A New Method Improving the Simulation of Streamflow in Climate models

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Abstract Climate models perform poorly in terms of their prediction of streamflow. They tend to deal with the land surface hydrology using either an extremely simplified bucket model or a highly parameterized Soil Vegetation Atmosphere Transfer (SVAT) scheme. Hydrologists, on the other hand, have developed a full spectrum of surface hydrology models, from simple empirical to more complex, physically based schemes, which perform quite well at predicting streamflow. Here a surface hydrology model of moderate complexity (7 parameters) is used in conjunction with a regional climate model to predict streamflow. This approach improves the climate models streamflow prediction considerably, even though much of the discrepancy can be attributed to the prediction of rainfall by the climate model.

1 INTRODUCTION

Climate models have been developed predominantly by atmospheric scientists who were investigating atmospheric phenomena. As a result little attention was given to processes occurring at the land surface. The earliest attempts at developing a simple model of land surface hydrology occurred in the mid-60s [Manabe et al., 1965]. Manabe used Budyko's "bucket" model which works using the simple idea that the soil acts like a bucket which is filled by rainfall and overflows as runoff. It does not reproduce observed processes at the land surface.

Over the last few decades the importance of modelling the land surface more satisfactorily has become more apparent; in terms of getting the energy and water balance at the surface correct, including the atmospheric feedbacks involved, as well as the interest in potential impacts of climate and/or land use change on streamflows. As a result the development of these land surface hydrology components inside climate models has received much more attention and has lead to some very complicated Soil-Vegetation-Atmosphere Transfer (SVAT) schemes for dealing with these land surface processes [Abramopoulos et al., 1988, Dickinson et al., 1986, Sellers et al., 1986]. The introduction of these complex models has brought new problems, such as over-parameterization and the large amounts of computer time required to run them as part of the climate model.

Meanwhile, hydrologists have developed a plethora of surface hydrology models, over a wide range of complexities, which are able to reproduce observations well. Several attempts have been made to modify existing hydrological models for use within climate models [Bobinski et al., 1993, Dumenil and Todini, 1992, Wood et al., 1992]. While these attempts have yielded better results than the climate models which incorporate bucket type land surface schemes, they still have difficulty reproducing observations.

Several studies have looked at land surface schemes in climate models in terms of atmospheric feedbacks (latent and sensible heat etc.) as well as surface processes such as runoff [Dumenil and Todini, 1992, Entekhabi and Eagleson, 1989, Franks, 1998, Garratt et al., 1993, Kuhl and Miller, 1992, Polcher et al., 1996, Timbal et al., 1997, Wood et al., 1991, Wood et al., 1992]. It was generally found that the climate models perform reasonably in terms of atmospheric feedbacks but they tend to perform poorly in terms of runoff.

Here, we have used a regional climate model developed at the National Centre for Atmospheric Research (NCAR) USA, RegCM2 to compare the land surface predictions of discharge made using the Biosphere- Atmosphere Transfer Scheme (BATS) SVAT [Dickinson et al., 1986] with those made using a relatively simple rainfall-runoff model, IHACRES [Evans and Jakeman, 1998, Jakeman and Hornberger, 1993, Jakeman et al., 1990] The investigation was performed over central Kansas, USA and comparison is made with data collected during the First ISLSCP Field Experiment (FIFE).

2 MODEL DESCRIPTIONS

2.1 IHACRES

The rainfall-evapotranspiration-runoff model used 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, Jakeman et al., 1990, Jakeman et al., 1994]. 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 used here is given in Evans and Jakeman [1998] and 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

$$CMD_k = CMD_{k-1} - P_k + E_k + D_k \tag{1}$$

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

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

$$D_k = \begin{cases} \frac{-c_2}{c_1} CMD_k + c_2 & CMD_k < c_1 \\ 0 & CMD_k \geq c_1 \end{cases} \tag{2}$$

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)

$$E_k = PE_k c_3 \exp(-c_4 CMD_k) \tag{3}$$

where c_3 and c_4 are positive constants.

2.2 BATS

The Biosphere-Atmosphere Transfer Scheme, described by Dickinson et al. [1986, 1992], 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 allow it 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 colour 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 vapour 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 temperatures 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 vapour equations of the climate model as lower boundary conditions.

Several sensitivity studies have been performed on BATS. The one-at-a-time parameter investigations [Dickinson and Henderson-Sellers, 1988, Wilson et al., 1987a, 1987b] 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 it's 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.

2.3 RegCM2

The second generation NCAR Regional climate model (RegCM2) was built upon the National Center for Atmospheric Research-Pennsylvania State University Mesoscale Model version MM4, an atmospheric circulation model. Several of the MM4's physics parameterizations were modified to adapt its use to long-term climate simulations. Most prominently, these are detailed representations of radiative transfer [Briegleb, 1992], surface physics-soil hydrology processes [Dickinson et al., 1992], 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 [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 to date [Bates et al., 1995, Giorgi et al., 1994, Hostetler and Giorgi, 1992].

