Predictions in Ungauged Basins: Promise and Progress (Proceedings of symposium S7 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April 2005). IAHS Publ. 303, 2006.

PUB Working Group on Orographic Precipitation, Surface Water and Groundwater Interactions, and their Impacts on Water Resources

XU LIANG[1], L. RUBY LEUNG[2], MAOYI HUANG[3], YUN QIAN[2], MARK S. WIGMOSTA[2], GEORGE B. MATANGA[4] & DAVE MATTHEWS[5]

1 *University of California, Berkeley, California, USA*

2 *Pacific Northwest National Laboratory, Richland, Washington, USA*

3 *Department of Global Ecology, Carnegie Institution of Washington, Stanford, California, USA*

4 *US Bureau of Reclamation, Sacramento, California, USA*

5 *US Bureau of Reclamation, Denver, Colorado, USA*

Abstract This paper introduces the motivations, objectives, and scope of a PUB working group to investigate the linkage between orographic precipitation, surface water and groundwater interactions, and their impacts on water resources. The ultimate goal of the working group is to assess the reduction of uncertainties in hydrological predictions for ungauged basins through improvements of two important physical processes of land–atmosphere interactions: orographic precipitation and surface water and groundwater interactions. In particular, we will focus on, in our current work, cold season orographic precipitation, snowmelt recharge to groundwater bodies, and their impacts on water resources. Our objectives are to: (1) improve the prediction of cold season orographic precipitation processes in mountainous regions and estimate their impacts on hydrological predictions and regional climate through land–atmosphere interactions; (2) improve our understanding of snowmelt recharge to groundwater bodies and surface water and groundwater interactions; and (3) improve the management of water resources through improved understanding and predictions of snowpack and surface water and groundwater interactions. Preliminary results are presented based on a regional-scale coupled land–atmosphere model that has been recently developed to address science questions of the working group. The model includes a subgrid parameterization of orographic precipitation and dynamic surface water–groundwater interactions. Simulations with and without the dynamic groundwater component have been compared to investigate the potential impacts of surface water and groundwater interactions.

Key words dynamic groundwater table; orographic precipitation; regional climate model; snowmelt recharge; land surface model; snowpack; surface water and groundwater interactions; water resources

INTRODUCTION

Mountain hydrology is one of the many challenging subjects in hydrology. It includes a wide range of topics, such as monitoring of water and energy budgets for mountain catchments, orographic precipitation for both the cold and warm seasons, influence of mountain forests and biogeochemistry on water and energy budgets, identifying and modelling special characteristics of hydrological processes associated with mountain catchments, etc. In this paper, the motivations, objectives, and scope of a PUB working group to investigate the linkage between cold season orographic precipitation, snowmelt recharge to groundwater, and their impacts on water resources are introduced. The long-term goal of this working group is to improve hydrological predictions in mountainous areas through deeper understanding and better representation of important hydrological processes (e.g. orographic precipitation, surface water and groundwater interactions, etc.), and to assess the reduction of uncertainties in hydrological predictions for ungauged basins. A modelling approach and preliminary results are also presented as an example of a first step towards achieving our goals.

Snow is an important component of the land surface energy and water budgets. Realistic simulation of snow cover and snowpack in climate and hydrological models is essential for correctly representing land–atmosphere feedback and the surface energy balance, as well as for understanding winter water storage and predicting year-round runoff. Seasonal snow can cover more than 50% of the land surface in the contiguous US during a single winter, leading to the largest annual and interannual differences in albedo that strongly affects surface temperature (Groisman *et al.*, 1994). In the western US, mountain snowmelt accounts for more than 70% of the annual streamflow that supports irrigation in the semiarid Central Valley and Columbia Basin, hydropower generation, and navigation in the major river basins.

Although snowpack plays an important role in atmospheric and hydrological predictions, to adequately prescribe and predict snowpack is far from trivial. Mountain snowpack is spatially heterogeneous, both in terms of snow water equivalent and snow properties; neither *in situ* measurements nor remote sensing can adequately describe the snow states. Predicting snowpack is perhaps even more challenging because snow accumulation and melt depend strongly on precipitation, which is notoriously difficult to predict by atmospheric models in regions of complex orography. While most numerical weather prediction or climate models can realistically simulate the seasonal cycle of total precipitation amount in relatively large river basins, they have difficulties simulating the regional spatial features to a degree satisfactory for hydrological predictions.

In mountainous areas, snowmelt provides not only a major source of freshwater through surface runoff, but a large fraction of snowmelt also recharges the groundwater body. For example, recent isotope research suggests that mountain snowmelt provides significant recharge to groundwater in the western US (Williams *et al.*, 2005). Among the three branches of the water cycle, including atmospheric, surface water, and sub-surface water, groundwater is the largest reservoir of the hydrological system and provides a large fraction of up to 90% of drinking water across different states in the US. Hence understanding how snowmelt recharges groundwater and predicting the groundwater table and its seasonal and interannual variability is important for managing the conjunctive use of surface water and groundwater and its long term effects.

