Coupling a Regional Precipitation Runoff Model to Global and Regional Climate Models

Zengquan Fan and Robert J. Oglesby, Dept. of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907, USA;
Anthony J. Jakeman, Centre for Resource and Environmental Studies, Australian National University

Abstract We have developed a new approach that involves coupling a lumped-parameter rainfall-runoff model into global and regional climate models. This coupled model is based on an explicit water balance that describes the dynamic relationships between precipitation and stream discharge. The rainfall-runoff model IHACRES is calibrated empirically to observations for specific drainage basins, and then used in conjunction with the climate models locally and globally to simulate stream discharge. Our goal is to improve the representation of surface runoff and thus stream discharge in models that are used to simulate climate and climatic change. We are especially interested in the impact of climatic changes on the local, regional, and global hydrologic cycle. We have used IHACRES with NCAR Community Climate Models (CCM) and more recently the new version CCM3 to examine the universality of the empirical parameters of IHACRES. We compared results for the Goulburn Basin (Victoria Australia) to those for the French Broad River (North Carolina US) using the same model parameters that were empirically obtained for the Goulburn Basin. The considerable agreement we obtained suggests that the parameters are capturing essentially universal climatic and surface features.

1. INTRODUCTION

The hydrologic cycle plays a fundamental role in the climate system and is crucial to human life. Successful simulation of this cycle is therefore: (i) a required component of models that are used to simulate the present-day climate and to assess possible future climatic changes and (ii) essential to an understanding of the impacts of climatic changes on human water supplies and other natural resources as well as potential disasters such as floods and droughts. An ideal surface hydrology model component should be capable, on a global or regional basis, of producing accurate time series of water and energy outputs based on inputs of variables such as precipitation and temperature and physical descriptors of the land surface. To date, climate models have used either extremely simple bucket model representations to compute simple evaporation or complicated, biophysical models. The latter usually model the soil-vegetation-atmosphere transfer (SVAT) process and attempt to simulate processes involved in transpiration. Neither of these approaches makes any explicit attempt to balance the overall water budget of the earth system. We are exploring methods by which we can couple a hydrologic, rainfall-runoff model (IHACRES) that explicitly accounts for a surface water balance into global and regional climate models. The budget property makes our model, IHACRES, distinguishable from other coupled hydrologic models for global and regional climate models.

We proceed with this coupling in two stages: (i) a fast-track approach, which makes a very rough (and somewhat subjective) classification of surface types, and applies the IHACRES parameters calibrated locally over a number of control regions (catchments) to regions of the same land types globally; (ii) a long-term approach, in which IHACRES parameters are determined by the physical properties of land surfaces. This latter stage will be accomplished in part based on the understanding gained from the fast-track approach.

We are particularly interested in exploring the generality of IHACRES when applied globally, and the feasibility of coupling SVAT schemes in determining the excessive rainfall which is required by IHACRES. Two basins, Goulburn Basin and French Broad River are initially selected for use in the fast-track approach. The universality of the empirical parameters of IHACRES are investigated when the same set of model parameters are applied to both regions.

2. IHACRES RAINFALL-RUNOFF MODEL

The IHACRES rainfall-runoff model requires rainfall and surface temperature as input, and then returns as output the total streamflow, evaporation, and (in principle) groundwater infiltration. The model was developed by Jakeman et al. [1990] and later enhanced by Jakeman and Hornberger [1993]. The basic IHACRES model is based on three factors: (i) representation of the total streamflow response as a linear convolution of the instantaneous unit hydrograph with rainfall excess or effective rainfall; (ii) approximation of (i) in discretized time by use of a rational transfer function relationship which involves an efficient and flexible parameterization; and (iii) use of a refined, simplified instrumental-variable method of parameter estimation as the major tool to determine the number of identifiable flow components and to estimate their dynamic contributions to the instantaneous unit hydrograph.

The primary convolution integral is expressed by:

$$y(t) = \int_0^t h(t-s)u(s)ds \qquad (1)$$

where point or spatially-averaged rainfall excess u(s) is operated on by h(t-s) and integrated over time t to yield y(t) at some stream location. The function h(t) is well-known as the instantaneous unit hydrograph (IUH) [Chow, 1964]. Here IUH is the total streamflow response resulting from unit rainfall excess applied to the catchment over an infinitesimally short period. While not being physically-detailed, this approach has considerable utility because: (i) it assumes a linear relationship between rainfall excess and streamflow response. This means that only minimal observational data are required in the form of historic time series of precipitation and streamflow. (ii) It employs a plausible and adaptable physical analogy of linear reservoirs configured in series and/or in parallel, which allows the reproduction of total streamflow and its dominant quick and slow components with considerable accuracy.

