERA and QC_NRA) have smaller runoff biases varying from –21% to +10% (–0.44 to +0.14 mm day^{-1}). The QC_ERA runoff is in better agreement with $\overline{R}_{OBS}$ (biases vary from –17% to +10%). It is interesting to note that, with an arbitrary confidence interval of ±10% for R_{OBS}, a Student paired *t*-test shows that, for 16 of the 21 watersheds, the difference between the QC_ERA and observed runoff is not statistically significant.

The simulations performed over the large AMNO domain are characterized by systematically dryer climate when compared to the QC simulations, resulting in higher runoff underestimation (biases vary from –10% up to –38%). Centred RMSD between the simulated and observed runoff

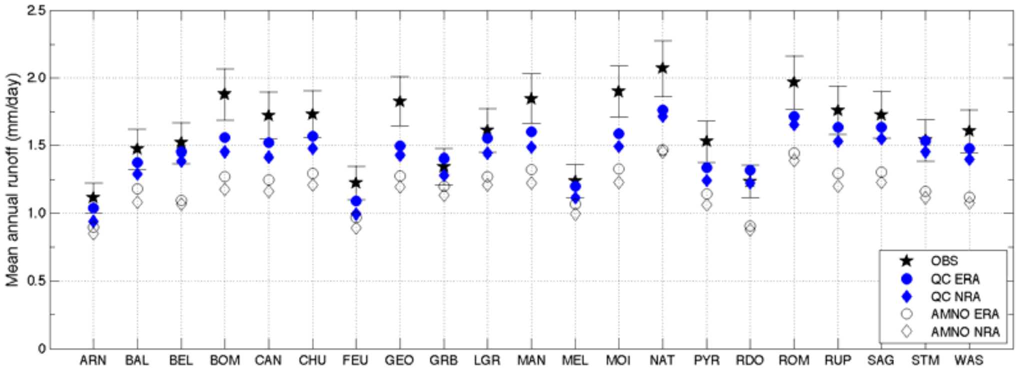

Fig. 3 Comparison of 1961–1999 annual mean runoff (mm day^{-1}) computed from the QC_ERA, QC_NRA, AMNO_ERA and AMNO_NRA simulations with observed runoff. An arbitrary confidence interval of ±10% is assigned to $\bar{R}_{OBS}$.

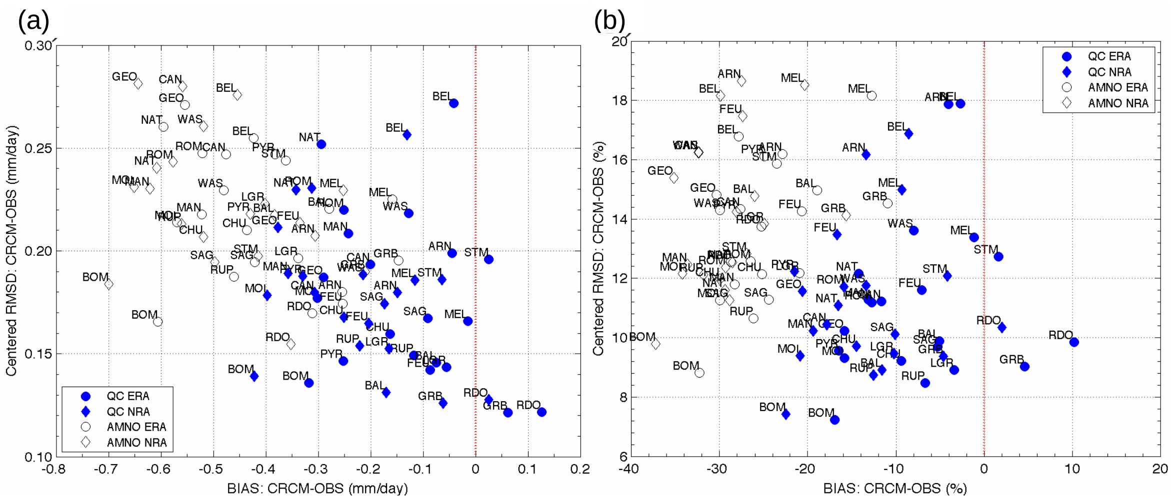

Fig. 4 Biases of the 1961–1999 QC_ERA, QC_NRA, AMNO_ERA and AMNO_NRA runoff and centred RMSD between the simulated and observed annual runoff in: (a) mm day^{-1}, and (b) in %.