Here RegCM2 is implemented on 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. BATS was run online with RegCM2 while IHACRES was run offline.

3 SITE DESCRIPTION

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 on 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.

RegCM2 results used in this study were given by the average result of the two grid points closest to the center of the FIFE site. Even though a RegCM2 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].

4 IHACRES ET FORMULATION

Clearly, before the IHACRES runoff model can be used some method for estimating PE in (3) must be chosen. Three formulations were investigated. The first, given in (4), simply uses temperature as a surrogate for PE, while (5) shows the PE formulation suggested by Priestley and Taylor [1972]. It assumes PE is controlled by radiant energy. Equation (6) is the PE formulation of Penman [1956], which contains both energy and advection terms.

$$PE_k = T_k \tag{4}$$

$$PE_k = \frac{\Delta}{\Delta + \gamma}\left(R_n - G\right) \tag{5}$$

$$PE_k = \frac{\Delta}{\Delta + \gamma}\left(R_n - G\right) + \frac{\gamma}{\Delta + \gamma} f(\overline{u})\left(e_a^* - e_a\right) \tag{6}$$

where T is the air temperature near the surface, $\Delta = (de^*/dT)$ is the slope of the saturation water vapour pressure curve, γ is the psychrometric constant, R_n is the specific flux of net incoming radiation, G is the specific flux of heat conducted into the Earth, $f(\overline{u}) = 0.26(1 + 0.54\overline{u})$ where $\overline{u}$ is the mean wind speed at 2m above the surface, and e_a is the vapour pressure in the air with * denoting the saturation value.

Each of the PE equations above becomes successively more complex, requiring the collection of a larger number of meteorological variables in order to implement the formulation. So while (4) is clearly the simplest possibility, it has the advantage of requiring only temperature data which, along with precipitation, is the most commonly available meteorological variable. Both of the other methods require data which are often not available and hence implementation is restricted to locations such as FIFE where all the necessary meteorological variables have been measured, or for use with an atmospheric model which can provide the required variables.

Figure 1 shows the ET estimates given by the three methods above and compares them with the observed ET, for 140 days in 1987 over the FIFE site. These measured data were put together as a site average by Betts and Ball [1998], who used as many as 22 surface flux stations to estimate this site average. Of these 22 surface flux stations, 6 sites measured fluxes by the eddy correlation method and 16 by the Bowen ratio method.

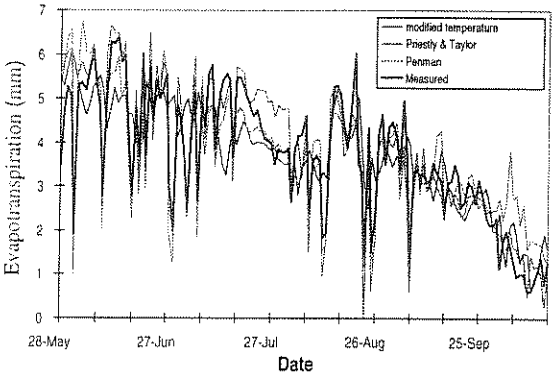

Figure 1: The performance of various ET formulations over FIFE, 1987.

In all cases in Figure 1 the total amount evaporated over the 140 day period is within a few percent of the measured value. Using temperature as a surrogate for PE provides the correct overall trends, even though much of the day-to-day detail is lost. The Priestly and Taylor method picks up the high frequency nature of ET but seems to have more variation than the measured ET with consistent under and/or over prediction. The Penman method seems to perform the best except at the start and end of the records. Discrepancies at the start of the record could be due to the catchment being assumed saturated. This effect though does not appear to last more than a few days.

Subesequent analysis is done using (4) as our PE formulation in IHACRES. This represents the most widely applicable but least accurate method and hence the results reported for IHACRES below are likely to improve when PE formulations given in (5) and (6) are further implemented.

5 MODEL COMPARISONS

In this section we compare the modelling results from BATS and IHACRES over the FIFE site during 1987 and 1988. Here the simplest form of IHACRES has been used, i.e. ET is given by a modified temperature formulation given in (3) and (4). BATS, on the other hand, deals explicitly with many of the processes occurring at the land surface; including canopy interception, evaporation, transpiration and leaf drip from canopy, and movement of soil moisture through three soil layers.

Figure 2 shows the ET estimates given by a two year run of RegCM2/BATS over the FIFE site, along with the results of a two year run of IHACRES and observations taken during intensive field campaigns in both 1987 and 1988. Clearly ET from BATS and IHACRES follow similar trends through the years, though in neither case is the ET estimated in early to mid-summer high enough according to the observations. BATS does much better in terms of reproducing the extent of the day-to-day variability though this does not translate well into reproducing the observations, especially late in 1988 where BATS has consistently under estimates the ET, performing worse than IHACRES.