Although groundwater discharge and recharge are important components of the water cycle, relatively little is known about the impacts of groundwater on the climate system. Observations showed that surface water and groundwater can interact to alter hydrological processes such as runoff production (e.g. Waddington *et al.*, 1993), water table fluctuations, and surface hydrology (e.g. Taylor & Pierson, 1985; Whiteley & Irwin, 1986; Devito and Dillon, 1993; Devito *et al.*, 1996; Katz *et al.*, 1997). However, how effective the interactions between surface water and groundwater are in linking groundwater and climate at regional, continental, and global scales is not known. Hence the NRC report (2003) states that "the roles of groundwater storage, and recharge and discharge fluxes in the climate system are under-appreciated and poorly understood" and "characterization of the linkage between groundwater and climate is crucial".

The establishment of the PUB working group on "Orographic Precipitation, Surface Water and Groundwater Interactions, and their Impacts on Water Resources" is one of the recent efforts made in response to the critical needs of investigating surface water and groundwater interactions and mountain hydrology under the auspices of PUB. This paper describes the science questions, approach, and objectives of the working group (Section 2). It also describes preliminary work on developing a modelling system that facilitates investigation of orographic precipitation and surface water and groundwater interactions. Section 3 describes the coupled modelling system, and Section 4 shows initial results of testing the coupled modelling system over the western United States. We hope this paper will motivate more researchers to join our working group or to establish other working groups focusing on relevant issues in mountain hydrology to collectively advance hydrological predictions for mountain catchments.

SCIENCE QUESTIONS, APPROACH, AND OBJECTIVES

This PUB working group will focus on, at present, cold season orographic precipitation, snowmelt recharge to the groundwater, and their impacts on water resources, with the long-term goal of improving hydrological predictions in remote mountainous areas. Some of the science questions that will be investigated by the working group include:

- What dominating physical processes govern orographic precipitation and its seasonal to interannual variations?
- How do different approaches (including dynamical and statistical) of modelling orographic precipitation compare, and what are the essential elements for successful simulation of orographic precipitation?
- What is the role of land–atmosphere interactions in orographic precipitation?
- How are biases in predicting orographic precipitation reflected in biases in hydrological predictions in snow dominated, rain dominated, and mixed river basins of various sizes?
- What is the role of snowmelt recharge to groundwater and surface water?
- What is the role of surface water and groundwater interactions on regional climate in areas of complex terrain?
- How can land data assimilation (e.g. soil moisture and snowpack) improve hydrological predictions in mountainous regions?
- How can uncertainty in hydrological predictions be represented in managing water resources?

To address these science questions, we will use a combination of data analysis and numerical modelling. There are three main elements to our approach. First, we will perform intercomparison of approaches, both dynamical and statistical, for modelling orographic precipitation and surface water–groundwater interactions. Sections 3 and 4 describe an example of a modelling system that is being developed to simulate oro–graphic precipitation and surface water and groundwater interactions. The intercomparison studies should focus on the strengths and weaknesses of each modelling approach in representing the processes at different spatial and temporal scales.

Second, the working group will review existing data sets and document uncertainties associated with the data sets. Data sets that are particularly important for our investigations include precipitation, snowpack, soil moisture, and groundwater. For some of these variables, our main task may be to document the various sources of data and discrepancies. For other variables such as groundwater, existing observation data are not well documented and may not be sufficient to adequately describe temporal and spatial variations over a large region. A useful product of the working group may be to provide an inventory of observation data that currently reside in many different sources, covering different time periods and spatial locations. Lastly, the working group will develop demonstration projects to work with water resource managers in developing approaches to apply hydrological predictions to water management.

Through coordinated activities of the working group, we aim to achieve the objectives to:

– Improve the prediction of cold season orographic precipitation in mountainous regions by atmospheric models and estimate the impacts on hydrological predictions and regional climate through land–atmosphere interactions.
– Improve our understanding of snowmelt recharge to groundwater and surface water and groundwater interactions in mountainous regions.
– Improve the management of water resources through improved understanding and predictions of orographic precipitation, snowpack, and snowmelt runoff and the partitioning between surface water and groundwater in regions of complex terrain.

COUPLED LAND–ATMOSPHERE MODEL

To achieve the proposed objectives of the working group, a coupled land–atmosphere model has been developed at the regional scale to address the relevant science questions. The atmospheric component is a regional climate model based on the Penn State/NCAR Mesoscale Model MM5 (Grell *et al*., 1994). Recognizing the inadequacy of representing orographic effects even at the 10–30 km spatial resolution (e.g. Leung & Qian, 2003), Leung & Ghan (1995; 1998) developed a subgrid parameterization of orographic precipitation and tested the method in MM5 for climate applications. With the subgrid scheme, climate models can be applied at relatively coarse spatial resolutions such as 90 km in regional models (Leung & Ghan 1998) and about 2.5 degree in global models (Ghan *et al*., 2002), while still accounting for subgrid surface topography which impacts local hydrology. An off-line distributed hydrology model applied to remote mountain watersheds showed that the simulation of streamflow and snowpack was much improved using meteorological inputs simulated with the subgrid method at coarser grid resolution than without the subgrid method, even though the latter simulation was performed at finer grid resolution and at much higher computational cost (Leung *et al*., 1996; Leung & Wigmosta, 1999).

In a series of papers, Leung and her colleagues studied the hydroclimate of the western US with the regional model. They evaluated the seasonal and interannual climate variability as well as extreme precipitation of a 20-year regional climate simulation driven by the NCEP/NCAR reanalysis (Leung *et al*., 2003a,b). Their simulation realistically captured the spatial distribution of seasonal mean and daily extreme precipitation across the region.

