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Coupled regional modelling of atmospheric–hydrologic processes for reconstruction of hydro-climate data and climate change assessment

M. L. KAVVAS[1], **Z. Q. CHEN**[2], **N. OHARA**[1], **M. L. ANDERSON**[2], **A. J. SHAABAN**[3] **& M. Z. M. AMIN**[3]

1 *Hydrologic Research Laboratory, Dept of Civil and Environmental Engineering, University of California, Davis, California 95616, USA*
mlkavvas@ucdavis.edu

2 *California Dept of Water Resources, 1416 9th St, Sacramento, California 95814, USA*

3 *National Hydraulics Research Institute of Malaysia (NAHRIM), 43300 Seri Kembangan, Selangor, Malaysia*

Abstract We describe the modelling of the Earth system over regions of varying spatial scale as a fully-coupled system of atmospheric processes aloft, coupled with the atmospheric boundary layer, land surface processes, and surface and subsurface hydrological processes. The interactions among the various component processes within the Earth system over a specified region are described, and an approach for modelling these interactions toward reconstruction of sparse hydro-climate data and assessment of climate change is discussed. The application of the resulting Regional Hydro-Climate Model (RegHCM) to several regions around the world is presented.

Key words coupled atmospheric–hydrologic processes; regional hydro-climate model

INTRODUCTION

In order to perform simulation studies of the water balances over a geographical region it is necessary to first develop a regional hydro-climate model for the region, and then validate this model with historical data. Once this model is validated against historical atmospheric and hydrological data, it can then be used to study the water balances of the region under various water resources development scenarios. The regional hydro-climate model may be utilized to simulate precipitation (rain or snow), radiation, surface temperature, wind, snowmelt, interception, infiltration, soil water flow, direct runoff, evapotranspiration, and irrigation water demand conditions over the geographical region of interest, and to simulate streamflow at selected river locations over the selected region.

Over many regions of the world historical hydro-climate data are not available at the desired fine time–space coverage for performing reliable water balance studies. Hence, it is necessary to reconstruct such historical data by means of a regional hydro-climate model that will downscale the historical coarse-spatial-resolution (~2.5°) atmospheric data from US National Center for Environmental Prediction (NCEP) to a sufficiently fine grid resolution (~9–20 km range) over the modelled region. For studies on the assessment of the impact of climate change on the water resources of a region one faces a similar problem with the coarse-resolution (~180–450 km) climate simulation data from general circulation models (GCMs). Again, in order to be able to perform meaningful water balance studies over the region of interest, it is necessary to downscale the GCMs' climate simulation data to fine grid resolution (~9–20 km).

In order to perform water inventory studies over various geographical regions around the world, a Regional Hydro-Climate Model (RegHCM) was developed. RegHCM has four major modules: an atmospheric module, a snow module, a soil/vegetation module, and a river module. The RegHCM will be described first, and then its applications to Peninsular Malaysia and to the Tigris-Euphrates river basin will be presented.

REGIONAL HYDRO-CLIMATE MODEL (RegHCM)

The atmospheric module of RegHCM utilizes the MM5 (fifth generation mesoscale model of US NCAR (National Center for Atmospheric Research)/Pennsylvania University) (Grell *et al.*, 1995), and is capable of simulating meteorological variables, such as air temperature, precipitation, radiation, relative humidity and wind speed at hourly time intervals, and at any desired spatial grid resolution as fine as 1 km. MM5 is a nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict regional-scale atmospheric circulation over any area on Earth. It has many options for modelling cumulus convective precipitation, cloud moisture microphysics, radiation, etc. The atmospheric module of MM5, as the atmospheric module of the RegHCM, is able to provide its soil/vegetation module with the necessary inputs, such as the spatially distributed precipitation, temperature, radiation, specific humidity and wind fields in time and space. These inputs are essential for the computation of such hydrological processes as evapotranspiration, infiltration and runoff.

Water resources in many regions around the world (such as California, Tigris-Euphrates watershed, etc.) rely on winter rainfall and snowmelt. The winter precipitation is mostly stored as snowpack on the mountains until spring comes. As such, the modelling of snow is an indispensable component of the water balance studies in such regions. A physically-based distributed snow model (Ohara & Kavvas, 2006) has been developed and incorporated into the RegHCM. The snow module of RegHCM is capable of estimating snowpack depth, snow water equivalent, and snowmelt from the snowpack. It computes snow accumulation, snowmelt and snow cover fraction by applying the energy balance approach in the snow pack. In this model, the snowmelt process is essentially described by three equations: an energy conservation equation for snow surface temperature, a mass conservation equation for snow depth, and a depth-averaged snow density equation. It is assumed that the snowpack is made up of three layers: a skin layer, a top active layer and a lower inactive layer. The thickness of the active layer and snow surface temperature are controlled by surface energy exchange. It is assumed that the vertical temperature of snow varies linearly with depth until the freezing depth is reached (Kondo & Yamazaki, 1990). Below this level the temperature remains constant at 0°C. The snow surface energy exchange in this model consists of the following components: short-wave and long-wave radiation, sensible heat flux, latent heat flux, and rain heat flux when rain falls on snow. Air temperature, wind speed, precipitation and relative humidity are the required inputs to the snow module of RegHCM, and are provided by the MM5 atmospheric module of the RegHCM.

