ATMOSPHERE-CRYOSPHERE COUPLED MODEL DEVELOPMENT AND ITS APPLICATION FOR REGIONAL CLIMATE STUDIES

Ki-Hong Min*[1] and Wen-Yih Sun[2]
[1]Department of Geography and Meteorology, Valparaiso University
[2]National Center for High Performance Computing, Hsinchu, Taiwan

1. INTRODUCTION

Accurate simulation of snowmelt runoff and infiltration is crucial for the mesoscale numerical simulation of atmosphere-land interactions (Gutzler and Preston 1997; Small 2001). Including snow physics can, not only improve seasonal cycle of snowmelt runoff in climate simulations, but also the surface energy budget in high and temperate latitudes (Bosilovich and Sun 1999). Studies suggest that soil moisture, temperature, and snow exhibit persistence on seasonal to inter-annual time scales (Koster and Suarez 1995; Houser 2000). Together with external forcing and internal land surface dynamics, this seasonal persistence has important implications for the extended prediction of climatic and hydrologic extremes. Accurate prediction of snow, snowmelt, and frozen soil processes are important to the accuracy of regional climate simulation from winter to spring. Although considerable model variability exists for snow simulations, the onset and duration of snowmelt is of critical importance to both predicted atmospheric fluxes and the hydrological cycle (Stieglitz *et al.*, 2001).

Regional climate over North America is not only an atmospheric response to the differential heating between the land mass and its nearby ocean but also the cause of such forcing. Specifically, most of the winter and spring precipitation in this region is due primarily to the propagation of synoptic wave systems. In spite of many previous studies on the impacts of land-surface processes in regional climate simulations, research has mainly focused on the summer season over North America and the European continents, and relatively little work has been done from winter to spring. The lack of studies covering this season is surprising since winter snow storm and spring snowmelt contribute to the major disaster and large-scale circulation feature of regional and global climate.

Two major problems exist in modeling the atmosphere over cold land: (a) not enough in-situ data, and (b) the lack of accurate physical description of snow and frozen soil in land models. Recent studies attempt to address these problems by: (a) the proper utilization of remote sensing data, and (b) the development of multi-layer land-surface model for use with Global/Regional Climate Models that are suitable from the winter to spring period and at high latitudes. The former can improve model precipitation forecasts by accurate initialization of the surface boundary conditions. The latter is important because snow strongly affects the winter-to-spring surface energy budget. Therefore, accurate initialization and representation of the snow processes in a coupled regional climate model are essential for atmospheric and hydrologic predictions.

2. METHODOLOGY

In order to study the regional climate during the transition period from winter to spring, we have replaced the current land-surface scheme (LSS, Bosilovich and Sun 1995) of Purdue Regional Climate Model (PRCM) with the new one-dimensional, multi-layer Soil-Snow Model (SSM, Sun and Chern 2005) based on the conservation of heat and water substance inside the soil and snow in PRCM. The new land model includes the physics of snow and the phase change of water which can be applied to simulate atmospheric feedback of snow-covered vegetation, snow water equivalent, and snowmelt.

2.1 *Experiment Design*

2.1.1 *Case Overview*

The period chosen to assess and validate the coupled model (PRCM-SSM)'s regional climate simulation capability and study its impact is March and April of 1997 in Northern Plains. According to the National Weather Service's assessments of significant floods (http://www.nws.noaa.gov/oh/Dis_Svy), the most catastrophic flooding disaster of the 1997 season occurred in Minnesota and the Dakotas

---

*Corresponding author address: Ki-Hong Min, Department of Geography and Meteorology, Valparaiso University, 1809 Chapel Dr., Valparaiso, IN 46383 (email: kmin@valpo.edu)

due to heavy spring snowmelt. Floods on the Red River of the North occurred in the context of these unusual conditions and led to serious flooding throughout much of the upper Midwest.

Flooding of the Red River in 1997 established twentieth-century records at most locations and was particularly devastating in the towns of Grand Forks, North Dakota, and East Grand Forks, Minnesota. Estimated damage for the event, including all of the United States portions of the Red River, totaled approximately $4 billion and involved 11 casualties. Of this, $3.6 billion was lost in the immediate vicinity of Grand Forks/East Grand Forks.

2.1.2 *Model Setup*

The current PRCM-LSS allows for one layer of snow and uses a simple snowmelt process. The effective snow albedo calculation can distinguish between the fractions of vegetation or bare ground covered by snow. The amount of snowmelt is calculated by assuming all of the solar heating will be used when surface temperature is greater than 273.15 K. The PRCM coupled with SSM can have a multi-layer soil model to emulate the effects of soil type on soil heat flux and heat content, soil moisture content, and evapo-transpiration by vegetation. As with other aspects of surface physics, the use of an interactive soil model marks a vast improvement from the cruder methods used earlier. However, in this experiment the maximum number of soil layers is limited to three layers due to model initial condition constraints. The ECMWF reanalysis data provides only 4-layers of soil analysis to the public domain. The PRCM with the new soil-snow module can improve the ground heat and moisture fluxes, because it includes the effect of frozen soil and snow cover on the surface. The detailed discussions of SSM processes can be found from Min (2005).