To improve the simulation of land surface hydrology, the three-layer Variable Infiltration Capacity land surface model (i.e. VIC-3L) (Liang *et al*., 1994, 1996a,b, 1999, 2003; Liang & Xie, 2001, Cherkauer & Lettenmaier, 2003) has recently been coupled to MM5. VIC has several distinguishing features including the representation of subgrid spatial variability of soil properties and precipitation. It accounts for both infiltration and saturation excess runoff generation mechanisms by considering subgrid spatial variability. It can represent the dynamic movement of groundwater table under unsteady state conditions, and simulate snow and frozen soil processes for cold climate conditions. VIC has been applied to various basins of different scales with good performance (e.g. Nijssen *et al*., 1997; Wood *et al*., 1997; Liang *et al*., 1998; Lohmann *et al*., 1998; Wood *et al*., 1998; Liang & Xie, 2001; Parada *et al*., 2003).

The coupling of MM5 and VIC was achieved in a way similar to that described by Chen & Dudhia (2001), who coupled MM5 to the OSU land surface model. That is, VIC is coupled to MM5 through the model's lowest level represented by a surface layer parameterization that provides surface exchange coefficients for momentum, heat, and moisture that determine their fluxes between the land surface and the atmosphere. The surface layer parameterization is handled through the nonlocal boundary layer scheme of Troen & Mahrt (1986), which calls VIC through an argument list that exchanges input and output variables. The VIC model used to couple with MM5 has been extensively modified to adopt a "space before time" structure, as opposed to the "time before space" structure in the offline VIC where time integration is performed for the whole simulation period one grid cell at a time. This step is necessary for coupling with any spatially distributed models such as MM5.

In the coupled model, most vegetation and soil parameters are determined through lookup tables by two primary variables, namely land cover type and soil texture type, which are determined by the MM5 preprocessor for each model grid cell based on the 1-km Advanced Very High Resolution Radiometer (AVHRR) satellite data defined for 24 USGS land cover categories, and the 1-km resolution multilayer 16 category soil characteristics data set of Miller & White (1998), respectively. Seasonal variations of vegetation cover are captured by the monthly leaf area index (LAI) defined in VIC.

Besides the parameters defined by land cover type and soil texture, VIC requires several additional parameters that are not provided by the MM5 preprocessor. These include the infiltration or b-parameter, which measures the subgrid variability of the soil moisture capacity. These parameters are currently set equal to constant values based on those suggested by the VIC documentation (http://www.hydro.washington.edu/Lettenmaier/Models/VIC/VIChome.html), regardless of the geographical locations. In the future, the technique of Huang *et al*. (2003) can be used to determine the spatial distribution of these parameters based on soil properties described in the STATSGO data set. The depths of the three soil layers are defined as 0.10, 0.4, and 4.5 m below the surface, respectively.

The new version of VIC-3L that is coupled to MM5 includes a new module that represents the dynamic movements of the groundwater table in the soil column and surface water and groundwater interactions (Liang *et al*. 2003). In this version of VIC-3L, a moving boundary condition is used to account for the fluctuations of groundwater table. Xie *et al*. (2004) proposed a mathematical transformation to cast the moving boundary problem (Liang *et al*., 2003) into a fixed boundary problem and showed that the computational efficiency could be significantly improved by reducing the number of soil layers used in Liang *et al*. (2003), but without much loss of accuracy.

In this application, the approach of Liang *et al*. (2003) is used in which a soil depth of 5 m is prescribed for each grid due to lack of spatial information on soil depth, and the soil column is discretized into 100 soil layers to allow more accurate estimation of groundwater table that lies within the top 5 m soil. However, not all of the 100 layers need to be used in the computation in general, unless the groundwater table is close to the bedrock (i.e. the 5 m prescribed depth); rather only the soil layers between the land surface and groundwater table are used in the computation. The groundwater table is initialized uniformly within the study domain at 0.5 m below the surface for lack of information on the spatial distribution of groundwater table. The soil moisture profile corresponding to this prescribed initial groundwater table is obtained through iteration (see Liang *et al*., 2003 for details).

Although the selection of the initial groundwater table at 0.5 m depth is arbitrary, it serves well for the purpose of this initial study, which is to demonstrate the validity of the coupled model and the dynamic groundwater component, and to understand the impacts of surface water and groundwater interactions on water and energy fluxes in the land–atmosphere system, when the groundwater table is shallow. In the future, we will initialize the groundwater table from observations, or perform long term simulations with the offline VIC model until the groundwater table reaches an equilibrium, which will then be used to initialize the coupled model. In the latter, we will investigate the convergence issue for an arbitrary initial groundwater table similar to the analysis of Liang *et al*. (2003). It is worth mentioning that in this study, a spatially heterogeneous distribution of groundwater table emerged a few months into the simulation where deviations from the initial homogeneous groundwater table are as large as 2 m in the western United States. The soil moisture profile obtained for the soil column calculated for the fine soil layers is mapped back to VIC-3L in this study, as described in Liang *et al*. (2003), for comparison with the MM5-VIC simulation that did not include the groundwater component.