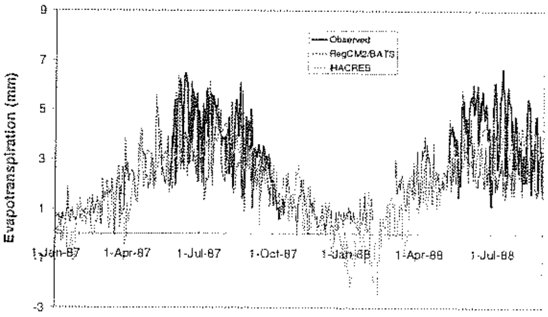

Figure 2: ET estimates over the FIFE site, 1987-1988.

Due to the simple formulation used in IHACRES, whenever the temperature falls below 0°C IHACRES predicts some dewfall or frost. The amount of dewfall predicted is significant and is much more than that predicted by BATS. While no observations were taken during winter we suspect that BATS is closer to the truth for this period.

Given the general under estimation of ET above we would expect there to be an over estimation of runoff, and this is in fact the case for both BATS and IHACRES when driven by RegCM2. When IHACRES is driven by observed climate forcing data it reproduces the observed flow very well, capturing both the flow peaks and recession curves, except the flow peak occurring in late May 1987.

BATS does not reproduce the recession curves at all. Runoff from BATS consists of a series of extremely spiked events. It does capture the runoff peak in late May 1987, which IHACRES fails to capture properly, but it massively over estimates the peaks in April 1987 and 1988. BATS also predicts a series of flow peaks during July 1987, which are not seen in the observations at all and Figure 4 suggests they are simply an artifact of the RegCM2 precipitation. The over estimate of flow

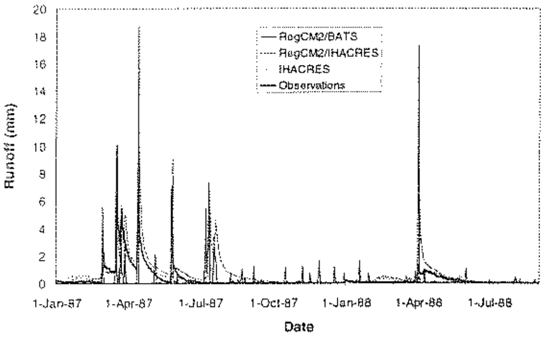

Figure 3: Runoff estimates over the FIFE site, 1987-88.

peaks in April 1987 and 1988 would suggest massive over estimations of precipitation but this is not seen in Figure 4, where only moderate (20-30%) over estimations occur. This precipitation over estimate seems to agree more with the streamflow provided by the RegCM2/IHACRES combination.

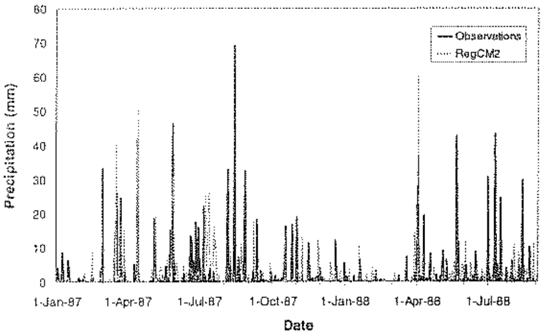

Figure 4: Observed and estimated precipitation over FIFE, 1987-88.

RegCM2 over estimates the total precipitation here by only a few percent, though the distribution of the rainfall is somewhat different. The observations contain many more large precipitation events (>20mm) and many more zero precipitation days. This is typical of a climate model's tendency to "drizzle".

6 DISCUSSION AND CONCLUSIONS

From Figure 1 we see that in order to estimate the trend in ET it is enough to know the temperature, but if the aim is to estimate actual daily values a more complex scheme such as those proposed by Priestley and Taylor [1972] or Penman [1956] is required. Figure 2 shows that using a complex SVAT scheme such as BATS does not necessarily mean that ET estimates will be better than estimates obtained using a simple modified temperature approach. Here no parameter values were used to "tune" the ET estimates. If we were to do this we would expect the BATS estimates to improve considerably more than the IHACRES estimates since it has significantly more "tunable" parameters.

Figure 3 indicates that BATS runoff generation mechanisms are unable to produce even a reasonable hydrograph. Using IHACRES with RegCM2 produces believable streamflow recession curves and reasonable agreement with observed streamflow. A large part of the difference between IHACRES forced by observed climate and IHACRES or BATS forced by RegCM2 modelled climate is explained by the difference in precipitation shown in Figure 4.

In this study we have demonstrated the use of a simple surface hydrology model as the land surface component of a regional climate model. It appears to perform as well as the complex SVAT model currently employed even though it is an order of magnitude less computationally demanding.

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