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Improving the characteristics of streamflow modeled by regional climate models

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Abstract

The introduction of complex land surface parameterization schemes into regional climate models (RCMs) has been focused on improving the modeling of land surface feedbacks to the atmosphere. As such the modeling of streamflow was considered a by-product of the water balance and until recently it received relatively little attention. Comparison of four RCMs (RegCM2, MM5/BATS, MM5/SHEELS and MM5/OSU) and a simple hydrology model, Catchment Moisture Deficit–Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data (CMD-IHACRES) demonstrates the improvement in the characteristics of the streamflow prediction, which may be achieved using CMD-IHACRES. The conceptual structure of CMD-IHACRES allows it to be 'incorporated' into the RCMs, improving their streamflow predictions, as is demonstrated for the FIFE region of central USA.

Keywords: Regional climate models; Runoff parameterization; Streamflow characteristics; USA

1. Introduction

While only a small fraction of the world's water is present in rivers at any given time, they remain a major component of the earth's hydrological cycle. In particular, they provide a critical pathway for returning water from continents to the oceans. The role of rivers in the long-term global water budget has been discussed by others (Baumgartner and Reichel, 1975; Milliman and Meade, 1983; Russell and Miller, 1990). This freshwater flux from the continents to the oceans influences both the thermohaline circulation in the ocean and the formation of sea-ice via its influence on salinity. In a fully coupled climate model with a closed hydrological cycle, this river sourced freshwater feedback to the oceans can possess a climacteric nature. For example, Mysak et al. (1990) suggest that salinity anomalies in the North Atlantic Ocean, which could affect the thermohaline circulation, are related to ice transport through the Fram Strait, which in turn may be related to anomalous river flow into the Arctic Ocean.

An ideal land-surface parameterisation in a climate model should be capable of producing realistic time series of water and energy outputs based upon climatic inputs and spatially varying physical descriptors of the land surface (including terrain, soil and vegetation characteristics). Unfortunately, data available to validate regional climate model (RCM)

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hydrologic descriptions of precipitation, evapotranspiration (ET) and soil moisture storage are lacking due to several reasons. Most importantly, they are generally point measurements compared to the areal average values simulated by the climate model. River runoff on the other hand, is an important spatial integrator of the hydrologic cycle and data are readily available. The importance of river runoff data in validating climate models has been discussed by others, for example Liston et al. (1994), Miller et al. (1994) and Arnell (1995).

Most current land-surface schemes, regardless of whether they are relatively simple (e.g. bucket model) or complex (e.g. a soil–vegetation–atmosphere transfer scheme), contain highly simplified treatments of runoff. This is particularly true in comparison to the treatment of other hydrological components such as ET. This dichotomy in the treatment of various parts of the hydrological cycle is a cause for concern. Viterbo and Illari (1994) highlight the importance of runoff and soil moisture formulations. While Koster and Milly (1997) note that "even a 'perfect' description of canopy structure and stomatal behavior, toward which many land-surface models strive, does not ensure realistic evaporation rates if the runoff formulation remains relatively crude or incompatible."

Several studies have compared climate model-simulated runoff to observed river runoff in order to validate the model or to investigate the impact of global warming (Hansen et al., 1983; Kuhl and Miller, 1992; Miller and Russell, 1992; Milliman and Meade, 1983; Russell and Miller, 1990). Further studies on large river basins have introduced river runoff routing models, such as that found in Naden (1993), Lohmann et al. (1998) and Mengelkamp et al. (2001), to realistically route the flow through and between grid cells. Possibly the first hydrologic model to be incorporated into a climate model is the Nanjing model (Zhao, 1977), variations of which have also been termed the Arno model by Franchini and Pacciani (1991) and the variable infiltration capacity model (VIC), (Wood et al., 1992). Various forms of this model have also been used for GCM land-surface parameterizations by Stamm et al. (1994) in the GFDL model, by Laval et al. (1994) in the LMD model, by Rowntree and Lean (1994) in the UK Meteorological Office model, by Habets et al. (1999a,b) in the ISBA land-surface scheme, and by Warrach et al. (2002) (who also included the hydrologic model TOPMODEL) in the SEWAB land-surface scheme. In all cases the model performance is highly subject to the validity of the storage capacity distribution curve chosen.

In current land-surface schemes in RCMs assumptions concerning the total soil water holding capacity are made despite this quantity being impossible to measure at the horizontal scales required. Through the use of the hydrological model, Catchment Moisture Deficit–Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data (CMD-IHACRES) the need for this assumption is removed. While RCMs may not reproduce observed streamflows due to errors in the estimated precipitation, they should reproduce streamflow characteristics (flow durations, etc.). In this paper the effects of including the hydrological model CMD-IHACRES as the runoff parameterization in RCMs is explored in an effort to improve the characteristics of runoff simulations while minimizing any additional computational burden. The generality of these improvements is tested by comparison with four RCMs developed in part at the National Center for Atmospheric Research (NCAR), USA. Section 2 gives descriptions of the models used. Section 3 provides a description of the Field Experiment (FIFE) site and the experiment performed. The results are presented in Section 4, followed by the discussion (Section 5) and conclusions (Section 6).

2. Model descriptions

This section presents brief descriptions of the models used. A summary of the main components of the climate models can be found in Table 1.

2.1. CMD-IHACRES

The rainfall–evapotranspiration–runoff model is based on the structure of the IHACRES metric/conceptual rainfall–runoff model, developed at the Institute of Hydrology UK and the Center for Resource and Environmental Studies, Australian National University (Evans and Jakeman, 1998; Jakeman and Hornberger, 1993; Jakeman et al.,

Table 1
Summary description of the regional climate models

RCM	MM5	RegCM2	
Longwave radiation scheme	Broadband emissivity method (Stephens, 1984)	Band-absorptance technique including contributions of CO_2, O_3, H_2O and clouds (Kiehl and Briegleb, 1991)	
Short-wave radiation scheme	Scattering and absorption by clouds, clear air and water vapor (Grell et al., 1994)	δ-Eddington approximation (Joseph et al., 1976)	
Stable precipitation	Dudhia (1989)	Hsie et al. (1984)	
Convective precipitation	Grell scheme (Grell, 1993)	Grell scheme (Grell, 1993)	
Planetary boundary layer	Non-local-*K* approach (Hong and Pan, 1996)	Non-local-*K* approach (Holtslag et al., 1990b)	
LAND SURFACE	BATS	SHEELS	OSU
Number of layers for temperature	3	3	4
Temperature methodology	Force-restore (Deardorff, 1978)	Force-restore (Deardorff, 1978)	Diffusion equation (Mahrt and Ek, 1984)
Number of layers for soil moisture	3 nested	11 discrete	4 discrete
Soil moisture methodology	Darcy's law	Darcy's law	Darcy's law
Canopy methodology	Penman/Monteith	Penman/Monteith	Penman/stability-dependant resistance

1990, 1994). This model undertakes identification of hydrographs and component flows purely from rainfall, temperature and streamflow data. The IHACRES module structure consists of a non-linear loss module, which converts observed rainfall to effective rainfall or rainfall excess, and a linear streamflow routing module, which extends the concept from unit hydrograph theory that, the relationship between rainfall excess and total streamflow (not just quick flow) is conservative and linear. This model structure is presented schematically in Fig. 1.

