Prediction of Streamflow by Regional Climate Models

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Abstract: The introduction of complex land surface parameterization schemes into regional climate models has been focused on improving the modeling of land surface feedbacks to the atmosphere. As such the modeling of streamflow by these models has received relatively little attention, and has generally been considered a by-product of the water balance. Comparison of three regional climate models (RegCM2, MM5/BATS and MM5/SHEELS) and a simple hydrology model (CMD-IHACRES) demonstrates the improvement in streamflow characteristics and prediction which may be achieved using CMD-IHACRES. The conceptual structure of CMD-IHACRES allows it to be 'incorporated' into the regional climate models, improving their streamflow predictions, as is demonstrated for the FIFE region of central USA.

Keywords: Regional climate; Hydrology; Streamflow; Modelling

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 [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.

An ideal land-surface parameterization 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 climate model hydrologic descriptions of precipitation, 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, it is measured more accurately than other components of the hydrologic cycle and river runoff data are readily available. The importance of river runoff data in validating climate models has been discussed by others, for example Arnell [1995] and Liston et al. [1994].

Most current land-surface schemes, regardless of whether they are relatively simple (e.g. bucket model) or complex (e.g. a SVAT 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 [Kuhl and Miller, 1992; Miller and Russell, 1992]. Further studies on large river basins have introduced river runoff routing models, such as that found in Lohmann et al. [1998], 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 this model have also been used for GCM land-surface parameterizations in the GFDL model, in the LMD model, in the UK Meteorological Office model, and in the ISBA land-surface scheme. In all cases the model performance is highly subject to the validity of the storage capacity distribution curve chosen.

In this paper the effects of including hydrological model CMD-IHACRES as the runoff parameterization in the climate models below is explored in an effort to improve the runoff simulations of the LAMs while minimizing any additional computational burden. Section 2 gives descriptions of the models used. Section 3 provides a description of the experiment and FIFE site. The results are presented in section 4 followed by the discussion and conclusion in section 5.

2 MODEL DESCRIPTIONS

2.1 IHACRES

The rainfall-evapotranspiration-runoff model is based on the structure of the IHACRES metric/conceptual rainfall-runoff model. This model undertakes identification of hydrographs and component flows purely from rainfall, temperature and streamflow data [Evans and Jakeman, 1998; Jakeman and Hornberger, 1993]. 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.

The IHACRES loss module is given in Evans and Jakeman [1998]. It is a quasi-physically based catchment moisture store accounting scheme. The accounting scheme calculates Catchment Moisture Deficit at time step k, CMD_k, according to

$$CMD_k = CMD_{k-1} - P_k + E_k + D_k \qquad (1)$$

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

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

$$D_k = \begin{cases} \dfrac{-c_2}{c_1} CMD_k + c_2 & CMD_k < c_1 \\ 0 & CMD_k \geq c_1 \end{cases} \qquad (2)$$

where c_1 and c_2 are non-negative constants.

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

$$E_k = PE_k c_3 \exp(-c_4 CMD_k) \qquad (3)$$

where c_3 and c_4 are positive constants.

2.2 BATS

The Biosphere-Atmosphere Transfer Scheme, 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.

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

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

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

$$G = P + S_m - E \qquad (5)$$

here S_m is the rate of snow melt.

2.3 SHEELS

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

$$R_u = (P - I) \bullet \sin\phi \qquad (6)$$

2.4 RegCM2

The second generation NCAR Regional climate model (RegCM2) is based on the National Center for Atmospheric Research-Pennsylvania State University Mesoscale Model version 4, 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., 1990] and convective precipitation schemes [Giorgi, 1991]. Much of the development of RegCM2 can be found in Giorgi et al. [1993a; 1993b].

The dynamical component of RegCM2 is essentially the same as that of the standard MM4. 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.

2.5 MM5

The National Center for Atmospheric Research-Pennsylvania State University Mesoscale Model version 5, MM5, is described in Grell et al. [1994]. It is a non-hydrostatic, compressible, primitive equation, terrain following σ vertical coordinate model. MM5 has been used largely in numerical model. MM5 has been used largely in numerical weather forecasting and process studies. As a result it has accrued several options for each physical parameterization.

The parameterizations used in this study are the longwave radiation scheme of Stephens [1984], the shortwave radiation scheme described in Grell et al., [1994], the simple micro-physics scheme discussed in Dudhia [1989], the cumulus parameterization of Grell [1993] and the planetary boundary layer parameterization is the nonlocal-K approach of Hong and Pan [1996]. MM5 was run twice, once with each of the land surface parameterization schemes outlined above, BATS and SHEELS.

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 15km × 15km 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.

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 using a 20km grid centered over the FIFE site and covering a total area of around 75,000 km^2. The model time step was 1 minute. The models were run for the 2 year period, 1987-1988. BATS and SHEELS were run online with the climate models while IHACRES was run offline.

4 MODEL COMPARISONS

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 Figure 3). That is, the climate models have difficulty producing low flows while they have a tendency to overestimate peak flows.

Figure 1 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 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 LAMs 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 and SHEELS (equations 4 & 6). This near linearity of the relationship between runoff and precipitation simulated by the LAMs demonstrates clearly the potential for the inclusion of a CMD-IHACRES style runoff parameterization.