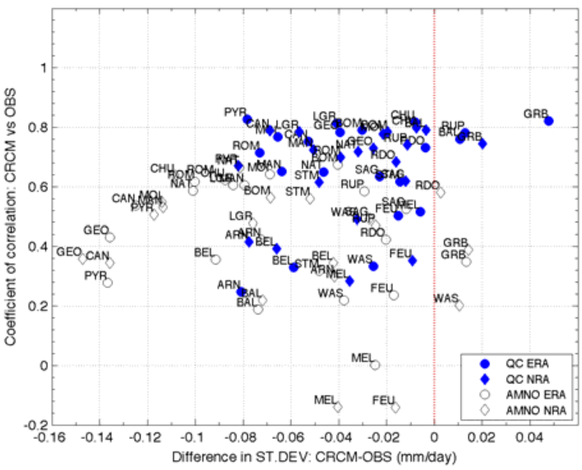

Fig. 5 Differences in standard deviation (mm day^{-1}) and correlation coefficients between the simulated and observed annual runoff over the period 1961–1999.

(y-axis in Fig. 4) also tends to be smaller for the QC simulations. Temporal patterns of observed annual runoff are therefore better reproduced in QC than in AMNO simulations. This can also be seen in Fig. 5, where differences in standard deviations between the simulated and observed annual runoff and correlation coefficients are shown. Furthermore, Fig. 5 shows that simulated runoff in all simulations is, in general, characterized by an underestimation of observed standard deviation. However, the differences in standard deviations of simulated and observed runoff are relatively small in all simulations (smaller than 0.15 mm day^{-1}, which represents less than 10% when expressed in percent of observed values, i.e. normalized by observed annual means). To get a better idea of how well the observed interannual variability is captured, the coefficients of variation (CV) of simulated and observed runoff are also compared (see Fig. 6). The CV is the ratio of standard deviation to annual mean and is a useful non-dimensional statistic for comparing the variability of variables with different annual means. In all the simulations, differences in CV are evenly distributed around zero, within ±0.08 (not shown). It can therefore be concluded that overall interannual variability of observed runoff is relatively well captured in all simulations. The correlation coefficient between the simulated and observed annual runoff (y-axis in Fig. 5), which is a measure of synchronism between the two time series, spans quite a large interval: from –0.15 to 0.83. A low correlation detected for some watersheds is mainly due to the model's inability to reproduce the extremely wet year of 1979. Note that QC_ERA annual runoff is, in general, better correlated with observations than runoff in the other three simulations: for 12 watersheds the correlation coefficients exceed 0.70.

The results above clearly show that the choice of simulation domain has a considerable effect on the simulated hydrological regime at the watershed scale. The simulations in the smaller QC domain are more strongly constrained by lateral boundary conditions coming from the atmospheric re-analyses than simulations in the larger AMNO domain, thereby resulting in a more accurate reproduction of annual evolution of the observed atmospheric circulation (Frigon *et al.*, 2007b). Lower values of the biases and the centred RMSD for most of the investigated watersheds (better correlation coefficient and slightly better capture of interannual variability) in the QC simulations may therefore be related to the stronger influence of the driving data.