The soil/vegetation module of RegHCM is capable of predicting the distribution patterns of infiltration, soil water content profile, soil water storage, direct runoff volume, soil temperature, and evapotranspiration rates as areally-averaged hydrological quantities at the scale of each computational grid area (Chen *et al.*, 1994a,b; Kavvas *et al.*, 1998). The soil/vegetation module uses the land hydrological components of the Integrated Regional-Scale Atmospheric–Hydrologic Model IRSAHM (Kavvas *et al.*, 1998) or of the Watershed Environmental Hydrology (WEHY) model (Kavvas *et al.*, 2004). It is fully coupled with the MM5 atmospheric module of RegHCM through a boundary layer component (Kavvas *et al.*, 1998) which is based upon Monin-Obukhov parameterization and Blackadar's vertical divergence scheme. The soil/vegetation module of RegHCM also computes consumptive water use by crops in a region and the required net water withdrawal quantities from the rivers in the region. The land surface hydrological flow processes in the current soil/vegetation module of RegHCM are described by five model components: an atmospheric boundary layer model which does the coupling between the land surface and the atmosphere, a heat balance model for computing the temperature of the top soil layer, a vegetation model for precipitation interception by vegetation, an evapotranspiration model, and a soil water flow model for infiltration and direct runoff. The first two models deal with both moisture fluxes and heat fluxes, while the last three models deal only with moisture (water) fluxes. Since the moisture fluxes and heat fluxes are closely related, all five models are coupled with each other and are solved together in RegHCM. The vegetation model computes interception of precipitation by vegetation, throughfall to the ground, and direct evaporation from vegetation leaves which requires the temperature values that are estimated from the heat balance model and atmospheric boundary layer model. However, the heat balance model requires the evapotranspiration values, which are estimated from the soil water flow model and the evapotranspiration model. The soil water flow model predicts the ground surface water content and soil water storage, and the direct runoff volumes at the land surface, which are calculated from the infiltration excess of rainfall by means of areally-averaged rectangular profile variably-saturated flow equations (Chen *et al*., 1994a,b).

RegHCM's atmospheric boundary layer model uses a modified Monin-Obukhov similarity theory (Haltiner & Williams, 1980; Kavvas *et al*., 1998) to describe the temperature, wind, and moisture distributions in the vertical direction at the surface layer between the first atmospheric layer and the land surface. This surface boundary layer model, together with RegHCM's atmospheric module and the land surface heat balance model, supplies the land-surface water flow model with the temperature and humidity of the air above the plant canopy, the ground surface temperature, the bulk transfer coefficient, and the surface pressure which are used to determine the saturated mixing ratio at the ground surface. The boundary layer parameters are dependent upon the aerodynamic roughness height, the potential temperature of the first layer of the atmospheric model, and the temperature of the land surface. The land surface moisture flux to the atmosphere (evapotranspiration), is estimated from the turbulent velocity scale (friction velocity) and the humidity scale that are scaling state variables of the surface boundary layer on the one hand, and from the soil water flow process and plant physiology that dictate the soil moisture availability, on the other. Consequently, in order to be able to predict the future evapotranspiration (ET) fluxes from the land surfaces to the atmosphere under various atmospheric boundary layer states (unstable, neutral, etc.), it is necessary to have a fully coupled atmospheric boundary layer/land surface hydrology model that is then coupled to the model of the upper atmosphere (MM5's atmospheric module). The feedbacks, described above, can be summarized by Fig. 1 below. As seen from Fig. 1, under Monin-Obukhov similarity theory (Haltiner & Williams, 1980), the state of the atmospheric constant flux surface boundary layer, determined in terms of surface layer scaling variables friction velocity u_*, temperature scale θ_*, and humidity scale q_* and its momentum, temperature and humidity profiles, are dependent on land surface temperature T_{surf}. However, T_{surf} is an outcome of the heat budget of the land surface which, in turn, varies with ET (denoted by "E" in the figure) and sensible heat flux H, as well as with the ground heat flux G which itself is a function of the state of soil moisture. As such, the land/atmosphere system is a nonlinear system with very strong feedbacks between the land surface processes and atmospheric processes. In Fig. 1, in addition to the previously defined variables, q(z) denotes specific humidity profile as function of elevation z, P denotes precipitation, R_n denotes net radiation, w_s denotes water content at the soil surface, θ_1 and q_1 are the potential temperature and specific humidity at the first atmospheric layer, and $F_{\theta\sigma 1}$ and $F_{q\sigma 1}$ are respectively the vertical turbulence heat and moisture flux divergences at the first atmospheric layer, which is taken at $\sigma = 0.995$ atmospheric pressure in RegHCM. Consequently, a realistic way for the prediction of the ET and sensible heat fluxes is to solve all the land/atmosphere system equations together in a completely coupled way. This is the approach taken in RegHCM.