INITIAL RESULTS

The coupled land–atmosphere model (i.e. VIC-MM5) was applied to the western US at 30 km horizontal resolution. The model was initialized using large scale atmospheric conditions and lower boundary conditions including sea surface temperature and land conditions such as soil temperature and soil moisture from the NCEP/NCAR global reanalysis (Kalnay *et al*. 1998). The NCEP/NCAR large scale conditions also provide lateral boundary conditions to MM5 that are updated every six hours. Two one-year simulations were performed for July 1979–June 1980 using MM5-VIC, with (called MM5-VIC-ground) and without (called MM5-VIC-old) the dynamic groundwater component, for comparison.

In addition, another simulation was performed using MM5 coupled to the OSU land surface scheme. Note that both MM5-VIC and MM5-OSU essentially prescribe

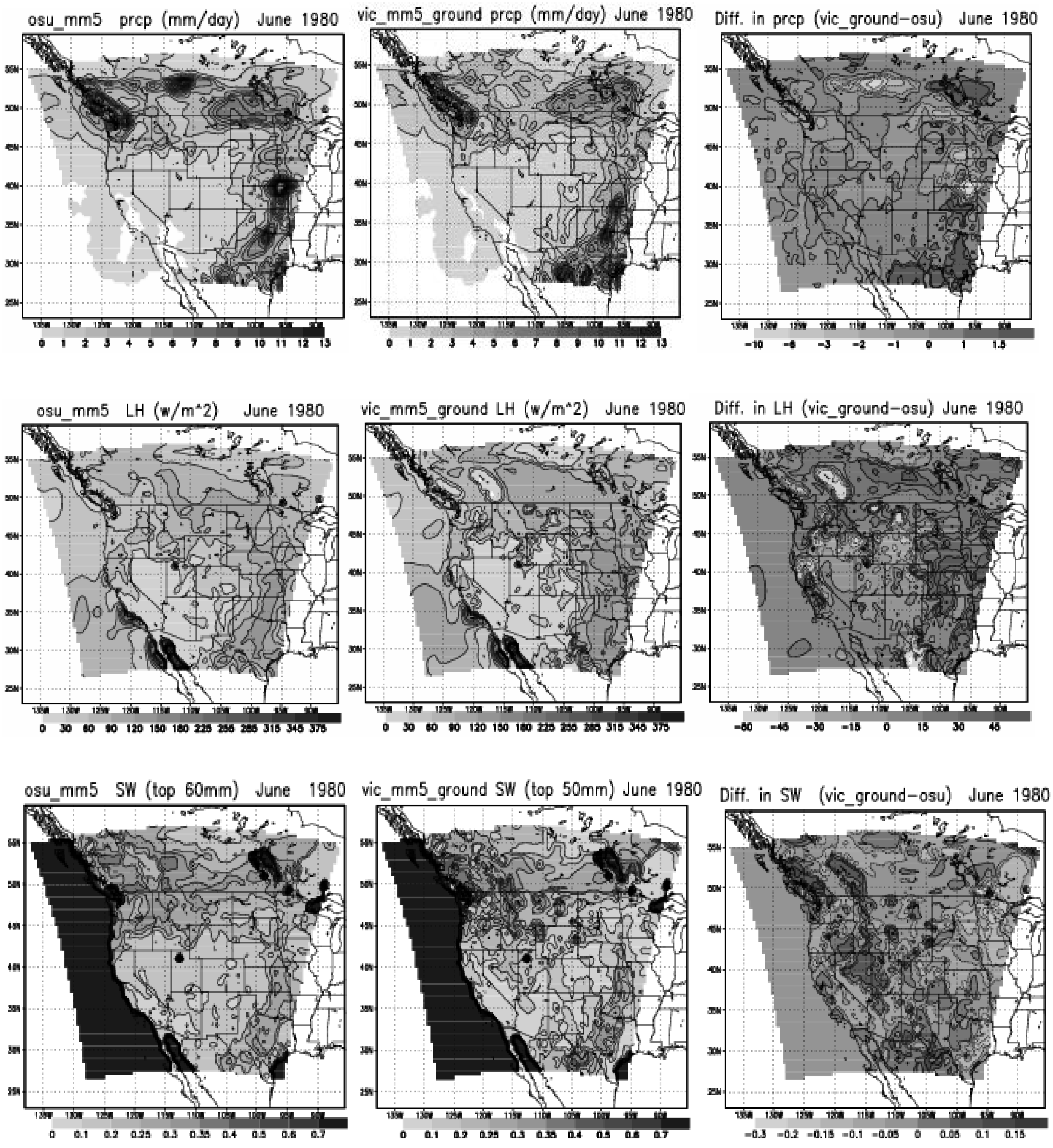

Fig. 1 Comparison of the precipitation (in mm day^{-1}, upper panel), latent heat flux (in W m^{-2}, middle panel), and soil moisture (in mm, bottom panel) in the top layer simulated by MM5-OSU, MM5-VIC-ground and their differences for the averaged conditions of June 1980.

the same land cover and soil parameters that are in common to both VIC and the OSU land surface model based on the outputs of the MM5 preprocessor. Both models were also initialized based on the same soil temperature and soil moisture profiles derived from the global reanalysis. Hence, differences between the MM5-VIC-ground (or MM5-VIC-old) and MM5-OSU simulations mainly reflect differences in the formulation of the land surface processes, including the subgrid treatments of spatial variability and dynamic groundwater table movement in VIC. Our main goals are to establish the validity of MM5-VIC-ground for providing reasonable simulations of land surface processes, and to determine the effects of surface water and groundwater interactions in MM5-VIC-ground. The subgrid orographic precipitation scheme was not used in these simulations.

