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

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ABSTRACT We have developed an entirely new approach that involves coupling a lumped-parameter rainfall-runoff model (IHACRES) into global (CCM2) and regional (RegCM2) climate models. This coupled model is based on an explicit water balance that describes the dynamic relationships between precipitation and stream discharge. Our goal is to improve the representation of surface runoff, stream discharge, and evaporation in models that are used to simulate climate and climatic change. We are especially concerned with the impact of climatic changes on the local, regional, and global hydrologic cycle.

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 that attempt to simulate the poorly-known processes involved in transpiration. Neither of these approaches makes an 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 distinguished 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 limited regions (catchments) to 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 upon the understanding gained from the fast-track approach.

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 involve 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 that the above discussion focuses on rainfall excess, i.e., that portion of rainfall which becomes streamflow, not total precipitation. 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 essentially 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.

Fig.1 gives an example of comparisons between IHACRES model simulation and the observed discharge over the Ovens River at Bright for 730 days starting from March 3, 1977. The simulated discharge catches all the major peaks and base flows, as well as the basic trend of time evolution of the observed discharge. Only some minor discrepancy exists at some period with small rainfall events.

3. CLIMATE MODELS

The GCM we employ is the National Center for Atmospheric Research's Community Climate Model, version 2 (NCAR CCM2). The CCM2 is a global, pseudo-spectral T42 18-layer hybrid 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°. Shortwave properties of water clouds are parameterized following Slingo (1989). A δ-Eddington approximation calculates solar absorption for 18 spectral bands, and the longwave radiation is similar to that in CCM1. CCM2 adopts a shape-preserving semi-Lagrangian transport scheme for advecting water vapor. A comprehensive account of the routines in CCM2 are described in Hack et al. (1993), while basic results and comparisons with observations are given by Hack et al. (1994). Hansen et al. (1995) describe how CCM2 has been implemented on ANU computers as a precursor to this coupling model.

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; Anthes and Warner 1978, 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 (e.g., Giorgi et al. 1993a, b; 1994). RegCM2

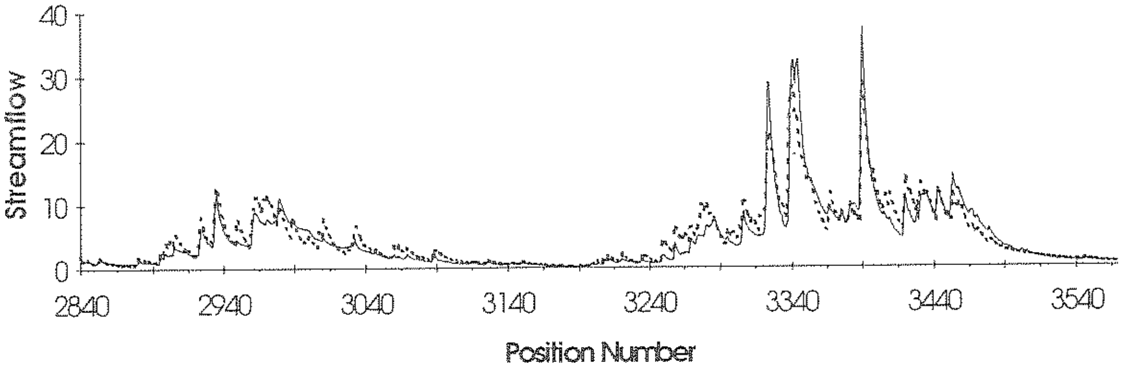

Figure 1: Comparison between IHACRES model simulated (dashed line) and the observed (solid line) discharge over the Ovens River at Bright for 730 days starting from March 3, 1977.

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. Larson et al. (1995) describe how RegCM2 has been ported to ANU computers and used to simulate the climate of Australia.

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. DISCUSSION

Key questions that we encounter as we proceed with this study include: (i) Can IHACRES calibrated in only a limited number of regions (or basins) be applied with CCM2 or RegCM2 universally over the globe, i.e., how sensitive is the model 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?

(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.

The major difficulties arise from the non-compatibility in both spatial and temporal scales between IHACRES and a climate model, as well as the data availability for model calibration and verification: (i) IHACRES is using daily data as this is a conveniently available temporal scale for observations of discharge, while climate models typically have time steps only of a few minutes (for example, CCM2 has only a 20-minute time step for forward integration the standard version). This means IHACRES cannot be called for each time step. In other words, the evaporation obtained from it cannot be updated for every time step. (ii) IHACRES is calibrated on a catchment or basin scale, which is incompatible with the grid box of the GCM. Usually a catchment is far smaller than a GCM gridbox. This requires either up-scaling the IHACRES catchments into a grid box, or down-scaling the grid box into several catchments, (i.e., consideration of sub-grid variability). (iii) Considerable observational data and geographical information are needed for both approaches (fast track and long-term) in order to accomplish the coupling of GCMs and IHACRES. An extensive calibration of IHACRES over a globally representative range of catchments must be done before a meaningful usage of IHACRES in a GCM to simulate global climate.

6. ACKNOWLEDGMENTS

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