The heat balance model estimates the soil surface temperature by taking into account all of the surface heat fluxes, i.e. solar radiation, long-wave radiation, sensible heat flux, latent heat flux and heat conduction from deep ground to the surface soil layer. The sensible heat flux is estimated by means of the boundary layer model with the estimated land surface temperature, and it is computed using the turbulent velocity scale and temperature scale of the Monin-Obukhov similarity theory (Haltiner & Williams, 1980). The vegetation model is based on the physical concepts proposed by Deardorff (1978). A single layer with negligible heat capacity is used to represent vegetation in this model. The interception component of this model is used to estimate the liquid water storage on vegetation leaves (see Kavvas *et al*., 1998, for details).

The core of the land-surface water flow model in RegHCM is the spatially horizontally averaged rectangular water content profile model for computing infiltration/unsaturated flow over areally heterogeneous soils (Chen *et al*., 1994a,b). Water movement in the soil at laboratory scale

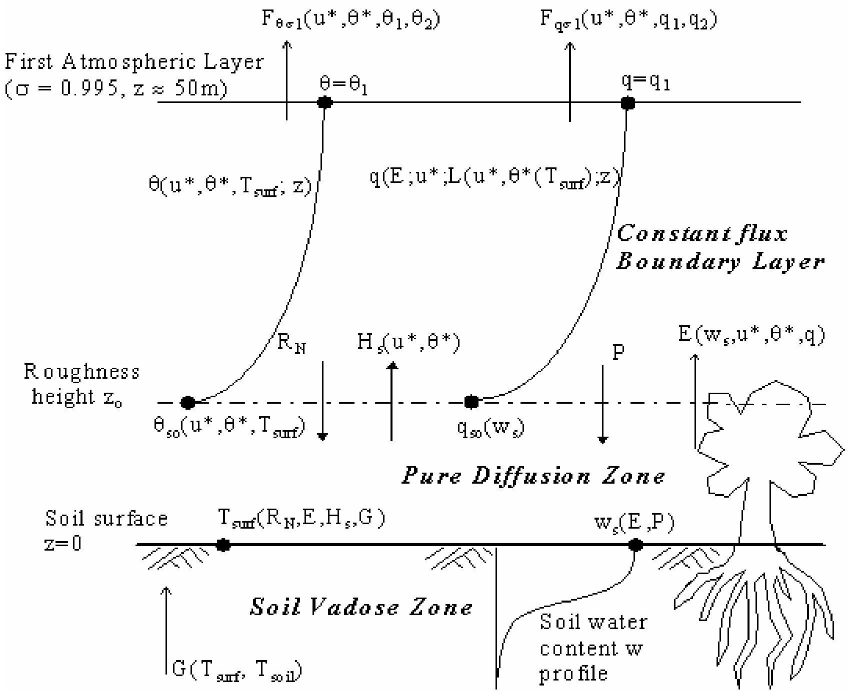

Fig. 1 Coupling of atmospheric and land hydrological processes by means of the atmospheric boundary layer (from Kavvas *et al.*, 1998).

is frequently described by Richards equation, and the validity of this equation at the laboratory scale (point scale) has been established. However, Richards equation at the laboratory scale is a nonlinear partial differential equation and is based on Darcy's law. Simple geometric or arithmetic averages to describe the effective properties at a large scale fail to predict correct results. It has been shown that Richards equation at point scale is not suitable for determining the soil water content and fluxes at the 10–60 km grid scale of regional hydro-climate models (Chen *et al.*, 1994b). Usually, the depth of the soil that interacts with the atmosphere is of the order of metres. In this case, the scale of soil heterogeneity in the horizontal directions is much larger than the scale of soil heterogeneity in the vertical direction. The mean flow in the unsaturated soil over a large grid area in the order of a square km is essentially in the vertical direction over such large scales. Spatial variability of soil parameters that govern moisture availability becomes very significant at the grid scales typically used in such regional models. The soil/vegetation module of RegHCM treats the spatial variability of hydraulic conductivity as the primary cause of spatial variability in soil water content profiles that are approximated by rectangles in the infiltration model. By ensemble averaging the soil water content profiles with respect to the statistical behaviour of the hydraulic conductivity within a model grid (Kavvas *et al.*, 1998, 2004), the soil water flow model of RegHCM predicts grid area-averaged infiltration to the soil layer, the direct runoff over the soil surface, the grid area-averaged soil water flow/profile conditions in the soil layer, and grid area-averaged evapotranspiration to the atmosphere over the land surface. The evapotranspiration rate is estimated according to the concept of moisture availability and the atmospheric conditions, following the approach of Noilhan & Planton (1989).