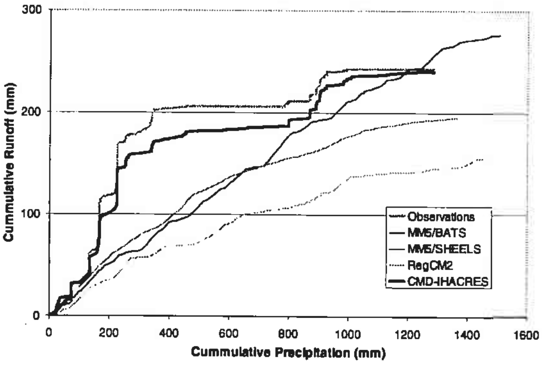

Figure 1: Double mass plots simulated by the models.

Investigating other streamflow characteristics, such as flow duration curves, indicates similar discrepancies between the observations and climate model runoff. The inclusion of CMD-IHACRES, even just in an off-line mode, greatly improves these streamflow characteristics. An example of the effect of using CMD-IHACRES to simulate runoff from MM5/SHEELS is given in Figure 2.

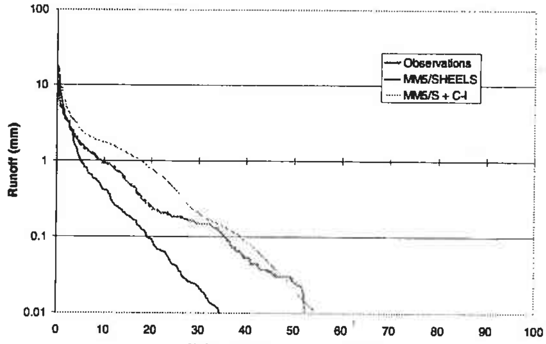

Figure 2: Flow duration curves simulated by MM5/SHEELS alone and by CMD-IHACRES run offline with MM5/SHEELS.

Essentially the inclusion of CMD-IHACRES in the simulation of runoff by these climate models greatly improves the characteristics of the runoff. However, the ability to actually reproduce observed streamflow is still strongly controlled by the models simulated precipitation. This can be seen in Figure 3 where the runoff simulated by MM5/BATS + CMD-IHACRES acts much more like the observed runoff than that produced by MM5/BATS alone. Note the false peaks in July 1987 are still present in the offline simulation, this is due to the strong model precipitation forcing which occurred during this month.

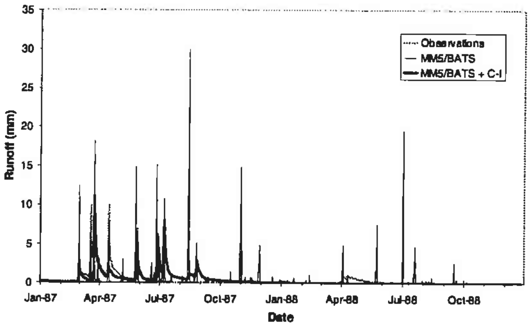

Figure 3: runoff simulated by MM5/BATS alone and with CMD-IHACRES run offline with MM5/BATS.

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]. 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. Here the two quantities defined by Koster and Milly [1997] above are derived for all three climate models (MM5/BATS, MM5/SHEELS and RegCM2), CMD-IHACRES and the observations with the results shown in Table 1.

Of the stand alone experiments CMD-IHACRES is best able to reproduce the observed evaporation efficiency and runoff fraction. RegCM2 also performs reasonably well, while the MM5 based climate models perform relatively poorly. In the offline experiments the performance of all of the climate models is improved with RegCM2 + C-I performing particularly well in reproducing the observed quantities.

Table 1: Derived values of $\langle \beta \rangle$ (dimensionless) and f_R (dimensionless) for the observations, CMD-IHACRES and the three LAMs.

Model	$\langle \beta \rangle$	f_R
Observations	0.912	0.74
CMD-IHACRES	0.911	0.67
MM5/BATS	0.843	0.96
MM5/SHEELS	0.815	0.89
RegCM2	0.901	0.83
MM5/B + C-I	0.881	0.72
MM5/S + C-I	0.883	0.66
RegCM2 + C-I	0.911	0.74

5 DISCUSSION AND CONCLUSIONS

From equations 4-6 it can be seen that while the SHEELS approach to runoff is quite different to the approach taken in BATS, it nevertheless has 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. This is demonstrated in figures 2 and 3, and table 1.

Examination of the non-dimensional quantities defined in section 4 reveals the MM5 based climate models to have low ET efficiency, $\langle \beta \rangle$. That is, they tend to underestimate the proportion of the potential ET which is converted to actual ET when compared to the observed for this two year period. All three climate models overestimate the fraction of the active soil moisture range over which runoff occurs, f_R. This may be largely related to the fact that the runoff formulation in both BATS and SHEELS 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 two year period. In particular, the combination of RegCM2 and CMD-IHACRES almost precisely reproduces the observed values of these parameters.

Possibly the most promising avenue for further investigation is treating the climate model simulated runoff as effective rainfall to drive the linear component of CMD-IHACRES. This allows the complex representation of vegetation to be retained, yet is enough to produce a reasonable hydrograph.

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 a regional climate model may well prove to be of practical use in investigating climate change effects on streamflows in data sparse areas. While these results suggest that further experiments with CMD-IHACRES run on-line with a LAM are warranted, the best way to incorporate CMD-IHACRES into a LAM is not clear. Further work investigating this "online" potential is currently under way.

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