The IHACRES loss module is given by Evans and Jakeman (1998). It is a conceptually based catchment moisture store accounting scheme. The accounting scheme calculates CMD at time step k, CMD_k, according to

$$\mathrm{CMD}_k = \mathrm{CMD}_{k-1} - P_k + E_k + D_k \tag{1}$$

CMD is zero when the catchment is saturated and increases as the catchment becomes progressively drier. P is the precipitation, E is the ET loss and D is drainage.

Drainage was assumed to be dependent only on the catchment moisture store and was calculated according to

$$D_k = \begin{cases} \dfrac{-c_2}{c_1}\mathrm{CMD}_k + c_2 & \mathrm{CMD}_k < c_1 \\ 0 & \mathrm{CMD}_k \geq c_1 \end{cases} \tag{2}$$

where c_1 and c_2 are non-negative constants.

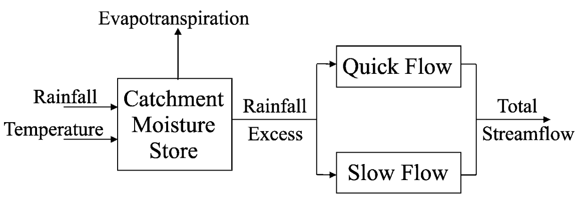

Fig. 1. Structure of CMD-IHACRES (Evans and Jakeman, 1998).

The actual ET loss is calculated by modifying an estimate of the potential evapotranspiration (PE) by a function of the available moisture in terms of the CMD, as given in Eq. (3)

$$E_k = \mathrm{PE}_k c_3 \exp(-c_4 \mathrm{CMD}_k) \tag{3}$$

where c_3 and c_4 are positive constants. Values of the constants given in Eqs. (2) and (3) are determined via calibration against observations as discussed in Section 4. The simplest possible ET formulation uses temperature as a surrogate for PE in Eq. (3).

Effective rainfall, U_k, is calculated from

$$U_k = \begin{cases} D_k & \mathrm{CMD}_k \geq 0 \\ D_k - \mathrm{CMD}_k & \mathrm{CMD}_k < 0 \end{cases} \tag{4}$$

The linear module allows any configuration of stores in parallel or series. From the application of CMD-IHACRES to many catchments it has been found that the best configuration is generally two stores in parallel. In the two-store configuration, at time step k, quickflow, $x_k^{(q)}$, and slowflow, $x_k^{(s)}$, combine additively to yield streamflow (discharge), q_k :

$$q_k = x_k^{(q)} + x_k^{(s)} \tag{5}$$

with

$$x_k^{(q)} = -\alpha_q x_{k-1}^{(q)} + \beta_q U_k \tag{6}$$

$$x_k^{(s)} = -\alpha_s x_{k-1}^{(s)} + \beta_s U_k \tag{7}$$

The parameters α_q and α_s can be expressed as time constants for the quick and slow flow stores, respectively,

$$\tau_q = -\Delta/\ln(-\alpha_q) \tag{8}$$

$$\tau_s = -\Delta/\ln(-\alpha_s) \tag{9}$$

where Δ is the time step. The model has been successfully applied on time scales ranging from hours to months. Here a daily time step is used.

Parameters expressing the relative volumes of quick and slow flow can also be calculated:

$$V_q = 1 - V_s = \frac{\beta_q}{1+\alpha_q} = 1 - \frac{\beta_s}{1+\alpha_s} \tag{10}$$

To measure the performance of the model estimate of streamflow, $\hat{q}_i$, two performance statistics are used: the bias (B) and the Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970). These are defined as

$$B = \frac{1}{n}\sum_{i=1}^{n}(q_i - \hat{q}_i) \tag{11}$$

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{N}(q_i - \hat{q}_i)^2}{\sum_{i=1}^{N}(q_i - q_{\mathrm{mean}})} \tag{12}$$

where $\hat{q}_i$ is the modeled streamflow, q_i is the observed streamflow and q_{mean} is the mean of the observed streamflow. Good model fit is indicated by a bias close to zero and NSE close to one.

2.2. Biosphere–Atmosphere Transfer Scheme (BATS)

BATS, described by Dickinson et al. (1993), incorporates a single vegetation layer, a multiple layer soil scheme, and provision for snow cover on the land surface. BATS contains 23 vegetation and soil parameters which are used to explicitly model many of the processes within the soil and vegetation canopy.

When coupled to a climate model, the vegetation type, soil texture, and soil color need to be specified for each grid point, along with the initial soil moisture, and ground and foliage temperatures. From the climate model, BATS requires as input: wind components, air density, temperature, and water vapor mixing ratio at the lowest atmospheric level, surface radiant fluxes at solar and infrared wavelengths, and precipitation. From these and other internally generated quantities, BATS calculates the temperature of the surface soil, deep soil, canopy foliage and canopy air, the soil moisture in three layers, snow cover, and surface fluxes of momentum, heat and moisture. The surface fluxes are then fed into the momentum, thermodynamics and water vapor equations of the climate model as lower boundary conditions.

Several sensitivity studies have been performed using BATS. The one-at-a-time parameter investigations (Dickinson and Henderson-Sellers, 1988; Wilson et al., 1987a,b) have found the most important parameters to include soil hydrologic conductivity and diffusivity parameters, the percentage of ground covered by vegetation and, in tropical forests, changes in surface roughness. Henderson-Sellers (1993) performed a factorial sensitivity analysis on BATS and found that two factor interactions including vegetation roughness length were more important than most of the single factors alone. The most important single factors were mean monthly temperature and its interaction with total monthly precipitation, vegetation roughness length, soil porosity, and a factor describing the sensitivity of the stomatal resistance of vegetation to the amount of photosynthetically active solar radiation.

Guided by the criteria that there should be small surface runoff at the soil moisture of field capacity and complete surface runoff at saturated soil, surface runoff is parameterized by

$$R_s = \begin{cases} \left(\dfrac{\rho_w}{\rho_{wsat}}\right)^4 G & T_{g1} \geq 0\,^\circ\mathrm{C} \\ \left(\dfrac{\rho_w}{\rho_{wsat}}\right) G & T_{g1} < 0\,^\circ\mathrm{C} \end{cases} \tag{13}$$

where ρ_{wsat} is the saturated soil water density and ρ_w is the soil water density weighted toward the top layer, T_{g1} is the surface soil temperature and

$$G = P + S_m - E \tag{14}$$

here S_m is the rate of snow melt.