A detailed description of the parameters for the soil/vegetation module of RegHCM has been given by Kavvas *et al.* (1998). The parameters that describe the soil characteristics are constants for all simulations. Vegetation related parameters, such as vegetation cover fraction and leaf area index, change with time at monthly time intervals.

The river module is capable of routing river flow through the stream network, lakes and reservoirs in the basin. It can also handle diversions from the rivers. It is based on the Muskingum river routing and storage indication algorithms.

RESULTS

REGHCM application to Peninsular Malaysia for assessment of the impact of climate change

The future projections of climate change by means of Global Climate Models (GCMs) of the Earth provide fundamental coarse-grid-resolution hydroclimate data for studies of the impact of climate change on the hydrological regime of a region. However, their coarse grid resolution is insufficient for the description of the local topography and land features. Hence, the GCM climate change simulations data need to be downscaled over the region of interest to a sufficiently fine grid scale in order to be able to assess the impact of climate change on the hydrological regime there. The climate change simulations of the Coupled Global Climate Model of the Canadian Center for Climate Modeling and Analysis (CGCM1 GCM) at around 410 km grid resolution over Peninsular Malaysia, based on the IS92a "business as usual" future emissions scenario, were downscaled by a RegHCM of Peninsular Malaysia (RegHCM-PM) to the scale of the watersheds of Peninsular Malaysia (PM) through three nested domains, respectively at 81 km grid resolution, 27 km grid resolution and 9 km grid resolution, and hourly time intervals, in order to assess the impact of future climate change on the hydrological regime over its prominent watersheds. The studied watersheds over PM are shown in Fig. 2. RegHCM-PM was calibrated objectively from the existing land databases, and was validated by historical hydroclimate data over PM during the 1984–1993 historical period. The climate simulation data for the historical period, produced by CGCM1, were used for initial conditions at all domains, and for the boundary conditions at the outermost 81 km resolution domain for RegHCM-PM simulations of the historical hydroclimate over PM during this period. These simulations were then compared against ground observations for the validation of the RegHCM-PM. A representative result of the comparisons between RegHCM-simulated and ground raingauge-observed monthly rainfall over PM watersheds, is shown for the Kelantan watershed in Fig. 3. Comparisons for air temperature and streamflows were also performed as part of the validation, but are not shown due to the space limitation.

Once the RegHCM-PM was validated, it was then used for downscaling the 2025–2034 and 2041–2050 future climate simulations of CGCM1 onto the PM region, with the same nesting procedure as in the historical period, for the IPCC IS92a emissions scenario that corresponds to a gradual yearly 1% increase in CO_2. Since the CGCM1 future climate simulation data were available to the authors only for the 2025–2034 and 2041–2050 periods in three-dimensional format that is necessary for hydrodynamic downscaling by MM5, these two 10 year periods were used for

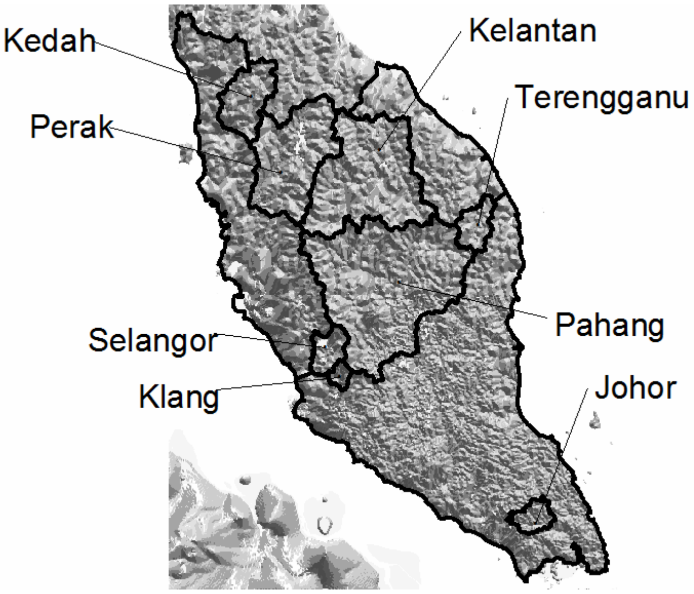

Fig. 2 Peninsular Malaysia watersheds that were studied for climate change impact assessment on their hydrological regimes.