Note, Equation (1) requires rainfall excess (i.e., that portion of rainfall which becomes streamflow), rather than the total rainfall as input. The rainfall excess cannot be obtained directly from observation, and therefore, the basic IHACRES uses a non-linear loss module to transform total precipitation into effective precipitation, by accounting implicitly for factors such as soil moisture and vegetation characteristics (i.e., evapotranspiration and storage). As described below, this provides a key interface with the climate models, which contain soil-vegetation-atmosphere transfer schemes (SVATs) that can serve as this nonlinear loss module when the climate models and IHACRES are coupled. This also opens a variety of options to adopt different SVATs as non-linear module for IHACRES depending on the complexity being considered and the observational data availability for calibration.

The non-linear module for the current version of IHACRES has three parameters and accounts for the short-term effect of antecedent weather conditions on the current state of soil moisture and vegetation conditions, and long-term effects such as evapotranspiration and storage. The effective rainfall is calculated from the observed rainfall and average surface temperature over a catchment.

3. CLIMATE MODELS

The general circulation model (GCM) we employ is the National Center for Atmospheric Research's Community Climate Model, version 3 (NCAR CCM3). A comprehensive description of the governing equations, physical parameterizations and numerical algorithms of CCM3 is presented by Kiehl et al. [1996]. A user's guide to CCM3 which details the code logic, flow chart, data structures and style, and how to modify and run CCM3 is provided by Acker et al. [1996].

The standard CCM3 is configured as a global, spectral T42, 18-layer hybrid vertical coordinate model with the top of the model atmosphere occurring at approximately 2.9 mb. The spectral transform grid has an effective horizontal resolution of 2.8° × 2.8°. Many aspects of the model formulation and implementation are identical to the CCM2. The basic CCM3 physical parameterizations include a nonlocal boundary layer parameterization and improved radiation and convective parameterizations. A number of important changes have been incorporated into the collection of parameterized physics to address the more serious systematic errors apparent in CCM2 simulations, such as the well known systematic biases in energy budgets at the top-of-atmosphere and surface, and the overestimation of the hydrologic cycle. In addition, the atmospheric model has been made more suitable for coupling to land, ocean, and sea-ice component models, and thus an optional slab mixed-layer/sea ice model is provided for the coupling, see Bettge et al. [1996]. The clear-sky radiation formalism includes the incorporation of trace gases (CH_4, N_2O, CFC11, CFC12) in the longwave parameterization, and the incorporation of a background aerosol (0.14 optical depth) in the shortwave parameterization. Improvements in all-sky radiation include the adoption of diagnosed cloud optical properties (effective radius and liquid water path), the incorporation of the radiative properties of ice clouds, and a number of minor modifications to the diagnosis of convective and layered cloud amount. The formulation of the atmospheric boundary layer parameterization has been revised. Parameterized convection has also been modified to use the deep moist convection formalism. Surface roughness over oceans is diagnosed as a function of surface wind speed and. The combination of these changes to hydrological and radiation components results in substantial reduction in magnitude of the hydrologic cycle and the associated latent heat transfer, which used to be overestimated in former versions of the model.

The Land Surface Model (LSM) developed by Bonan [1996] for land surface processes is incorporated into CCM3. This sophisticated one-dimensional land surface model provides a comprehensive treatment of energy, momentum, water, and CO_2 exchange between the atmosphere and land. The model accounts for ecological differences among vegetation types, hydraulic and thermal differences among soil types, and allows for multiple surface types including lakes and wetlands within a grid cell. LSM replaces the prescribed surfaces properties (i.e., wetness, snow cover, and albedo) in CCM2 with diagnosed variables, and replaces the land surface fluxes in CCM2, using parameterizations that include hydrological and ecological processes.

The regional climate model, RegCM2, has the same basic dynamic component as that in the standard version of the Pennsylvania State/ NCAR Mesoscale Model (MM4) as described in papers by Anthes and Warner [1978], and Anthes et al. [1987]. The MM4 is a hydrostatic, compressible, primitive equation, terrain following sigma-vertical coordinate model. The RegCM2 version of the MM4, adapted for climate studies, has been used in runs ranging from monthly to multi-year over different regions of the world, see Giorgi et al. [1993a, 1993b, and 1994]. RegCM2 includes parameterizations of radiative transfer, planetary boundary layer, surface physics, convective rain and pressure gradient force which make it more suitable than the standard MM4 for climate studies. A typical RegCM2 domain is about 60 points in longitude, 50 points in latitude and 17 vertical levels (from the surface to 80 mb), with 7 levels in the lowest 1.5 km of the troposphere, to allow for better resolution of the planetary boundary layer. Initial and lateral boundary conditions are provided typically by both ECMWF analyses of observations and CCM2 model output.