2.3. Simulator for hydrology and energy exchange at the land surface (SHEELS)

The physics of SHEELS are based on those present in BATS. The main difference between them occurs in the sub-surface hydrologic processes. Instead of the nested three layer approach of BATS, SHEELS uses a discrete layer approach with five 2 cm thick layers in the top 10 cm of soil, a root zone containing three 30 cm thick layers and a lower zone extending to 10 m depth and divided into three layers.

By considering the contributions of infiltration, evaporation, transpiration, diffusion and gravitational drainage, SHEELS determines the change in soil moisture content in each of the soil layers. The Green–Ampt equation (Green and Ampt, 1911) is used to calculate the infiltration, I, based on the amount of precipitation reaching the soil surface. Surface runoff is based on the local slope angle (ϕ) and infiltration excess:

$$R_s = (P - I)\sin\phi \tag{15}$$

2.4. Oregon State University (OSU) model

The OSU land surface scheme is described by Chen et al. (1996) and Chen and Dudhia (2001). The model has one vegetation canopy layer and four discrete soil layers (0.1, 0.3, 0.6, 1.0 m) aimed at capturing the daily, weekly and seasonal evolution of soil moisture, with the root zone in the top 1 m similar to BATS and SHEELS. OSU contains approximately 16 vegetation and soil parameters, which are used to model water and temperature in the soil layers as well as snow cover and atmospheric feedbacks. Surface runoff is calculated using the simple water balance (SWB) model (Schaake et al., 1996). The SWB is a two-reservoir hydrological model that attempts to account for the spatial heterogeneity of rainfall, soil moisture and runoff. The surface runoff is defined simply as the excess precipitation not infiltrated into the soil

$$R_s = P - I \tag{16}$$

2.5. Regional climate model V2 (RegCM2)

The second generation NCAR RegCM2 is based on the National Center for Atmospheric Research—Pennsylvania State University mesoscale model version four, MM4, an atmospheric circulation model. Several of the MM4's physics parameterizations were modified to adapt it to long-term climate simulations. Key modifications include detailed representations of radiative transfer (Briegleb, 1992), BATS land surface parameterization (Dickinson et al., 1993), the model planetary boundary layer (Holtslag et al., 1990a,b) and convective precipitation schemes (Giorgi, 1991). Much of the development of RegCM2 can be found in Giorgi et al. (1993a,b).

The dynamical component of RegCM2 is essentially the same as that of the standard MM4 (Anthes et al., 1987; Anthes and Warner, 1978). The MM4 is a hydrostatic, compressible, primitive equation, terrain following σ vertical coordinate model, where $\sigma = (p - p_{top})/(p_s - p_{top})$, p is pressure, p_{top}

is the pressure specified to be the model top, and p_s is the prognostic surface pressure. RegCM2 has been used in many climate studies (Bates et al., 1995; Giorgi et al., 1994; Hostetler and Giorgi, 1992).

2.6. PSU/NCAR mesoscale model V5 (MM5)

The PSU/NCAR mesoscale model 5 version 2-5 known as MM5 is described by Dudhia (1993) and Grell et al. (1994). The original coupled model system (MM5/BATS) is described by Lakhtakia and Warner (1994) and a subsequent model system (MM5/SHEELS) is described by Laymon and Crosson (1995) and Smith et al. (1993). The MM5 allows the choice of several different physical parameterization schemes for radiation, boundary-layer, and convective processes. In this study the model was implemented with the short-wave radiation scheme described by Grell et al. (1994), the non-local-K approach found in Hong and Pan (1996) and the Grell (1993) scheme for convective precipitation. The model has been successfully applied to study a wide range of atmospheric phenomena covering horizontal length scales on

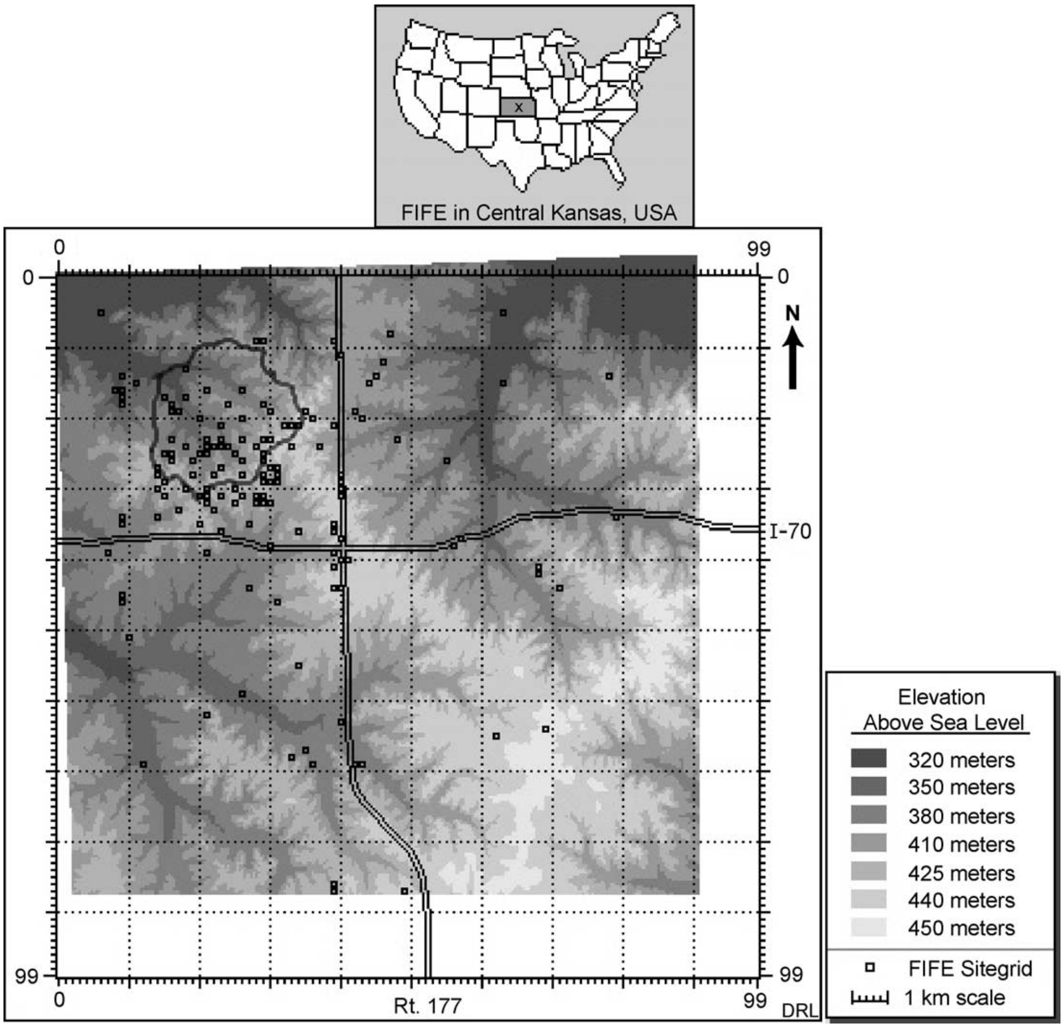

Fig. 2. FIFE site showing approximate location of Kings Creek catchment (encircled) in the north-west corner, ground measurement stations and the elevation.

order of a kilometer to several hundred kilometers (Anthes et al., 1985; Dudhia, 1989; Hines et al., 1995; Lapenta and Seaman, 1990), and requires lateral forcing provided either from observations or a GCM. The final RCM consists of MM5 version 3-4 (Grell et al., 1994) coupled to the OSU land surface scheme (Chen and Dudhia, 2001).