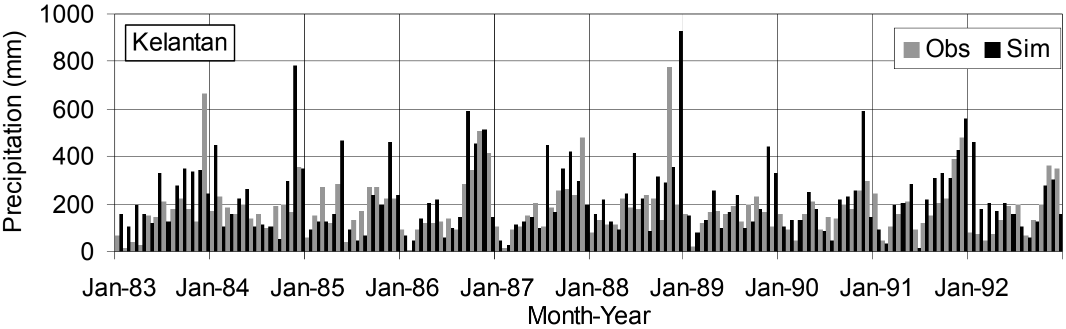

Fig. 3 Comparison between RegHCM-PM simulated and ground raingauge observed monthly rainfall at Kelantan watershed of PM.

the climate change assessments over PM. The downscaled hydroclimate data over PM for the future 2025–2034 and 2041–2050 periods were then compared against the corresponding historical hydro-climate data for the 1984–1993 period in order to assess the impact of climate change on the hydrology and water resources of PM in terms of rainfall, air temperature, evapotranspiration, soil water storage and river flow by graphical and statistical methods. Here, due to the space limitation, we focus on the river flow volumes. In Fig. 4 an assessment of the simulated historical and future mean monthly flows in the watersheds of Peninsular Malaysia (PM) that are shown in Fig. 2, are given for the historical (1984–1993) and future (2025–2034 and 2041–2050) periods, with the 95% confidence bands around the future flows. It is clear from Fig. 4 that high flow conditions will be magnified in some PM watersheds during the wet months, while low flows will be lower in some PM watersheds during the dry months at 95% confidence level.