Annual mean of simulated runoff is less sensitive to the driving data than to domain size. Figure 7 shows that differences in annual means of runoff between the simulations driven by ERA40 and those driven by NRA vary from around 0.02 to 0.12 mm day^{-1} (1% to 9%) for both QC and AMNO domains. The differences tend to be larger for simulations generated over the QC domain, probably because of stronger constraining of simulated climate in the smaller domain simulations. In fact, for the QC simulations, it was found that differences are larger than the CRCM's internal variability at a watershed scale, indicating that sensitivity is notable. On the other hand, the AMNO simulations are not sensitive to driving data: differences in annual runoff are found comparable to the internal variability of the model. Internal variability represents an intrinsic noise present in both the real and modelled climate systems, making them sensitive to

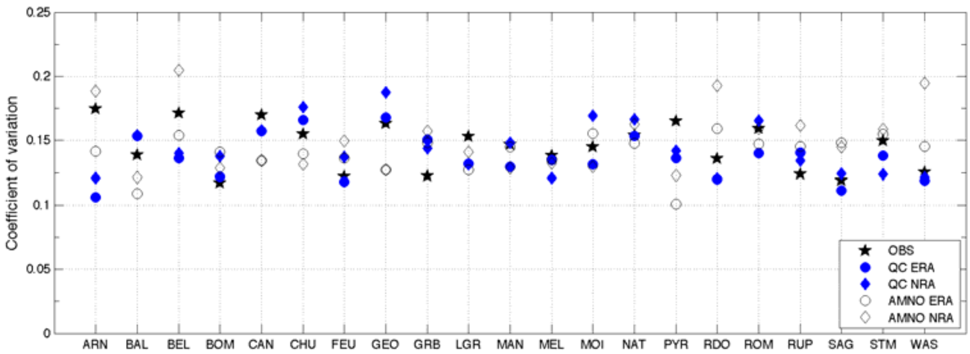

Fig. 6 Comparison of coefficient of variations of simulated and observed annual runoff over the period 1961–1999.

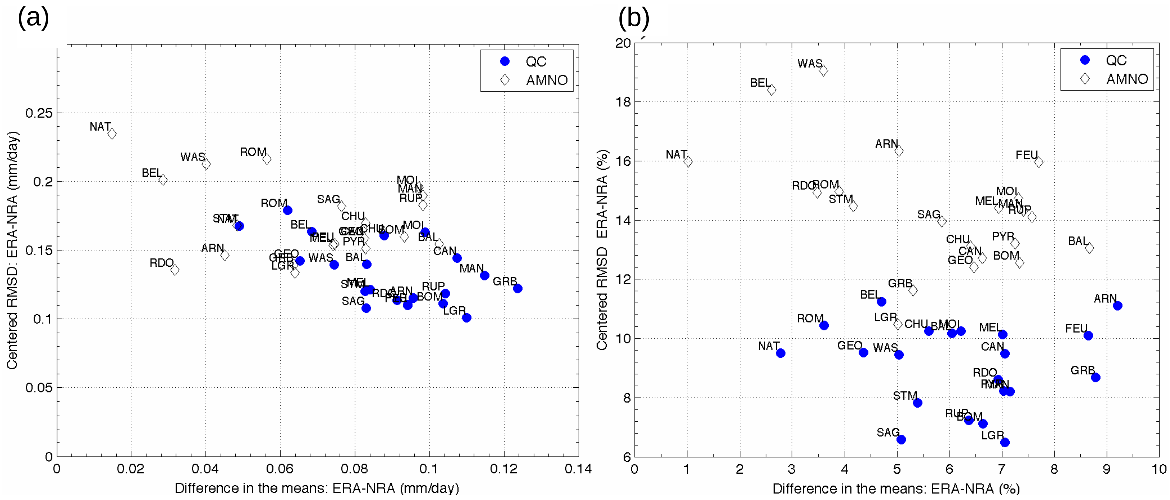

Fig. 7 Differences in 1961–1999 annual means and centred RMSD between the QC_ERA and QC_NRA runoff, and between the AMNO_ERA and AMNO_NRA runoff in mm day^{-1} (a) and in percentage (b).