4. METHODOLOGY

4.1 Extending the Non-linear Module Of IHACRES

IHACRES consists of two related, but technically separated modules: a non-linear loss module for the transformation from rainfall to effective rainfall, and a linear module to translate effective rainfall into runoff. This separation greatly facilities the extension of the non-linear module to include the effects of new physical processes. It is also possible to consider vegetation processes explicitly by use of a SVAT scheme for the non-linear module, as more insight into the physical and physiological processes (such as transpiration of plants, soil drainage, and leaf interception etc.) is obtained. In this project, we will increase the complexity of the non-linear module gradually, to identify the most proper degree of complexity for the interaction between climate models and IHACRES. Obviously the more parameters involved in the model, the more difficult the calibration.

4.2 Fast Track Approach

In the fast track approach, IHACRES is calibrated empirically to observations of discharge for specific drainage basins, and then used in conjunction with the climate models locally and globally to simulate evaporation and stream discharge. We make a very rough classification of land surfaces into several types according to physical properties pertinent to hydrological process, and then assign each land grid box of the climate model with one of these types. After that, we can apply the IHACRES, which is calibrated in one region, to those grid boxes with the same surface type as this calibration region. The fast track approach serves two purposes. First it will define the range of 'parameter space' necessary for categorizing different basins, and give us some sense of what types of basins may be more problematic than others. Second, it will test the feasibility of more complicated interactions between climate models and IHACRES through the non-linear module.

4.3 Full (Long-term) Approach

In this approach, physical descriptors for important characteristics of drainage basins are being developed that will largely eliminate the need for empirical calibration with observed discharge and therefore allows for more fully predictive computations to be made.

In order to be capable of predicting the hydrologic response to climatic changes, the parameters in IHACRES must be changed accordingly, since they are calibrated only for the current, specific and local conditions of climate and surface. We thus are developing a model to account for the changing climate conditions and the physical features of the land surface. Physical catchment descriptors (PCDs) and hydrological dynamic response characteristics (DRCs) are used as a physically-based model, where DRCs are determined by PCDs through the relationships within regions of hydrologic similarity. DRCs can typically be represented by 5-7 parameters, which are obtained by calibration of a precipitation-runoff model on a few years of data. PCDs are used mainly to define the spatial distribution of hydrological units within the catchments, and therefore to be able to determine DRCs under the reasonable perception that the ideal calibrated DRCs should be independent of the calibration data sets (i.e., the climate sequence in the estimation record. Each unit is selected to have generally similar hydrologic behavior on the basis of its vegetation, soils, and terrain. In the PCD-DRC scheme, we use PCDs to determine DRCs, and in turn use DRCs and precipitation to predict stream discharge and evapotranspiration. Further studies are expected to reveal which of the PCD-DRC relationships are region-dependent, i.e., transferable, as well as understanding where successful relationships can be developed at larger scales.

5. EXPERIMENT AND RESULTS

As the initial efforts for the fast-track approach, a series of experiments have been made in which IHACRES is driven off-line by CCM3. A 10-year T42 seasonal simulation, using climatological monthly averaged Sea-Surface Temperature (SST), is used for this experiment. A number of large basins (over 500 km^2), which have been well studied and have been used previously in IHACRES, are selected as regions of interest. The CCM3 grid cell that contain the corresponding region of interest is identified. The daily temperature and rainfall simulated by CCM3 are used as inputs to drive IHACRES to yield simulated runoff explicitly and evapotranspiration implicitly. Such regions of interest include Goulburn Basin (Victoria Australia) and the French Broad River (North Carolina US). Both basins similar in that they are mid-latitude, mountainous regions on the southeast side of continents, but they have very different geologic and soil substates. For comparison with CCM3 simulation and testing the universality of model parameters, the observational data of daily rainfall, streamflow and surface temperature are used. The observation period available for analysis were 16 years (from 1975 through 1990) for the Goulburn Basin, and 36 years (1953 through 1988) for the French Broad River.