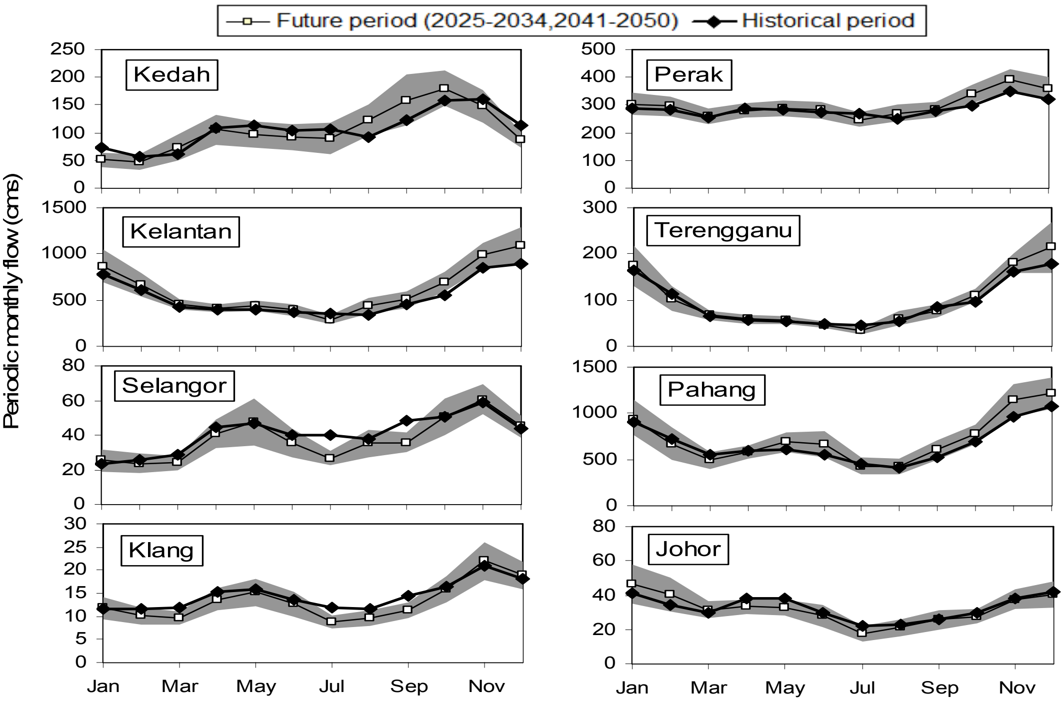

Fig. 4 Comparison of mean monthly flows at Kedah, Perak, Kelantan, Terengganu, Selangor, Pahang, Klang and Selangor watersheds of Peninsular Malaysia during historical and future periods. The grey bands in the figures denote the 95% confidence bands around future mean monthly flows.

Application of RegHCM to Tigris-Euphrates watershed for the reconstruction of historical hydro-climate data

The Tigris-Euphrates (TE) watershed covers a drainage area of 967 340 km^2, and has sections in Turkey, Syria and Iraq, with tributary flows coming from Saudi Arabia and Iran. In order to perform any water balance study over this large watershed, historical precipitation and runoff data are needed. However, very little historical hydro-climate data are available in the watershed. Therefore, a study was performed in order to reconstruct historical precipitation data at 15-km resolution over the whole watershed, and reconstruct historical streamflow data at selected sites along the Euphrates and Tigris rivers by means of RegHCM which was implemented for the watershed. After its calibration and validation over the watershed, the Regional Hydro-Climate Model of the Tigris-Euphrates watershed was called RegHCM-TE.

The US National Center for Atmospheric Research (NCAR) and National Center for Environmental Prediction (NCEP) have recreated historical atmospheric data over the whole world at 2.5° latitude × 2.5° longitude spatial grid resolution and at 6-h time increments from the 1950s to the present. The NCAR/NCEP re-analysis data result from the analysis of data sources such as land surface, ship, rawinsonde, pibal, aircraft and satellite. These data are assimilated into a GCM to create an atmospheric database that is uniform in space and time. Over the TE watershed, the 2.5° resolution corresponds approximately to a distance of about 285 km. At such spatial resolution it is impossible to obtain the necessary spatial detail for the historical atmospheric conditions since the atmospheric variables are significantly influenced by the complex topography and land surface conditions over the basin. However, those coarse resolution atmospheric data sets can be used as initial and boundary conditions for mesoscale atmospheric models in order to create atmospheric data at fine spatial and temporal resolutions. For the 1956–1969 critical historical dry–wet period, RegHCM-TE was utilized to downscale the coarse NCEP/NCAR historical climate data at around 285-km grid resolution over the TE watershed to 15-km spatial grid resolution and at hourly intervals over the watershed through a sequence of two nested domains, respectively at 45-km, and 15-km grid resolutions, with the outer 45-km resolution domain utilizing the NCEP/NCAR historical climate data for its boundary and initial conditions. The 15-km inner domain's initial conditions were again provided by the interpolated NCEP/NCAR historical data, while its boundary conditions were provided from the climate simulations of the 45-km outer domain model. Accordingly, an atmospheric–hydrological data set for the Tigris- Euphrates basin at a spatial resolution fine enough to be able to carry out the water balance study was reconstructed for this period.

The developed RegHCM-TE was applied to the TE watershed during the historical period of 1965–1967 for its validation by means of the comparison of model-simulated hydro-climate conditions against the corresponding observations during this period. In Fig. 5 the observed monthly precipitation field (top) over the TE watershed for January–March 1967, as given by Willmott *et al.* (1985) data at 0.5° grid resolution, and the corresponding model-simulated (bottom) monthly precipitation (mm) that were spatially interpolated to the same grid resolution, are compared as a typical case. It may be seen from Fig. 5 that the simulated precipitation fields match the observation fields quite well. It can also been seen that precipitation in the TE watershed takes place not only in Turkey but also over the Zagros Mountain range near the Iran–Iraq border. Hence, the tributaries near the Iran–Iraq boarder supply significant amounts of water to the watershed.