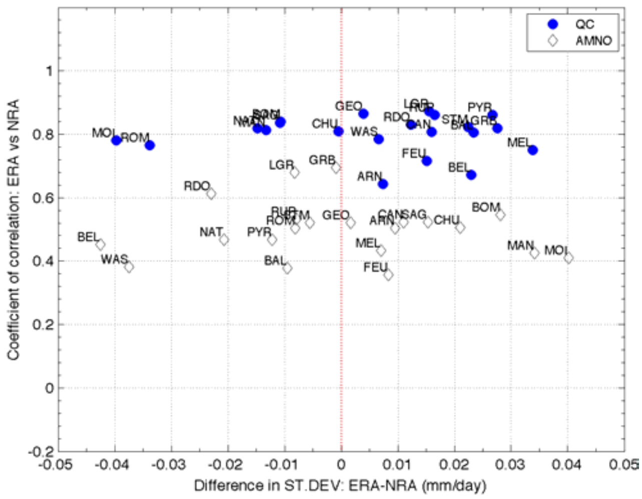

Fig. 8 Differences in 1961–1999 standard deviations (mm day^{-1}) and interannual correlation coefficients between the QC_ERA and QC_NRA runoff, and between the AMNO_ERA and AMNO_NRA runoff.

small perturbations. More details about internal variability of the CRCM hydrological variables at a watershed scale can be found in Frigon *et al.* (2008a).

On the other hand, centred RMSD (y-axis in Fig. 7) between the AMNO_ERA and AMNO_NRA have larger values when compared to those of QC_ERA *versus* QC_NRA; they range from about 12% to 19% and are comparable to the centred RMSD between the simulations and observations. For the QC domain simulations, the centred RMSD is smaller than 12% for all watersheds. Figure 8 shows that smaller centred RMSD for QC simulations is mainly due to better correlations between the ERA and NRA-driven simulations performed over the QC domain: the correlation coefficient is higher than 0.7 over 19 watersheds. For the AMNO domain simulations, it varies from 0.35 to 0.70. Differences in standard deviations are evenly distributed around zero, from about –0.05 to 0.05 (–5% to 5%), and are comparable over both domains. Differences in coefficients of variations vary in the same interval for both domains (–0.04 to 0.04; not shown).

SUMMARY AND CONCLUSIONS

Regional Climate Models (RCMs) find increasing use in projection of climate change impacts on regional hydrological regimes. The RCMs' main advantage is that they allow representation of the nonlinear nature of climate processes at the regional scale in a physically-based way. However, RCM hydrological outputs are usually subject to important systematic biases, particularly for water-related variables. The confidence level of the projected change in the hydrological regime over a given region depends, among other factors, on the RCM's capability to successfully simulate the present hydrological regime. This study is an evaluation of the hydrological performance of the Canadian Regional Climate Model (CRCM) over the Quebec/Labrador territory through assessing simulated runoff at a watershed scale that can be considered as spatial and temporal integrator of weather events. The sensitivity of simulated runoff to RCM domain size (AMNO; 201 × 193 *vs* QC; 112 × 88 grid points) and lateral boundary conditions (NRA *vs* ERA40) is also included in the analysis.

Results of the analysis shows that the CRCM tends to systematically underestimate the observed annual mean runoff over most of the investigated watersheds. Simulations in the larger AMNO domain show higher biases than the simulations performed over the smaller QC domain. Also, the temporal pattern of observed annual runoff is slightly better reproduced in the QC simulations. The best agreement between the simulated and observed runoff was found for simulation performed over the QC domain, driven by the ERA40 re-analysis. The choice of simulation domain, therefore, has a considerable effect on the simulated hydrological regime at the watershed scale. The simulations in the smaller QC domain are more strongly constrained by lateral boundary conditions coming from an atmospheric re-analysis than simulations in the AMNO domain, thereby resulting in a more accurate reproduction of observed runoff.