3. Site and experiment

The models were run over the First ISLSCP(International satellite Land Surface Climatology Project) Field Experiment (FIFE) site. The FIFE site is located in the Konza prairie, south of Manhattan, Kansas. FIFE observations were made over a 15 km × 15 km domain. Betts and Ball (1998) averaged the surface meteorological and flux data to give a single time series representative of the FIFE site for the time periods May–October 1987 and May–September 1988. A map of the FIFE site is shown in Fig. 2.

The model results are compared to observation taken during FIFE as well as data collected as part of the Konza prairie LTER site which is inside the FIFE domain. The FIFE domain also includes Kings Creek catchment in the north west corner. Runoff simulated by the RCMs was compared to streamflow from the Kings Creek catchment after it was scaled according to area. Climate model results used in this study were given by the single grid point closest to the center of the FIFE site. Even though this grid point is representative of an area somewhat larger than the FIFE site itself, there are several reasons why the comparison is meaningful. For the summer of 1987, conditions over the FIFE grassland site were relatively homogenous, so that simple averaging of the data gave a representative mean. The Konza prairie itself covers over 50,000 km^2, and the diurnal cycle over land integrates over considerable advection distances (up to 100–200 km^2) (Betts et al., 1998).

Here the climate models are implemented with 17 levels in the vertical, horizontal grid spacing of 20 km grid centered over the FIFE site and covering a total area of around 75,000 km^2. The model time step was 1 min. BATS, SHEELS and OSU were run online with the climate models while CMD-IHACRES was run offline. CMD-IHACRES was first calibrated simply using temperature as a surrogate for potential evaporation in Eq. (3). It was then run with the climate models also using temperature as a surrogate for potential evaporation, then using the climate model prediction of evaporation directly, followed by treating the climate model estimated runoff as the effective rainfall to drive CMD-IHACRES.

4. Results

The hydrological model, CMD-IHACRES, was calibrated for the Kings Creek catchment. The model was calibrated on daily data, over the 2 years 1987 and 1988 when the most reliable data were collected. These data were collected simultaneously at many locations within the FIFE site and combined into an areal average by Betts and Ball (1998). The calibration results are presented in Fig. 3, with the relevant statistics shown in Table 2.

It can be seen from Fig. 3 that CMD-IHACRES performs well in terms of runoff during the calibration period, and this is reflected in Table 2 where the calibration displays a high efficiency and a low bias and ARPE%. CMD-IHACRES is able to capture the small runoff in 1988 quite well. This is indicative of successful soil moisture accounting during the months when the stream is dry. From Table 2 it can be seen that the runoff is split with almost 70% of the runoff going through the slow store ($V_s = 0.694$). It takes 1.51 days for runoff to travel through the quick store

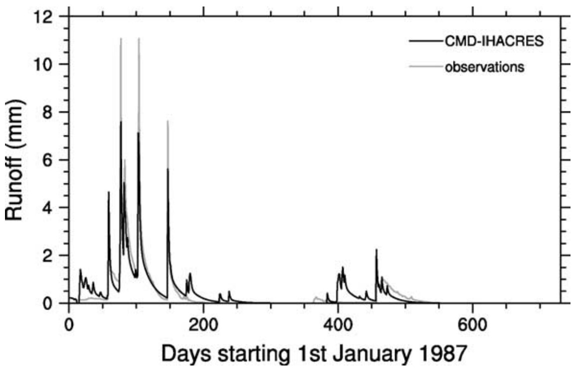

Fig. 3. CMD-IHACRES and observed daily runoff for the calibration period.

Table 2
CMD-IHACRES calibration and validation results

Model run and period	Model parameters							Model performance		
	c_1	c_2	c_3	c_4	τ_q (days)	τ_s (days)	V_s	ARPE (%)	B (mm/day)	E
Calibration 1/1/87–30/12/88	0.17	4	3	15	1.51	18.01	0.694	0.14	0.0	0.81
Validation 1/1/85–30/12/86	0.17	4	3	15	1.51	18.01	0.694		−0.05	0.61

(τ_q), while it takes 18 days for runoff to travel through the slow store (τ_s).

The model runoff performance was then validated on the two preceding years, 1985 and 1986. These data were put together as a historical data series for the FIFE site. It was collected by Kansas State University using a single precipitation gauge, almost 20 km from the center of the FIFE site. This precipitation series is therefore less representative of the precipitation within the FIFE site than the areally averaged data used in 1987 and 1988. This is reflected in the simulation results shown in Fig. 4 and Table 2 where it can be seen that the magnitude of the bias has increased marginally while the efficiency has decreased from 0.81 to 0.61.

In this section we compare the streamflow modeling results over the FIFE site during 1987 and 1988. First the models were run in stand-alone mode including CMD-IHACRES, which was calibrated with observations from the FIFE site. Generally the climate models do not reproduce the flow recession curves at all, instead the runoff consists of a series of extremely spiked events (see Fig. 5). That is, the climate models have difficulty producing low flows while they have a tendency to overestimate peak flows. This is largely due to the implicit assumption

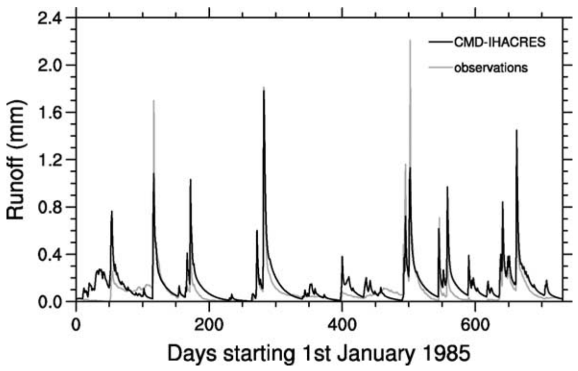

Fig. 4. CMD-IHACRES and observed daily runoff for the validation period.