The water resources in most of the TE watershed rely on winter rainfall and snowmelt. The winter precipitation is mostly stored on Taurus and Zagros mountains until spring comes; that is to say, snow plays the role of a "natural dam". Therefore, the modelling of snowmelt is an indispensable component of the water balance studies in this region. Accordingly, the above-described snow module of RegHCM-TE was applied to the TE watershed for the reconstruction of the snow conditions in the watershed during the 1956–1969 critical historical dry–wet period. Since no spatially distributed historical snow data during 1956–1969 could be retrieved for the mountains of the TE watershed, in order to check the plausibility of RegHCM-TE snow computations for the spatial distribution of snow cover, a comparison was made with the satellite

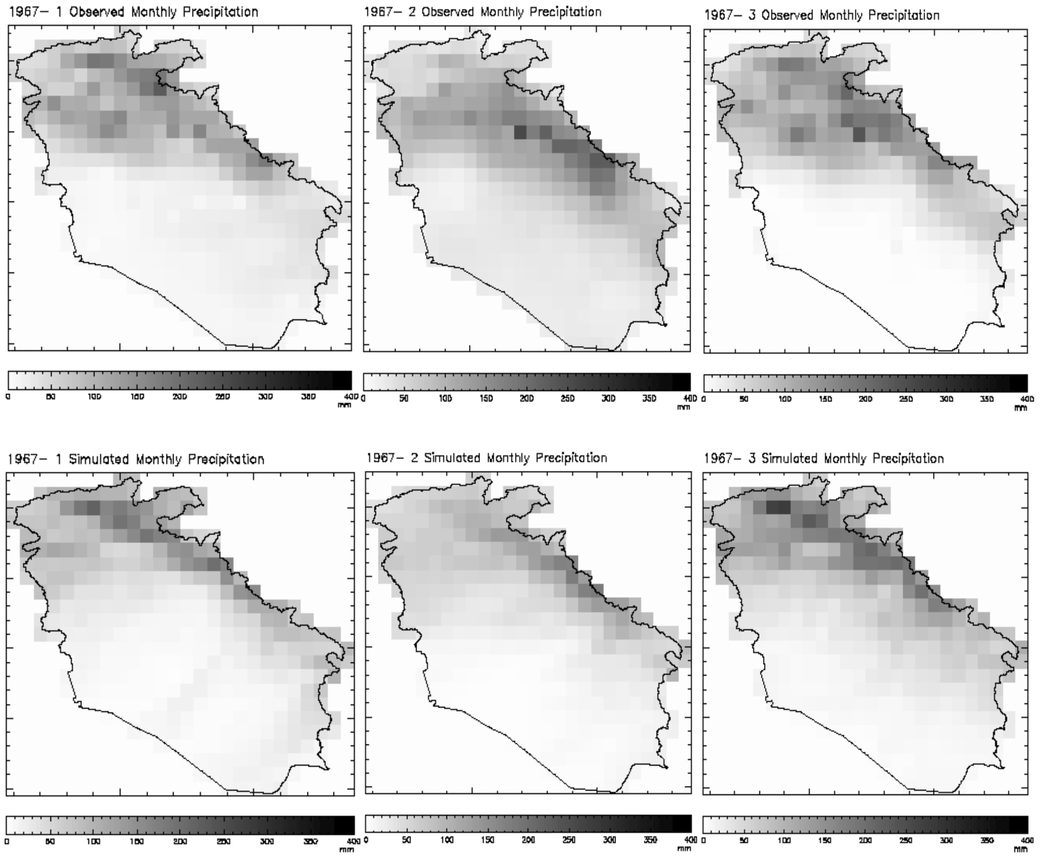

Fig. 5 Observed (top) and simulated (bottom) monthly precipitation (mm) in the Tigris-Euphrates basin from January 1967 to March 1967.

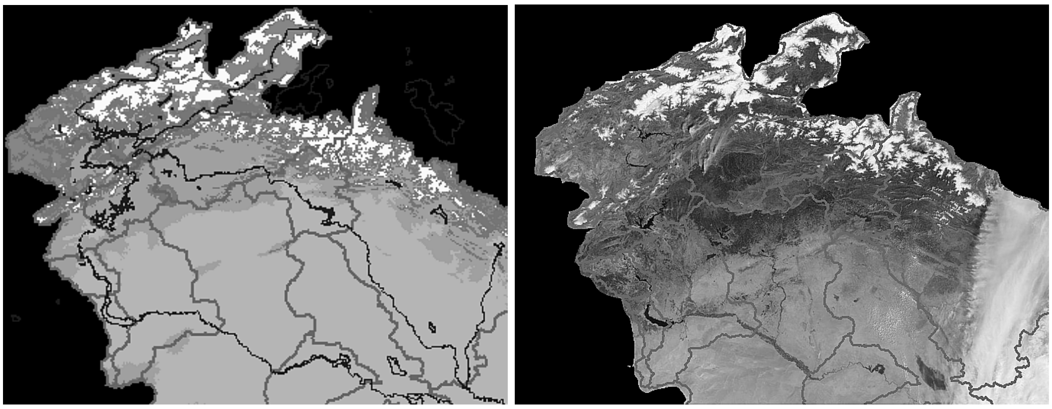

Fig. 6 A comparison of satellite-observed (Terra MODIS image on 11 April 2002) (right) and model-simulated (on 1 April 1957) (left) spatial distribution of snow cover (shown by white colour) over the TE watershed.

observations of snow cover *versus* the model simulations of snow cover. In Fig. 6, a comparison of satellite observed spatial distribution of snow cover during April 2002 is made against the model computed spatial distribution of snow cover for April 1957. It is encouraging to note that the observed and modelled spatial distributions of snow cover over the TE watershed are quite similar, although they correspond to different years.