Figure 1 shows a comparison of the precipitation, latent heat flux, and soil moisture in the top layer simulated by MM5-VIC-ground and MM5-OSU, and their differences, for the averaged conditions of June 1980. Results showed that the spatial distributions of precipitation simulated by the two models were comparable. MM5-VIC-ground produced slightly more precipitation over the southwest, but the differences were within 30%. In the intermountain zone and parts of the Rockies, MM5-OSU produced more precipitation. For soil moisture in the top layer, MM5-VIC-ground was generally drier than MM5-OSU. There was almost no correlation between the spatial distributions of precipitation and soil moisture differences. Similarly, differences in the latent heat flux between the simulations also appeared to

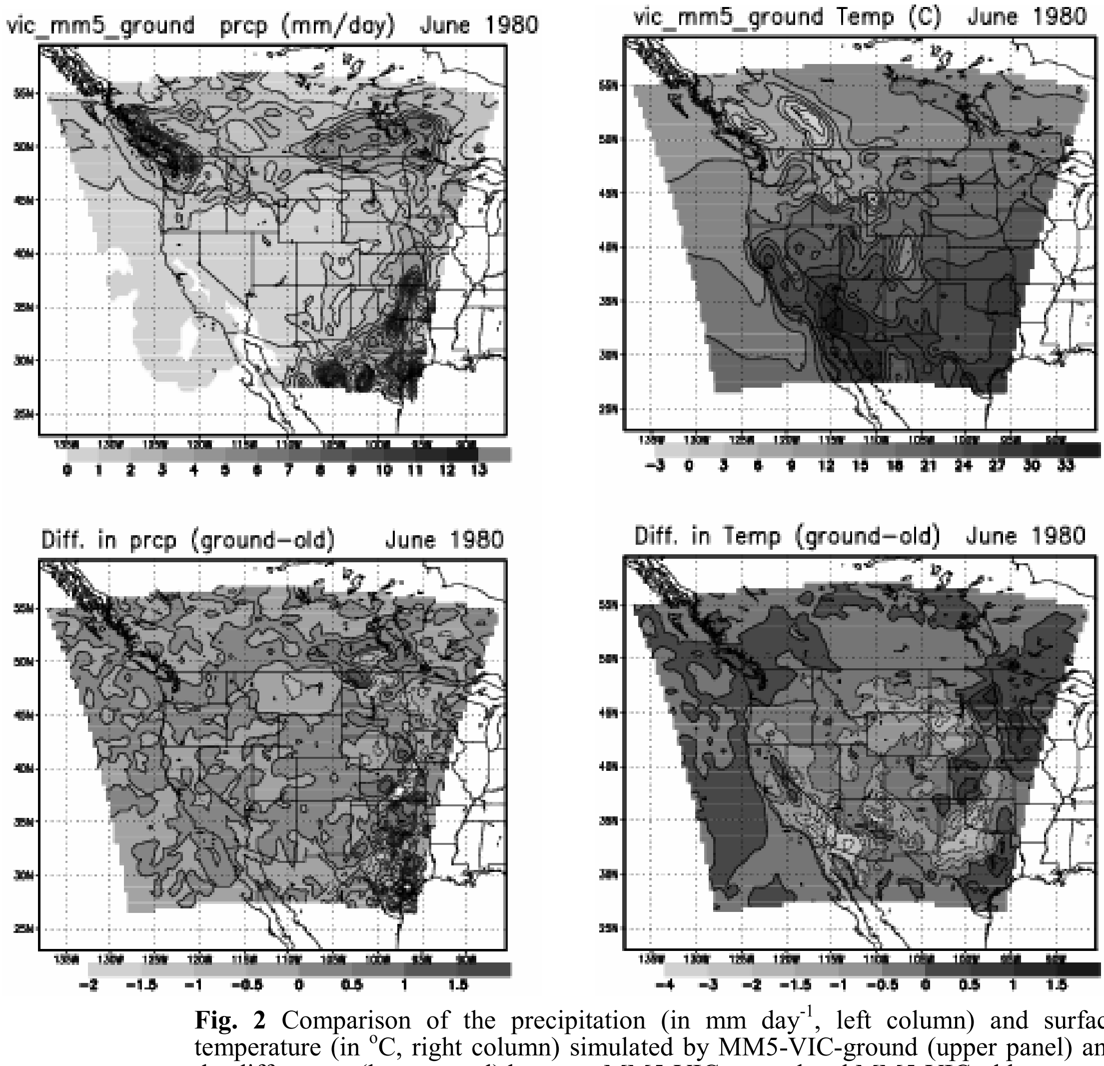

Fig. 2 Comparison of the precipitation (in mm day^{-1}, left column) and surface temperature (in ^{o}C, right column) simulated by MM5-VIC-ground (upper panel) and the differences (lower panel) between MM5-VIC-ground and MM5-VIC-old.

be uncorrelated to precipitation or soil moisture differences. This suggests that systematic differences, if any, between the two simulations were minor.