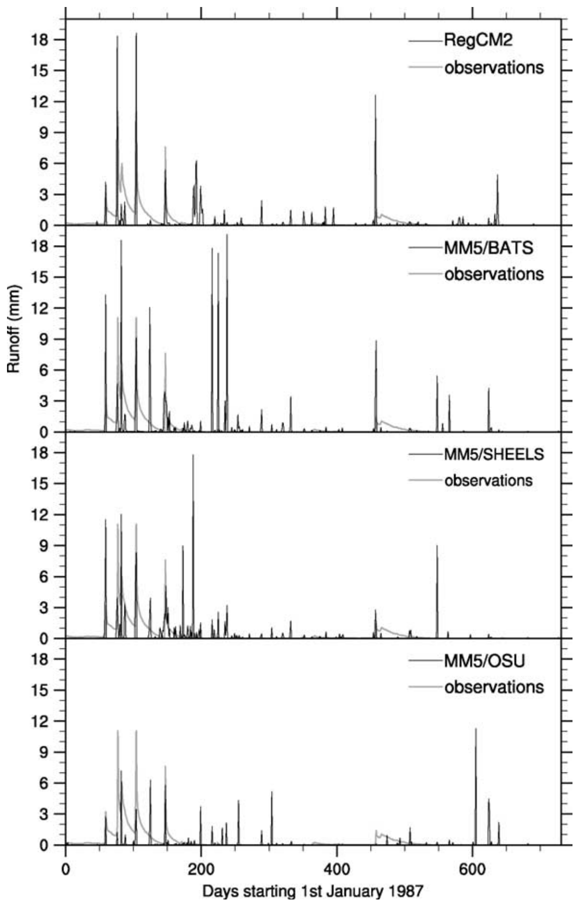

Fig. 5. Daily runoff from Kings creek catchment given by observations (thick gray line) and regional climate models (thin black line).

within the RCMs that runoff exits a grid cell instantaneaously.

An advantage of using the simple formulation for ET given in Eq. (5) is that the number of parameters and required data are kept to a minimum, allowing simple and reasonably unambiguous calibration. The result is an adequate though less than optimum estimation of ET. The more complicated and physically realistic formulations of ET found in the RCMs are better able to reproduce the observed variance in the time series though they do not necessarily produce quantitatively better results as can be seen from Fig. 6. The ET estimated using the RCMs temperature to drive Eq. (5) is shown in Fig. 6 (RCM + C − I). It can be seen that in general less ET is estimated this way than by the RCMs alone. This is made clear in Table 3 where a decrease in the means is clearly seen.

Fig. 7 presents the double mass plots simulated by the models. These plots present the relationship between runoff and precipitation in terms of accumulated daily values. Clearly the observed runoff

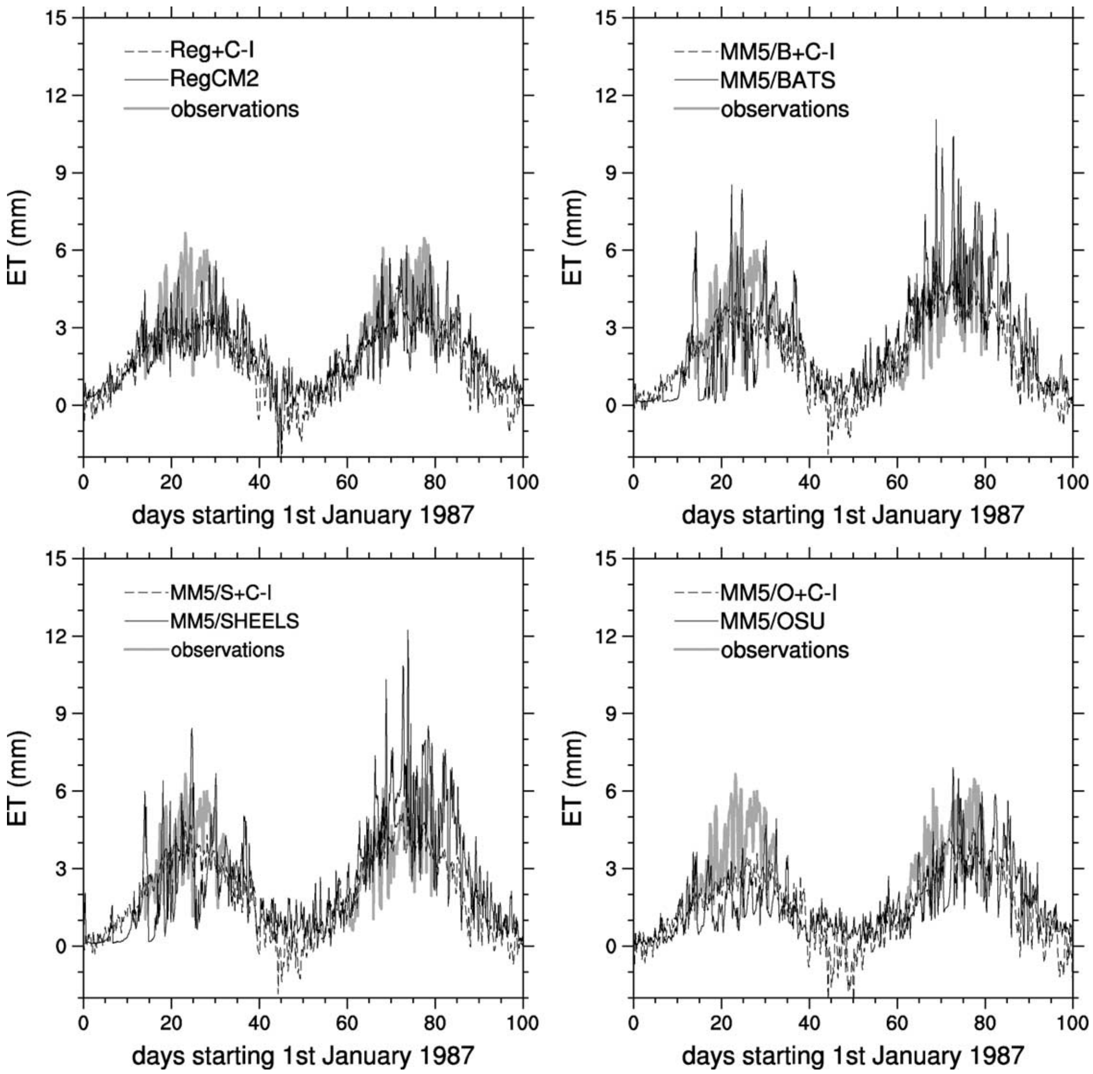

Fig. 6. Evapotranspiration estimated by the models and observed.