In order to reconstruct the historical streamflow during the 1956–1969 critical historical dry–wet period throughout the stream network of the TE watershed, the direct runoff and baseflow from the hillslopes and lands adjacent to the stream network, that were simulated by the soil/vegetation module of RegHCM-TE, were input to the river module of RegHCM-TE, and then these inflows were routed throughout the stream network of the TE watershed by the RegHCM-TE river module. Monthly irrigation diversions within the system, computed by RegHCM-TE, were also subtracted from streamflows within the system. The streamflow data of 1965 were used for calibration of the river module. Then the monthly flow data during 1966 and 1967 were used for validation purposes. Figure 7 shows observed and model-simulated monthly flows at two representative river sites within the basin in 1967. As seen from Fig. 7, the model performs reasonably well in the prediction of the monthly flow volumes for the representative sites.

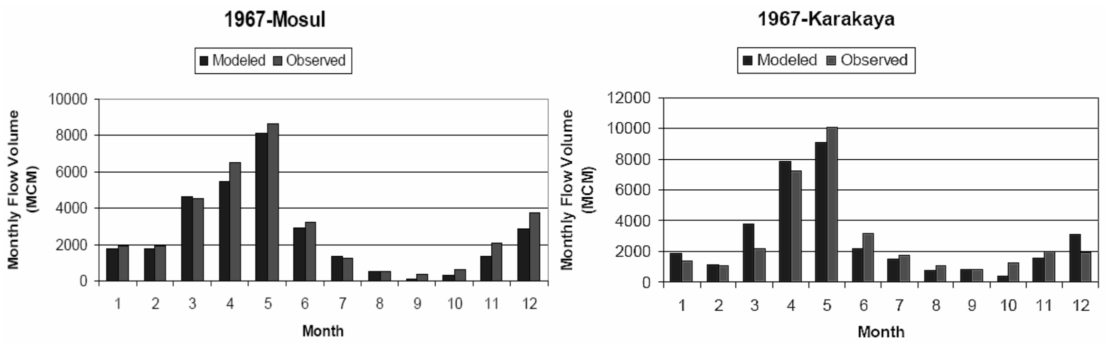

Fig. 7 Observed and modelled monthly flows at Mosul (Tigris) and Karakaya (Euphrates) stream gauging sites; black colour denotes modelled flow and grey denotes observed flow.

SUMMARY AND CONCLUSIONS

A regional hydro-climate model, called RegHCM, that describes a fully-coupled system of atmospheric processes aloft coupled with atmospheric boundary layer, land surface processes, and surface and subsurface hydrological processes, was developed and is presented here. The application of RegHCM to the assessment of climate change over Peninsular Malaysia, and to the reconstruction of historical hydro-climate data over the Tigris-Euphrates watershed is also presented.

From a statistical comparison of mean monthly flows at various watersheds of Peninsular Malaysia during historical and future periods, as shown in Fig. 4, one can conclude that the impact of climate change on the monthly flows over Peninsular Malaysia is not spatially uniform, and varies from watershed to watershed and from season to season. Based on the results in Fig. 4, the following specific conclusions may be reached concerning the impact of climate change on future monthly flows over Peninsular Malaysia: (1) the future monthly streamflow volumes will be decreasing at 95% confidence level at Klang and Selangor watersheds during the dry months of March and July, at Terengganu and Kelantan watersheds during the dry month of July, and at Kedah watershed during December and January; (2) the future monthly streamflow volumes will be increasing at 95% confidence level during the wet months at Terengganu (October–November), at Kelantan (October–December), at Pahang (November–December), and at Perak (October–November) watersheds. Therefore, high flow conditions will be magnified in Kelantan, Terengganu, Pahang and Perak watersheds, while low monthly flows will be significantly lower in Selangor, Klang, Kelantan and Terengganu watersheds.

As for the historical hydro-climate data reconstruction study over the Tigris-Euphrates watershed, one may conclude from the given application results that the hydrodynamic downscaling of the NCEP/NCAR 2.5° coarse resolution three-dimensional global historical climate data to a data-poor or ungauged region or watershed by means of a regional coupled atmospheric-hydrological model (RegHCM) may be an effective way of reconstructing the historical hydro-climate data over the specified region or watershed.

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