Next, we compare MM5-VIC-ground and MM5-VIC-old to examine the effects of the dynamic groundwater component in the simulations. Figure 2 shows the precipitation and surface temperature simulated by MM5-VIC-ground and the differences between MM5-VIC-ground and MM5-VIC-old. For precipitation, these differences were much smaller and spatially less coherent compared to the differences between MM5-VIC-ground and MM5-OSU. In most areas, MM5-VIC-ground was cooler by no more than 3°C compared to MM5-VIC-old.

Figure 3 shows a comparison of the latent heat flux and soil moisture at the top layer based on MM5-VIC-ground and MM5-VIC-old. Larger differences were found over Texas and the northern Plains for the latent and sensible heat fluxes. In most areas, MM5-VIC-ground produced drier conditions in the top soil layer.

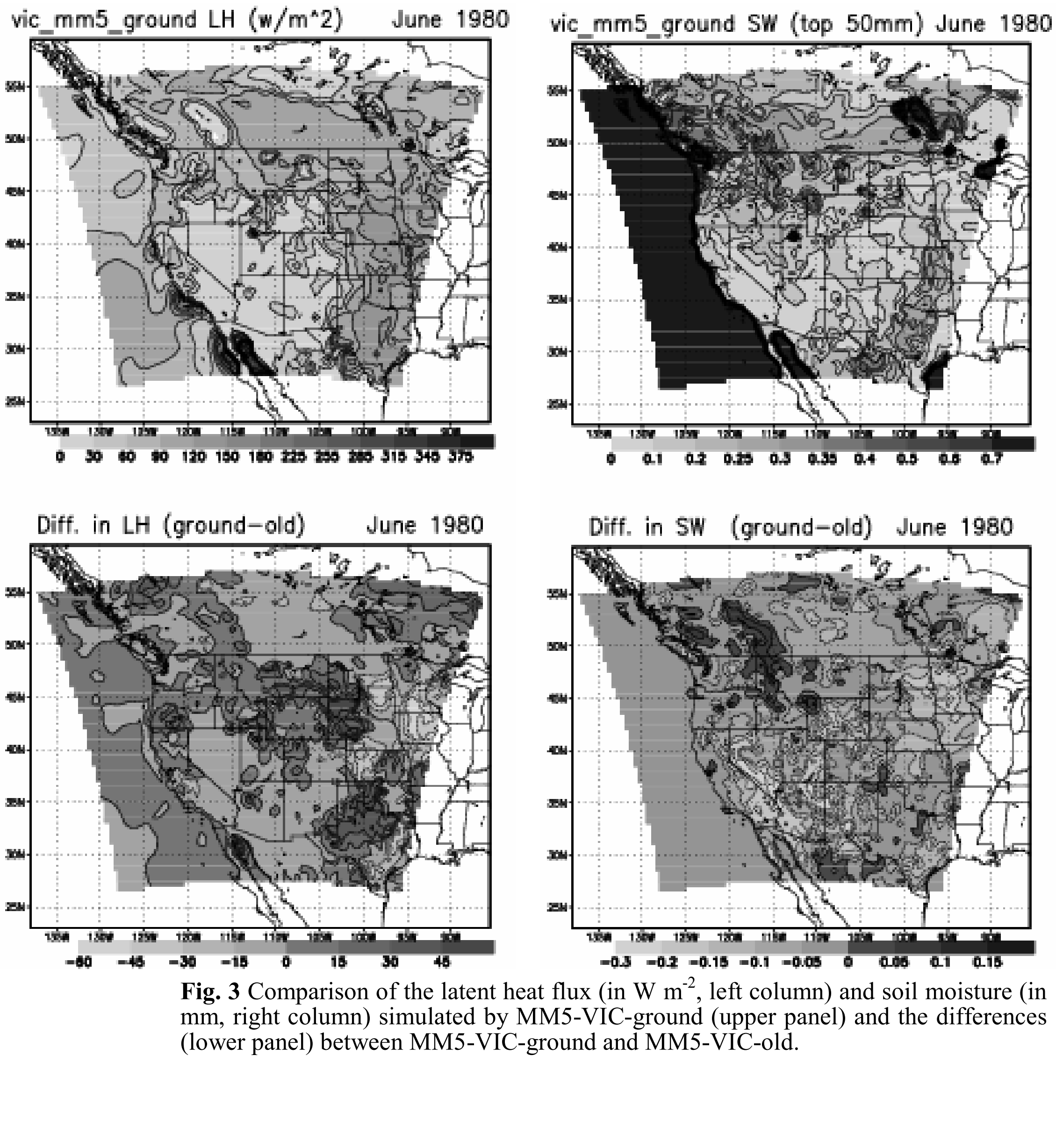

Fig. 3 Comparison of the latent heat flux (in W m^{-2}, left column) and soil moisture (in mm, right column) simulated by MM5-VIC-ground (upper panel) and the differences (lower panel) between MM5-VIC-ground and MM5-VIC-old.

CONCLUSIONS

Preliminary results from MM5-VIC, with and without the dynamic groundwater component, and MM5-OSU showed relatively small differences among the simulations. They suggest that MM5-VIC has been coupled successfully and that the dynamic groundwater component works properly within the coupled model framework. However, since the simulation length of one year is relatively short compared to subsurface processes, the results we showed were likely affected by model initialization, particularly related to the groundwater table. Depending on the soil properties and climate conditions, it may take 2 to 4 years for the groundwater table to attain an equilibrium in an uncoupled mode (e.g. Liang *et al*., 2003). For the coupled system, more studies need to be carried out to determine the equilibrium time under different conditions. We plan to evaluate this modelling tool more extensively by performing longer simulations over the conterminous US and performing sensitivity experiments to investigate the effects of model initialization and model parameters. Analysis of simulations with and without the dynamic groundwater component will be compared in depth to elucidate the effects of surface water and groundwater interactions on regional climate.