Comparison of simulations performed over the same domain but driven by different re-analyses indicates that, over the large AMNO domain, the differences in annual means are comparable to the CRCM's internal variability (i.e. the model's intrinsic noise). However, for the QC simulations, the differences are greater than the internal variability. Results also indicate that simulated runoff is less sensitive to the driving data than to domain size. It is important to keep in mind that, in this study, data from atmospheric re-analyses were used as lateral boundary conditions. Preliminary analysis of some CRCM simulations, generated recently over the AMNO domain to project future climate change, indicates also that differences in annual runoff between the simulations driven by the Canadian GCM and those driven by re-analyses, are in general comparable to the CRCM's internal variability. Finally, note that runoff generated by the CRCM_V4.2.0 is not routed along the river network. Work is presently underway to implement an appropriate routing scheme into the CRCM.

The CRCM development team continues its effort in addressing a number of issues, aiming to improve model performance. A new version of CLASS (Version 3.4), based on the mosaic approach, was recently implemented into the CRCM (Version 4.4). This allows each mosaic class (tile) within a land-surface grid cell to separately exchange water, energy and momentum with the overlying atmosphere. Inland lakes can be implemented as an additional class of the grid cell mosaic. Work is currently underway to choose an appropriate lake model to be coupled with the land-surface scheme (Martynov *et al*., 2009). Implementation of a lake model is expected to have non-negligible effects on simulated regional hydrological regime, especially in lake-rich regions such as Quebec/Labrador territory, by affecting surface fluxes of water vapour, heat and momentum.

Another important change from version 2.7 of CLASS (used in this study) to version 3.4 is modification of snow parameterization, i.e. an improved treatment of snow sublimation and interception as well as enhanced snow density. This should also affect CRCM simulated hydrology over the Quebec/Labrador territory because it is a snow-dominated region. It should be mentioned that Frigon *et al.* (2008b) have shown that maximum annual snow water equivalent (SWE) over the region, as simulated by the CRCM coupled to CLASS V2.7, is in general comparable to the available observations (i.e. it is within the range of difference in observation data sets).

It is important to mention that lateral transfers of soil water are not yet included in CLASS. In other words, the surface processes of each grid cell are modelled in isolation and, hence, water movement from uplands to lowlands, that is present in reality, is ignored. Lack of surface and subsurface water transfers between the grid cells affects soil moisture, which in turn affects simulated evapotranspiration and thus the whole grid water balance. As the horizontal resolution of climate simulations increases, the need to include lateral movement of soil water to the land surface schemes increases as well.

Finally, it should be stressed that any regional climate model contains errors resulting from modelling approximations and errors arising from the nesting approach. The nonlinear nature of the climate system makes it very difficult to isolate these errors. An experimental protocol called "Big-Brother Experiment (BBE)" has been designed at Université du Quebec à Montréal (UQAM) to isolate errors that are specific to the nesting method from errors contained in large scales of the lateral boundary conditions (LBC). Influence of large-scale errors in LBC on climate simulated by the CRCM can be investigated using a variant of the BBE: "Imperfect Big-Brother Experiment". More details of these techniques can be found in Laprise (2008).

Acknowledgements The authors are grateful to Hydro-Québec, the Churchill Falls and the Labrador Corporation (CFLCo), Alcan Inc. and the Quebec government department of "Développement durable, Environnement et Parcs" for providing streamflow data, and to the Ouranos Climate Simulation Team for generating and providing the CRCM data. A special thanks goes out to Mr Richard Harvey for helpful comments on the manuscript, and to Mr Mourad Labassi for technical support.

REFERENCES

Bartholome, E. & Belward, A. (2005) A new approach to global land cover mapping from Earth. *Int. J. Remote Sens.* **26**, 1959–1977.

Caya, D. & Laprise, R. (1999) A semi-implicit semi-Lagrangian regional climate model: the Canadian RCM. *Monthly Weather Rev.* **127**, 341–362.