Table 3
Mean and standard deviation of the modeled evapotranspiration

Model	Mean (mm)	Standard deviation (mm)
CMD-IHACRES	1.74	1.47
RegCM2	1.95	1.32
MM5/BATS	2.44	2.12
MM5/SHEELS	2.53	2.19
MM5/OSU	1.62	1.29
Reg + C − I	1.70	1.34
MM5/B + C − I	1.93	1.48
MM5/S + C − I	1.98	1.54
MM5/O + C − I	1.50	1.36

displays a significantly non-linear relationship between runoff and precipitation. CMD-IHACRES also simulates a similar non-linear relationship to that which is observed. While the RCMs all simulate different double mass plots they are all much closer to linear than the observations. Note that this similarity between the climate models occurs despite the actual runoff amounts being calculated quite differently in BATS, SHEELS and OSU (Eqs. (13), (15) and (16)). This near linearity of the relationship between runoff and precipitation simulated by the RCMs

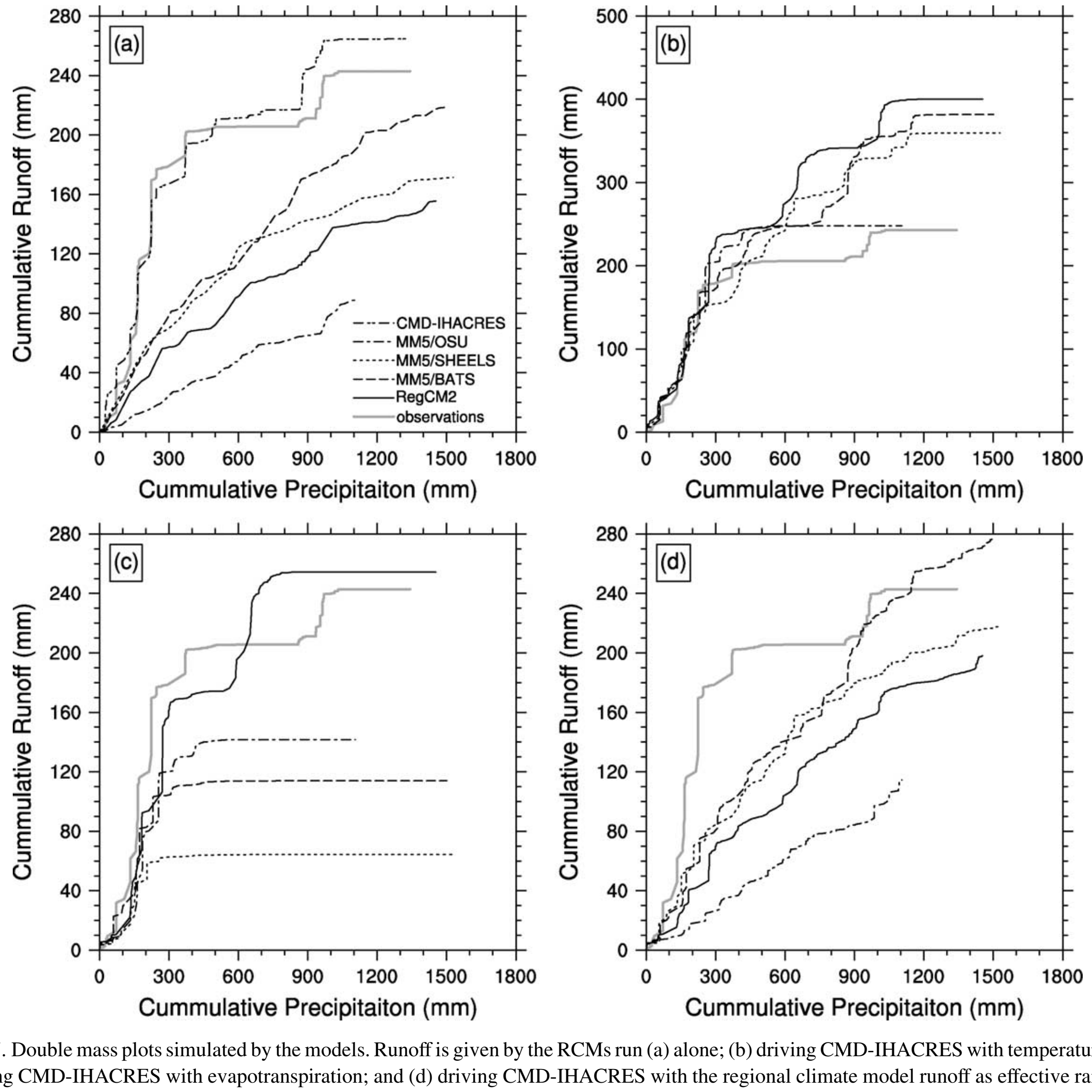

Fig. 7. Double mass plots simulated by the models. Runoff is given by the RCMs run (a) alone; (b) driving CMD-IHACRES with temperature; (c) driving CMD-IHACRES with evapotranspiration; and (d) driving CMD-IHACRES with the regional climate model runoff as effective rainfall.

demonstrates clearly the potential for the inclusion of a CMD-IHACRES style runoff parameterisation.

Comparing Fig. 7a and b reveals that inclusion of CMD-IHACRES to estimate runoff from the RCMs temperature and precipitation fields introduces the non-linearity seen from the observations but not in the raw RCM runoff fields. This desired non-linear behavior is also present when the RCMs ET and precipitation fields are used (Fig. 7c) though a significant decrease in the total runoff volume is evident. This change in total volume is due to the change in total ET predicted by the RCMs alone and when their temperature field is used to drive Eq. (5) as can be seen from Fig. 6.

Investigating other streamflow characteristics, such as flow duration curves, indicates similar discrepancies between the observations and climate model runoff (see Fig. 8). Examination of Fig. 8a