Orographic precipitation and snowmelt recharge to groundwater bodies are important processes over many mountainous regions worldwide. To improve hydrological predictions and water management in ungauged mountain basins, we need improved understanding and modelling tools to more accurately predict orographic precipitation, snow accumulation and melt, and surface water and groundwater interactions. While the research reported in this paper is preliminary and limited to numerical modelling, we welcome researchers who are interested in these topics to join our PUB working group to develop, evaluate, and intercompare techniques for modelling orographic precipitation using both dynamical and statistical methods, and develop and test methods for representing surface water and groundwater interactions, with the ultimate goal of improving hydrological predictions for remote mountainous basins. We also look forward to interacting with other PUB working groups in related topics to coordinate our efforts.

REFERENCES

Chen, F. & Dudhia, J. (2001) Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 modelling system. Part I: Model implementation and sensitivity. *Mon. Weath. Rev*. **129**, 569–585.

Cherkauer, K. A. & Lettenmaier, D. P. (2003) Simulation of spatial variability in snow and frozen soil. *J. Geophys. Res*. **108** (D22): Art. no. 8858.

Devito, K. J. & Dillon, P. J. (1993) The influence of hydrological condition and peat oxia on the phosphorus and nitrogen dynamics of a conifer swamp. *Water Resour. Res*. **29**, 2675–2685.

Devito, K. J., Hill, A. R. & Roulet, N. (1996) Groundwater–surface water interactions in headwater forested wetlands of the Canadian Shield. *J. Hydrol*. **181**, 127–147.

Ghan, S. J., Bian, X., Hunt, A. G. & Coleman, A. (2002) The thermodynamic influence of subgrid orography in a global climate model. *Climate Dyn*. **20**, 31–44.

Grell, G., Dudhia, J. & Stauffer, D. R. (1993) A description of the fifth generation Penn State/NCAR mesoscale model (MM5). *NCAR Tech. Note., NCAR/TN-398+IA*. Nat. Cent. for Atmos. Res., Boulder, Colorado, USA.

Groisman, P. Ya, Karl, T. R. & Knight, R. W. (1994) Observed impact of snow cover on heat balance and the rise of continental spring temperatures. *Science* **263**, 198–200.

Huang, M., Liang, X. & Liang, Y. (2003) A transferability study of model parameters for the variable infiltration capacity land surface scheme. *J. Geophys. Res*. **108**(D22), 8864.

Katz, B. G., DeHan, R. S. Hirten, J. J. & Catches, J. S. (1997) Interactions between groundwater and surface water in the Suwannee river basin, Florida. *J. Am. Water Resour. Assooc.* **33**, 1237–1254.

Leung, L. R., Qian, Y. Bian, X. & Hunt, A. (2003a) Hydroclimate of the western United States based on observations and regional climate simulation of 1981–2000. Part I: Seasonal statistics. *J. Climate* **16**(12), 1892–1911.

Leung, L. R., Qian, Y. Bian, X. & Hunt, A. (2003b) Hydroclimate of the western United States based on observations and regional climate simulation of 1981-2000. Part II: Mesoscale ENSO anomalies. *J. Climate* **16**(12), 1912–1928.

Leung, L. R. & Qian, Y. (2003) The sensitivity of simulated precipitation and snowpack to model resolution via nesting in regions of complex terrain. *J. Hydrometeorol*. **4**(6), 1025–1043.

Leung, L. R. & Wigmosta, M. S. (1999) Potential climate change impacts on mountain watersheds in the Pacific Northwest. *J. Amer. Water Resour. Assoc.* **35**(6), 1463–1471.

Leung, L. R. & Ghan, S. J. (1998) Parameterizing subgrid orographic precipitation and surface cover in climate models, *Mon. Weath. Rev*. **126**(12), 3271–3291.

Leung, L. R., Wigmosta, M. S. Ghan, S. J. Epstein, D. . & Vail, L. W. (1996) Application of a subgrid orographic precipitation/surface hydrology scheme to a mountain watershed. *J. Geophy. Res*. **101**(D8), 12803–12818.

Leung, L. R. & Ghan, S. J. (1995) A subgrid parameterization of orographic precipitation. *Theor. Appl. Climatol*. **52**, 95–118.

Liang, X., Lettenmaier, D. P., Wood, E. F. & Burges, S. J. (1994) A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *J. Geophys. Res*. 99(D7), **14**, 415–14, 428.

Liang, X., Wood, E. F. & Lettenmaier, D. P. (1996a) Surface soil moisture parameterization of the VIC-2L model: Evaluation and modifications. *Global and Planetary Change* **13**, 195–206.

Liang, X., Lettenmaier, D. P. & Wood, E. F. (1996b) A one-dimensional statistical dynamic representation of subgrid spatial variability of precipitation in the two-layer variable infiltration capacity model. *J. Geophys. Res*. 101(D16), **21**, 403–422.