Dickinson, R. E. (1984) Modeling evapotranspiration for three-dimensional global climate models. In: *Climate Processes and Climate Sensitivity: Maurice Ewing*, vol. 5, *Geophys. Monogr.* 29, 58–72. Am. Geophys. Union.

Dickinson, R. E., Shaikh, M., Bryant, R. & Graumlich, L. (1998) Interactive canopies for a climate model. *J. Climate* **11**, 2823–2836.

Entekhabi, D. & Eagleson, P. S. (1989) Land surface hydrology parameterization for atmospheric general circulation models including subgrid scale variability. *J. Climate* **2**, 816–831.

Flato, G. M. & Boer, G. J. (2001) Warming asymmetry in climate change simulations. *Geophys. Res. Lett.* **28**, 195–198.

Fiorino, M., (2001) AMIP II sea surface temperature and sea ice concentration observations. Available online at: http://www-pcmdi.llnl.gov/projects/amip/AMIP2EXPDSN/BCS_OBS/amip2_bcs.htm.

Frigon, A., Slivitzky, M., Caya, D. & Roy, R. (2007a) Construction of hydro-climatic projections and first-order estimation of their associated uncertainties from regional climate model simulations: Application to water management of hydropower reservoirs in Quebec. *La Houille Blanche* **6**, 97–103. doi: 10.1051/lhb:2007089.

Frigon, A., Slivitzky, M. & Caya, D. (2007b) Sensitivity of CRCM's hydrology to various configurations: analysis over a 10-basin composite in the Quebec/Labrador peninsula. Internal report. Available from Ouranos Consortium, 550 Sherbrooke St. West, 19th Floor, Montreal, QC H3A 1B9, Canada.

Frigon, A., Music, B. & Slivitzky, M. (2008a) Variabilité interne des variables hydrologiques du Modèle régional canadien du climat (MRCC) à l'échelle des 21 bassins versants du Québec/Labrador. Internal report. Available from Ouranos Consortium, 550 Sherbrooke St. West, 19th Floor, Montreal, QC H3A 1B9, Canada.

Frigon, A., Slivitzky, M. & Music, B. (2008b) Comparaison du couvert de neige du Modèle régional canadien du climat (MRCC) avec des données sur grille à l'échelle des 21 bassins versants du Québec/Labrador. Available from Ouranos Consortium, 550 Sherbrooke St. West, 19th Floor, Montreal, QC H3A 1B9, Canada.

Hagemann, S. & Gates, L. D. (2003) Improving a subgrid parameterization scheme for climate models by the use of high resolution data derived from satellite observations. *Climate Dynamics* **21**, 349–359.

IPCC (2007) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, E., Jenne, R. & Joseph, D. (1996) The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Met. Soc.* **77**, 437–471.

Laprise, R. (2008) Regional climate modelling. *J. Comput. Phys.* **227**, 3641–3666. Special issue on "Predicting weather, climate and extreme events".

Laprise, R., Caya, D., Giguère, M., Bergeron, G., Côté, H., Blanchet, J.-P., Boer, G. J. & McFarlane, N. (1998) Climate and climate change in western Canada as simulated by the Canadian Regional Climate Model. *Atmos.-Ocean*. **36**, 119–167.

Martynov, A., Sushama L. & Laprise R. (2009) Simulation of temperate freezing lakes by one-dimensional lake models: performance assessment for interactive coupling with regional climate models (submitted to *Boreal Environ. Res.*).

Mein, R. G. & Larson, C. L. (1973) Modelling infiltration during steady rain. *Water Resour. Res*. **9**, 384–394.

Murphy, A. H. (1988) Skill scores based on the mean square error and their relationships to the correlation coefficient. *Monthly Weather Rev.* **116**, 2417–2424.

Music, B. & Caya, D. (2007) Evaluation of the hydrological cycle over the Mississippi River Basin as simulated by the Canadian Regional Climate Model (CRCM). *J. Hydromet.* **8**, 969– 988.