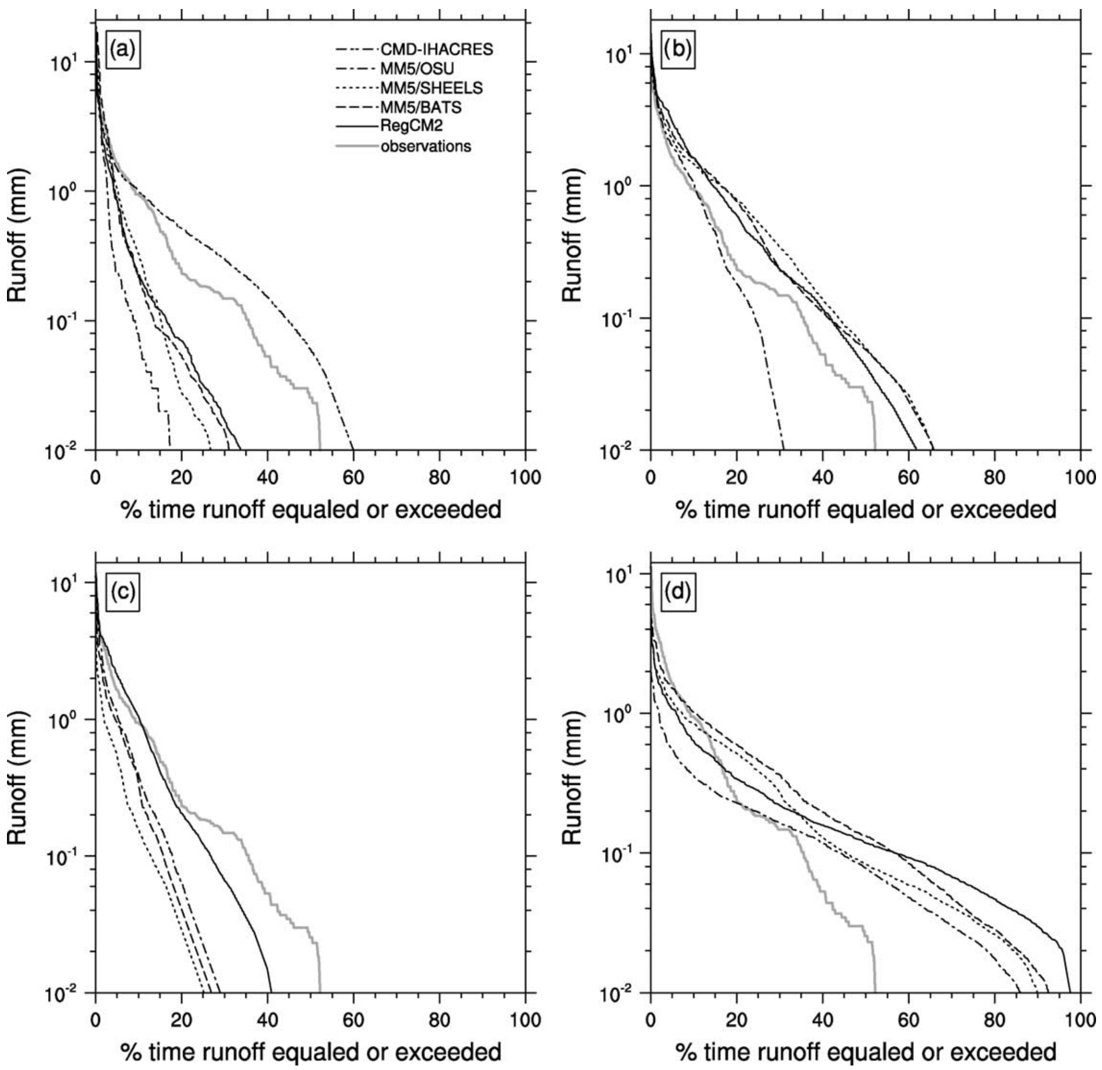

Fig. 8. Flow duration curves simulated by the models. Runoff is given by the RCMs run (a) alone; (b) driving CMD-IHACRES with temperature; (c) driving CMD-IHACRES with evapotranspiration; and (d) driving CMD-IHACRES with the regional climate model runoff as effective rainfall.

reveals that the RCMs have a tendency to underestimate the flow duration for most levels of flow. Inclusion of CMD-IHACRES to estimate runoff from the RCMs temperature and precipitation fields improves these flow duration curves considerably (Fig. 8b). When CMD-IHACRES is driven with the RCMs ET field directly (Fig. 8c) both RegCM2 and MM5/OSU show an improvement in the flow duration curve over the raw RCM runoff. Again this is largely due to the difference between the CMD-IHACRES calibrated ET field and the raw RCM ET fields. Table 3 shows that the RegCM2 and MM5/OSU ET fields mean and standard deviations change much less than the other RCMs.

The runoff formulations in the RCMs were developed in order to allow the maintenance of a reasonable long term water balance at a grid point. As such, little effort went into obtaining a formulation, which embodied the correct runoff timing and instead runoff was considered to be instantly lost from the water balance of a grid cell, i.e. it is no longer available to be evaporated and hence, is no longer of interest. This definition of runoff may be more akin to the effective rainfall used within CMD-IHACRES than to the streamflow itself. This would imply that to improve the runoff simulated by the RCMs it may be enough to treat the RCM simulated runoff as effective rainfall which can then be run through the linear routing component of CMD-IHACRES in order to obtain a true runoff time series.

In CMD-IHACRES it is the non-linear module which produces the effective rainfall and is responsible for the non-linearities seen from Fig. 7. The current runoff formulations in the RCMs are near linear and hence the double mass plots produced when treating the RCM runoff as effective rainfall remain near linear (Fig. 7d). A relatively large number of small runoff events are predicted by all of the RCM runoff parameterizations and this results in an overestimation of the flow duration curves for small flow volumes (Fig. 8d).

While the definition of RCM simulated runoff appears quite compatible with that of effective rainfall used by CMD-IHACRES it appears that successful application of this approach requires amending the current RCM runoff formulations to be more similar to the non-linear component of CMD-IHACRES. This would also improve the applicability of parameters obtained through the calibration of CMD-IHACRES on observed datasets.

5. Discussion

The results presented in Section 4 demonstrate that the inclusion of CMD-IHACRES, even just in an off-line mode, can greatly improve the simulation of streamflow characteristics. Comparing parts b and c of Figs. 7 and 8 reveals the impact different ET formulations have on the resulting streamflow characteristics. This interaction between ET and runoff formulation is analyzed further in Section 5.1.

5.1. Interplay between ET and runoff formulations

It has been recognized in previous land-surface and climate model intercomparison studies that due to the complexity of interactions among the components of the model, isolating and quantifying a given components contribution to the overall error is very difficult (Leung et al., 1999; Timbal and Henderson-Sellers, 1998; Wood et al., 1998). Insight into the intercomparison conducted here may be gained from the definition and comparison of a few bulk quantities, which characterize the models water balance dynamics. Koster and Milly (1997) derived two such quantities in terms of their relatively simple monthly water balance model (MWBM).

Analysis of this model led to two quantities that characterize the formulation of the soil water balance dynamics: (1) the efficiency of the soil's evaporation sink integrated over the active soil moisture range $\langle \beta \rangle$, and (2) the fraction of this range over which runoff is generated f_R. Koster and Milly (1997) calibrated the parameters of the MWBM against ET and runoff simulated by various land-surface models and claim that “Regardless of the land-surface model's complexity, the combination of these two derived parameters with rates of interception loss, potential evaporation, and precipitation provides a reasonable estimate for the land-surface model's simulated annual water balance.”

Here quantities based on those defined by Koster and Milly (1997) above are derived, without recourse to the MWBM, for all RCMs, CMD-IHACRES and the observations. The major differences in the derivations include: Koster and Milly (1997) remove the interception loss from the ET time series while it is included here; they perform a land-surface model run with a prescribed saturated surface to determine the potential evaporation while the method of Thornthwaite (1948) is used here; they define the 'active soil moisture range' in terms of parameters in the MWBM (the minimum value of soil moisture is that for which ET goes to zero, and the maximum value is that for which all precipitation is converted to runoff) while here it is defined simply as the range encountered during the observation period over the two years. Finally, they require the calibration of eight parameters in the MWBM before they can subsequently derive the two quantities of interest while these quantities are derived comparatively directly.