Liang, X., Wood, E. F., Lettenmaier, D. P, Lohmann, D., Boone, A., Chang, S., Chen, F., Dai, Y. J., Desborough, C., Dickinson, R. E., Duan, Q. Y., Ek, M., Gusev, Y. M., Habets, F., Irannejad, P., Koster, R., Mitchell, K. E., Nasonova, O. N., Noilhan, J., Schaake, J., Schlosser, A., Shao, Y. P., Shmakin, A. B., Verseghy, D., Warrach, K., Wetzel, P., Xue, Y. K., Yang, Z. L. & Zeng, Q. C., (1998) The project for intercomparison of land–surface parameterization schemes (PILPS) phase-2c Red-Arkansas river basin experiment: 2. Spatial and temporal analysis of energy fluxes. *Global and Planetary Change (special issue)* **19**(1–4), 137–159.

Liang, X., Wood, E. F. & Lettenmaier, D. P. (1999) Modelling ground heat flux in land surface parameterization schemes, *J. Geophys. Res*. **104**, 9581–9600.

Liang, X. & Xie, Z. (2001) A new surface runoff parameterization with subgrid-scale soil heterogeneity for land surface models. *Adv. Water Res.* **24**, 1173–1193.

Liang, X., Xie, Z. & Huang, M. (2003) A new parameterization for groundwater and surface water interactions and its impact on water budgets with the VIC land surface model, *J Geophys. Res.* **108**(D16), 8613.

Lohmann, D., Lettenmaier, D. P., Liang, X., Wood, E. F., Boone, A., Chang, S., Chen, F., Dai, Y. J., Desborough, C., Dickinson, R. E., Duan, Q. Y., Ek, M., Gusev, Y. M., Habets, F., Irannejad, P., Koster, R., Mitchell, K. E., Nasonova, O. N., Noilhan, J., Schaake, J., Schlosser, A., Shao, Y. P., Shmakin, A. B., Verseghy, D., Warrach, K., Wetzel, P., Xue, Y. K., Yang, Z L. & Zeng, Q. C., **(**1998) The Project for Intercomparison of Land–surface Parameterization Schemes (PILPS) phase 2(c) Red-Arkansas River Basin experiment: 3. Spatial and temporal analysis of water fluxes. *Global and Planetary Change (special issue)* **19**, 161–179.

Miller, D. A. & White, R. A. (1998) A conterminous United States multilayer soil characteristics data set for regional climate and hydrology modelling. *Earth Interactions* **2**, [Available online at http://EarthInteractions.org.].

National Research Council (2003) *Groundwater Fluxes Across Interfaces*. The National Academy Press, Washington, DC, USA.

Nijssen, B., Lettenmaier, D. P., Liang, X., Wetzel, S. & Wood, E. F. (1997) Streamflow simulation for continental-scale river basins. *Water Resour. Res*. **33**, 711–772.

Parada, L. M., Fram, J. P. & Liang, X. (2003) Multi-resolution calibration methodology for hydrological models: Applications to a sub-humid catchment. In: *Advances in Calibration of Watershed Models* (ed. by Q. Duan, H. Gupta, S. Sorooshian, A. Rousseau & R. Turcotte)*,* 197–211. Water Science and Application 6, American Geophy. Union.

Taylor, C. H. & Pierson, D. C. (1985) The effect of a small wetland on runoff response during spring snowmelt. *Atmos.-Ocean* **23**, 137–154.

Waddington, J. M., Roulet, N. T. & Hill, A. R. (1993) Runoff mechanisms in a forested groundwater discharge wetland. *J. Hydrol*. **147**, 37–60.

Whiteley, H. R. & Irwin, R. W. (1986) The hydrological response of wetlands in southern Ontario. *Can. Water Res. J.* **11**, 100–110.

Williams, M., Liu, F. & Wireman, M. (2005) The "Teflon Basin" myth debunked: Most snowmelt runoff is "old" water and not "new" water. In: *MTN2005 Conference* (1–4 March, 2005, Chico Hot Spring, Pray, Montana, USA) (http://www.fs.fed.us/psw/mtnclim/talks.html).

Wood, F., Lettenmaier, D. P., Liang, X., Nijssen, B. & Wetzel, S. W. (1997) Hydrological modelling of continental-scale basins. *Ann. Rev. Earth Planet. Sci.* **25**, 279–300.

Wood, E. F., Lettenmaier, D. P., Liang, X., Lohmann, D., Boone, A., Chang, S., Chen, F., Dai, Y. J., Desborough, C., Dickinson, R. E., Duan, Q. Y., Ek, M., Gusev, Y. M., Habets, F., Irannejad, P., Koster, R., Mitchell, K. E., Nasonova, O. N., Noilhan, J., Schaake, J., Schlosser, A., Shao, Y. P., Shmakin, A. B., Verseghy, D., Warrach, K., Wetzel, P., Xue, Y. K., Yang, Z. L. & Zeng, Q.C., (1998) The project for Intercomparison of land–surface parameterization schemes (PILPS) phase-2c Red-Arkansas river basin experiment: 1. Experiment description and summary intercomparisons. *Global and Planetary Change (special issue)* **19**(1–4), 115–135.

Xie, Z., Yang, H. & Liang, X. (2004) A moving boundary problem and its applications to land–atmosphere interactions. In: *Advances in Scientific Computing and Applications* (ed. by Y. Lu, W. Sun & T. Tang), 396–407. Science Press, Beijing, China.