To assess how IHACRES simulates runoff with input of observed precipitation and surface temperature, IHACRES simulation is compared with the observed stream discharge (a standard proxy for runoff). Figure 1 shows the observed and IHACRES simulated streamflow on a daily basis over the Goulburn Basin. The simulated daily runoff catches all the major peaks and base flows, as well as the basic trend of time evolution of the observed discharge, although some insignificant discrepancies exist, especially at periods corresponding to small specific rainfall events. The long-term mean seasonal variation shown in Figure 2, indicates that the simulated runoff is consistent with that of the observed climatology, but is generally underestimated for most months. Figure 3 shows the simulated stream flow for the French Broad River using IHACRES parameters obtained from the calibration over the Goulburn Basin. The considerable agreement we obtained suggests that the parameters are capturing essential climatic and surface features. The geology and soils make the agreement less than perfect, but are second order and do not affect the overall qualitative agreement.

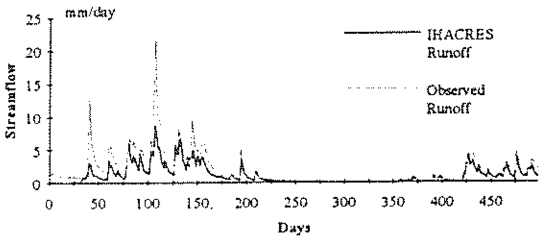

Figure 1: The daily distribution of Observed and IHACRES simulated streamflow for the Goulburn Basin.

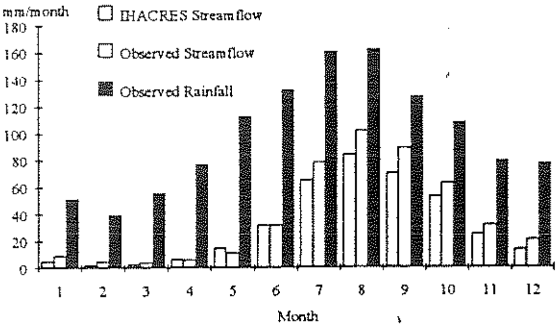

Figure 2: Mean monthly variations of observed rainfall and streamflow, and IHACRES simulation from the observational data of daily rainfall and surface temperature, over the Goulburn Basin for a 16-year period (from 1975 through 1990).

Figure 4 shows the 10-year mean monthly CCM3 simulated rainfall and the observed long-term mean over the Goulburn Basin, as well as the IHACRES simulated runoff using CCM3 data. The magnitude of CCM3 precipitation is close to observation for some months, but in general is overestimated for winter months, and underestimated for summer months. Although significant rainfall occurs in CCM3 simulation with the standard CCM3 LSM package, LSM yields virtually no runoff during the entire 10 year run; (in other words, Australia's largest river system does not exist). On the other hand, IHACRES produces runoff when driven by the above CCM3 results, and the runoff generally follows seasonal variation pattern of the rainfall and therefore is much more reasonable in context of rainfall-runoff processes. The results with CCM3 data being used to drive IHACRES for the French Broad river (figure not shown), show the characteristics similar to the Goulburn Basin.

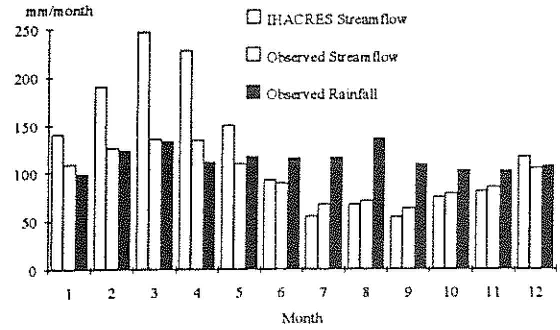

Figure 3: Mean monthly variations of the observed and IHACRES simulated streamflow, and the observed rainfall over the French Broad River basin, for a 36-year period (from 1953 through 1988). The simulation uses parameters empirically calibrated for the Goulburn Basin.

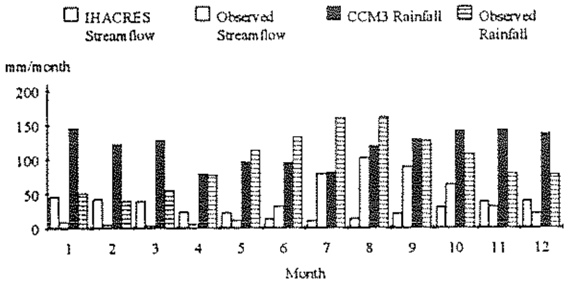

Figure 4: IHACRES simulated streamflow for the Goulburn Basin, using CCM3 data made with a T42 10-year simulation. The observational data of streamflow and rainfall are plotted for comparison.