The derived quantities are independent of the actual soil moisture values, allowing direct comparison between models even though they may simulate substantially different magnitudes for soil moisture. That is, the two derived parameters, $\langle\beta\rangle$ and f_R, in fact describe the *relative* positions of the ET efficiency and runoff functions. Koster and Milly (1997) claim "the absolute positions are, in a sense, irrelevant in terms of the land-surface models response to atmospheric forcing." While this may be true when focusing on the runoff and ET simulated by a RCM it cannot be considered true when assessing the RCM as a whole. For example, the surface albedo often depends directly on the magnitude of the soil moisture.

In order to derive the first of the quantities above, an ET efficiency, β, is defined as

$$E = \beta E_r \tag{17}$$

where E_r refers to the reference ET, and here it is calculated using the method of Thornthwaite (1948). This calculation was performed using monthly average values. $\langle\beta\rangle$ is then the average of β across the active soil moisture range which is defined here as the soil moisture range encountered during this two year simulation.

In order to derive the second quantity a linear regression between monthly runoff and soil moisture was first performed. From this regression an estimate of the soil moisture for which runoff is zero was obtained, SM_0. The fraction of the active soil moisture range over which runoff occurs is then given by

$$f_R = \frac{SM_{max} - SM_0}{SM_{max} - SM_{min}} \tag{18}$$

where SM_{max} and SM_{min} are the maximum and minimum soil moisture simulated during the observation period, respectively. The analogous equation in terms of CMD is given by

$$f_R = \frac{CMD_0}{CMD_{max}} \tag{19}$$

where CMD_0 is the CMD at which runoff reaches zero, and CMD_{max} is the maximum CMD reached during the observation period. The minimum value for CMD is zero.

Values for these two quantities were established for all the RCMs in both stand alone and offline mode, for CMD-IHACRES as well as for the observations and are presented in Table 4. In the case of the observations only data from the observation periods in each year were used, that is the observational quantities were based on a significantly shorter period than the other quantities and as such would contain greater uncertainty. Nevertheless it does serve to create targets which the models should aim to reproduce.

Of the stand alone experiments CMD-IHACRES is best able to reproduce the observed evaporation efficiency and runoff fraction. RegCM2 also performs best of the RCMs, while the MM5 based RCMs perform relatively poorly. In the offline experiments the performance of all of the RCMs is improved with

Table 4
Derived values of $\langle\beta\rangle$ (dimensionless) and f_R (dimensionless) for the observations, CMD-IHACRES and the three regional climate models

Model	$\langle\beta\rangle$	f_R
Observations	0.94	0.74
CMD-IHACRES	1.07	0.66
RegCM2	1.32	0.64
MM5/BATS	1.51	0.63
MM5/SHEELS	1.74	0.82
MM5/OSU	1.36	0.55
RegCM2 + C − I	1.08	0.79
MM5/B + C − I	1.27	0.65
MM5/S + C − I	1.29	0.64
MM5/O + C − I	1.11	0.73

RegCM2 and MM5/OSU coming closest to reproducing the observed quantities.

6. Conclusions

Examining the runoff formulation in several RCMs (RegCM2, MM5/BATS, MM5/SHEELS, MM5/OSU) reveals that despite the different approaches taken they nevertheless have similar implications for days with no precipitation. That is, if there is no precipitation there can be no runoff, which is not what is observed.

The inclusion of CMD-IHACRES removes this unrealistic assumption implicit in all the climate models and hence produces a significant improvement in the simulated runoff characteristics. In particular it produces the non-linear relationship observed between precipitation and runoff as well as improving the flow duration curves produced.

Examination of the non-dimensional quantities characterizing the water balance of the models reveals several shortcomings of the RCMs and the improvement possible by including CMD-IHACRES. All the RCMs simulate a high ET efficiency, $\langle\beta\rangle$, compared to the observations, particularly in the cold months. They also tend to underestimate the fraction of the active soil moisture range over which runoff occurs, f_R, except MM5/SHEELS which overestimates f_R. This may be largely related to the fact that the runoff formulation in all the RCMs is only secondarily related to soil moisture, while it is primarily a function of precipitation and ET or infiltration. Including CMD-IHACRES as the runoff formulation in the climate models significantly improves both their ET efficiency and runoff fraction over this 2-year period.

The best results were produced by driving CMD-IHACRES with the RCM simulated temperature and precipitation, that is with ET determined simply with temperature as a surrogate for potential evaporation in Eq. (3). For many studies, however, a more complex representation of vegetation may be required. While the results obtained using the RCMs native, relatively complex, ET formulation were not as good as those produced using only temperature, the desired non-linearities are present. The lack of any feedback between the CMD and the ET formulation in this 'offline' mode, is the likely cause of this relatively poor performance. Replacing the soil moisture dependence in the ET formulations with a CMD dependence, and running the hydrology model online would significantly improve the runoff characteristics obtained in this case.

In summary then, the inclusion of CMD-IHACRES run offline with the climate models significantly improves the runoff simulation. This suggests that the combination of CMD-IHACRES and RCM may well prove to be of practical use in investigating climate change effects on streamflows in data sparse areas. By implementing the models in an offline mode, however, there is no allowance for feedbacks between the catchment moisture and other components of the energy and water balance. These results suggest that further experiments with CMD-IHACRES run online with a RCM are warranted. Further work investigating this online potential, including the coupling between the CMD and energy terms, is currently under way.

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Appendix. A

Acronym	Meaning
BATS	Biosphere–Atmosphere Transfer Scheme
CMD-IHACRES	Catchment Moisture Deficit–Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data
ET	Evapotranspiration

(*continued on next page*)

(*continued*)

Acronym	Meaning
FIFE	First ISLSCP Field Experiment
GCM	Global Circulation (or climate) Model
GFDL	Geophysical Fluid Dynamics Laboratory
ISBA	Interactions between Soil, Biosphere and Atmosphere
ISLSCP	International Satellite Land Surface Climatology Project
LMD	Laboratoire de Meteorologie Dynamique
LTER	Long Term Ecological Reserve
MM5	PSU/NCAR mesoscale model v5
MWBM	Monthly Water Balance Model
NCAR	National Center for Atmospheric Research
PE	Potential evapotranspiration
PSU	Pennsylvania State University
RCM	Regional climate model
RegCM2	Regional climate model v2
SEWAB	Surface Energy and Water Balance
SHEELS	Simulator for Hydrology and Energy Exchange at the Land Surface
SWB	Simple Water Balance model
VIC	Variable infiltration capacity model

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