Music, B. & Caya, D. (2009) Investigation of the sensitivity of the water cycle components simulated by the Canadian Regional Climate Model (CRCM) to the land surface parameterization, the lateral boundary data and the internal variability. *J. Hydrometeorology* **10**, 3–21.

Riette, S. & Caya, D. (2002) Sensitivity of short simulations to the various parameters in the new CRCM spectral nudging. *Research Activities in Atmospheric and Oceanic Modeling* (ed. by H. Ritchie), 7.39–7.40. WMO/TD no 1105, Report no. 32.

Roads, J. R., Lawford, E. B., Berbery, H., Fekete, B., Gallo, K., Grundstein, A., Higgins, W., Janowiak, J., Kanamitsu, M., Lakshmi, V., Leathers, D., Lettenmaier, D., Li, Q., Luo, L., Maurer, E., Meyers, T, Miller, D., Mitchell, K., Mote, T., Pinker, R., Reichler, T., Robinson, D., Robock, A., Smith, J., Srinivasan, G., Vinnikov, K., von der Haar, T., Vorosmarty, C., Williams, S. & Yarosh, E. (2003) GCIP Water and Energy Budget Synthesis (WEBS). *J. Geophys. Res.* **108**, D16, 8609, doi:10.1029/2002JD002583.

Scinocca, J. F., McFarlane, N. A., Lazare, M., Li, J. & Plummer, D. (2008) The CCCma third generation AGCM and its extension into the middle atmosphere. *Atmos. Chem. Phys. Discuss.* **8**, 7883–7930.

Sellers, P. J., Mintz, Y., Sud, Y. C. & Dalcher, A. (1986) A simple biosphere model (Sib) for use within general circulation models. *J. Atmos. Sci.* **43**, 505–531.

Sellers, P. J., Collatz, G. J., Berry, J. A., Field, C. B., Dazlich, D. A., Zhang, C., Collelo, G. D. & Bounoua, L. (1996) A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: Model formulation. *J. Climate* **9**, 676–705.

Taylor, K. E. (2001) Summarizing multiple aspects of model performance in a single diagram. *J. Geophys. Res.* **106**, 7183–7192.

Uppala, S. M., Kallberg, P. W., Simmons, A. J., Andrae, U., da Costa Bechtold, V., Fiorino, M., Gibson, K. J., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Holm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., McNally, A. P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo P. & Woollen, J. (2005) The ERA-40 Reanalysis. *Quart. J. Roy. Met. Soc.* **131**, 2961–3012.

Verseghy, D. L. (1991) CLASS – A Canadian land surface scheme for GCMs. Part I: Soil model. *Int. J. Climatol.* **11**, 111–133.

Verseghy, D. L., McFarlane, N. A. & Lazare, M. (1993) CLASS – A Canadian land surface scheme for GCMs. Part II: Vegetation model and coupled runs. *Int. J. Climatol.* **13**, 347–370.

Webb, T., Bartlein, P. J., Harrison, S. P. & Anderson, K. H. (1993) Vegetation, lake levels, and climate in eastern North America for the past 18,000 years. In: *Global Climates since the Last Glacial Maximum* (ed. by H. E. Wright Jr, J. E. Kutzbach, T. Webb III, W. F. Ruddiman, F. A. Street-Perrot, & P. J. Bartlein), 415–467. University of Minnesota Press, Minneapolis, Minnesota, USA.

Wilks, D. S. (2006) *Statistical Methods in the Atmospheric Sciences* (second edn). Elsevier Academic Press, New York, USA.

Wilson, M. F. & Henderson-Sellers, A. (1985) A global archive of land cover and soils data for use in general-circulation climate models. *J. Climate* **5**, 119–143.

Wood, E. F., Lettenmaier, D. P. & Zartarian, V. G. (1992) A land-surface hydrology parameterization with subgrid variability for general circulation models. *J. Geophys. Res.* **97**, 2717–2728.