6. DISCUSSION AND CONCLUSION

In this project, we are particularly interested in exploring the following aspects: (i) Can IHACRES calibrated over only a limited number of regions (or basins) be incorporated into the climate models universally over the globe, i.e., how sensitive and how large the variability from region to region, are the model results to the parameters of IHACRES? (ii) Can we find realistic physical descriptors for IHACRES based on the surface type such as vegetation, topography, soil texture and surface slope? i.e., how to incorporate SVAT schemes into IHACRES? (iii) Other climatic factors can obviously affect the effective rainfall. For example, surface wind speed is an influencing factor for evaporation process, and currently is not explicitly considered in IHACRES.

This study shows that the incorporation of dynamical water balance model (such as IHACRES) into climate models is a viable approach for the parameterization of hydrologic processes. CCM3 itself yields virtually no or negligible amount of surface runoff over the two regions we studied. When off-line coupling IHACRES into CCM3, significant surface runoff is reproduced and therefore is more reasonable to compare with the observation, although its accuracy is confined greatly within the context of the simulated precipitation and other factors , such as surface temperature.

The current study focuses the coupling between CCM3 and IHACRES. In the future, RegCM2 coupling with IHACRES will also be used in order to study the regional climate in more detail.

7. ACKNOWLEDGMENTS

This research has been supported in part by IBM Environmental Research Program, Dr. Joseph Sarsenski, Program Manager.

8. REFERENCES

Acker, T.L., L.E. Buja, J.M. Rosinski, and J.E. Truesdale, Users' *Guide to NCAR CCM3,* NCAR Tech. Note, NCAR/TN-421+IA, 210pp., Boulder, Colorado, 1996.

Anthes, R.A., E.Y. Hsie and Y.H. Kuo, *Description of the Penn State/NCAR Mesoscale Model Version 4 (MM4),* NCAR Technical Note, NCAR/TN-282+STR, 66pp., Boulder, Colorado, 1987.

Anthes, R.A. and T.T. Warner, Development of hydrodynamical models suitable for air pollution and other mesometeorological studies, *Mon. Wea. Rev.*, **106**, 1045-1078, 1978.

Bettge, T.W., J.W. Weatherly, W.M. Washington, D. Pollard, B.P. Briegleb, and W.G. Strand Jr, *The NCAR CSM Sea Ice Model*, NCAR Tech. Note, NCAR/TN-425+STR, 25pp., Boulder, Colorado, 1996.

Bonan, G.B., *A Land Surface Model (LSM Version 1.0) for Ecological, Hydrological, and Atmospheric Studies: Technical Description and User's Guide*, NCAR Tech. Note, NCAR/TN-417+STR, 150pp., Boulder, Colorado, 1996.

Chow, T.V. (Editor), *Handbook of Applied Hydrology*, McGraw-Hill, New York, 1964.

Giorgi, F., M.R. Marinucci and G.T. Bates, Development of a second generation regional climate model (RegCM2), I: Boundary layer and radiative transfer processes, *Mon. Wea. Rev.*, **121**, 2794-2813, 1993a.

Giorgi, F., M.R. Marinucci, G.T. Bates and G. DeCanio, Development of a second generation regional climate model (RegCM2), II: Convective processes and assimilation of lateral boundary conditions, *Mon. Wea. Rev.*, **121**, 2814-2832, 1993b.

Giorgi, F., S.W. Hostetler and C. Shields Brodeur, Analysis of the surface hydrology in a regional climate model, *Quart. J. Roy. Meteor. Soc.*, **120**, 161-183, 1994.

Jakeman, A. J., and G. M. Hornberger, How much complexity is warranted in a rainfall-runoff model? *Water Resour. Res.*, **29**, 2637-2649, 1990.

Jakeman, A. J., T.-H. Chen, J. A. Post, G. M. Hornberger, I. G. Littlewood, and P. G. Whitehead, Assessing uncertainties in hydrological response to climate at large scale. In: *Macroscale Modelling of the Hydrosphere*, W. B. Wilkinson (ed.) IAHS Publication No. 214, pp. 37-47, 1993.

Kiehl, J.T. , J.J. Hack, G.B. Bonan, B.A. Boville, B.P. Briegleb, D.L. Williamson, and P.J. Rasch, *Description of the NCAR Community Climate Model (CCM3)*, NCAR Tech. Note, NCAR/TN-420+STR, 152pp., Boulder, Colorado, 1996.