As described, the current land model developed by Bosilovich and Sun (1995) does not consider detailed snow hydrology and frozen soil dynamics which are important processes from winter to spring. The control run (CTL) was performed using the current PRCM setup of the land-surface scheme and the ECMWF upper-air and surface data as lateral boundary conditions and surface initial conditions for land and the ocean. The experiment run (Exp) differs only by the use of SSM. The lateral boundary condition such as temperature, height and wind fields remain the same as the control run conditions. The surface characteristics are provided by Henderson-Sellers soil and vegetation data over the modeled domain. Two experiments conducted in this section are summarized in Table 1. Other configurations, including model dynamics and physics, except for the land surface scheme, are identical. The mother domain has a horizontal resolution of 45 km x 45 km over the continental U.S. with 28 vertical-layers. A detailed analysis is performed in box 2 over the Northern Plains where the heaviest flooding occurred (Fig. 1). Additionally, there is one layer for vegetation and 3 layers for soil below the surface.

2.1.3 *Numerical Experiments*

The period chosen for numerical simulations is March and April of 1997. With the new land-surface model (SSM) incorporated to the PRCM, experiments are designed to test and validate the hypothesis that the presence of snow and its melt from winter to spring affects the propagation of synoptic waves, amounts of precipitation, and floods over the Northern Plains. The new land model has the option to turn on or off the multi-layer snow process. But, we only present the numerical experiment with detailed snow process turned on in the land-surface model (Exp1). All initial conditions and lateral boundary forcing remain the same throughout the model simulations except for soil moisture.

In order to study the effects of cold land processes on the simulation of spring snowmelt flooding with a coupled modeling system, we investigate the monthly mean features and the time evolution of the event. We then compare the two model results with the ECMWF data and analyze the hydrologic budgets. A suspected weakness of the current experimental setup is that soil moisture initialization in PRCM-SSM requires a soil ice amount which is not readily available in ECMWF data nor surface observations. We have initially distinguished the amount of soil ice or liquid based on the soil temperature less than 273.15 K. Whereas, the PRCM-LSS has no soil ice included. This will allow how the new land parameterization scheme with detailed cold land physics affects the simulated forecasts and the atmospheric response during the spring 1997 snowmelt flooding event.

Table 1 Simulation design for this study.

	Settings	Physics	Remarks
Control Exp. (CTL)	I.C. & B.C.: ECMWF	3-layer soil and vegetation	One snow layer with simple snow process
New Land Exp. (Exp1)	Same as CTL	3-layer soil and multi-layer snow with vegetation	Frozen soil and snow processes

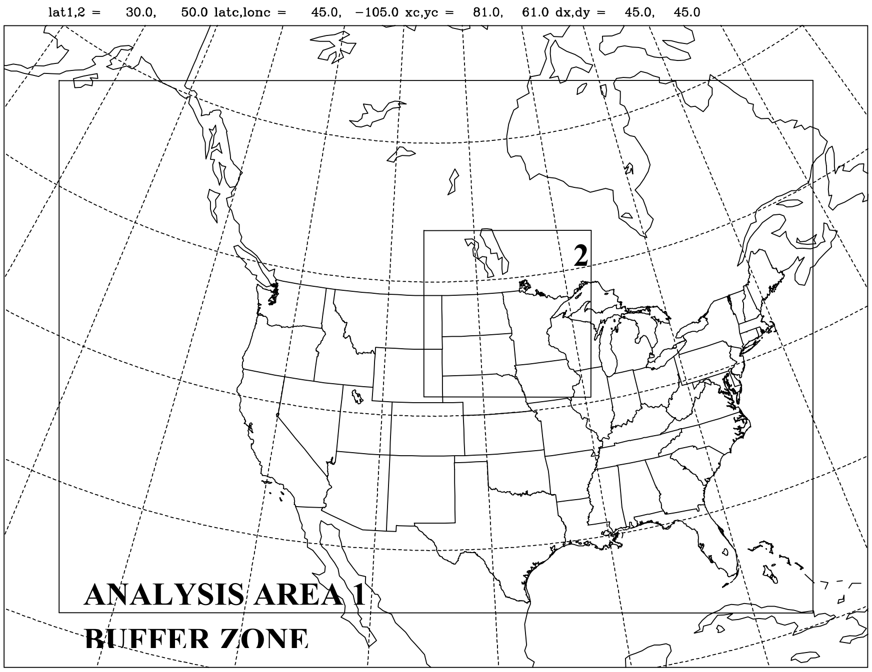

Fig. 1 Model domain with buffer zone and detailed analysis area (1, 2).

3. MODEL SIMULATION RESULTS

3.1 *Horizontal Mean Fields*

The PRCM coupled with a multi-layer SSM (EXP1) has successfully reproduced the spring snowmelt floods over the Northern Plains of the U.S. during March and April of 1997.

Compared with the simple snow-soil parameterization, which consists of one-layer snow and the soil without frozen mechanism (CTL), the simulations from the PRCM with new SSM agree much better with the observations in snow coverage, the surface temperature, pressure, precipitation, and snow accumulation over the flooding area in the Northern Plains of the U.S. (figures 2 to 5). The effect of including the multi-layers of frozen soil and snow lowers the surface temperature due to initial frozen soil and higher albedo over the snow surface, which changes the horizontal temperature gradients,

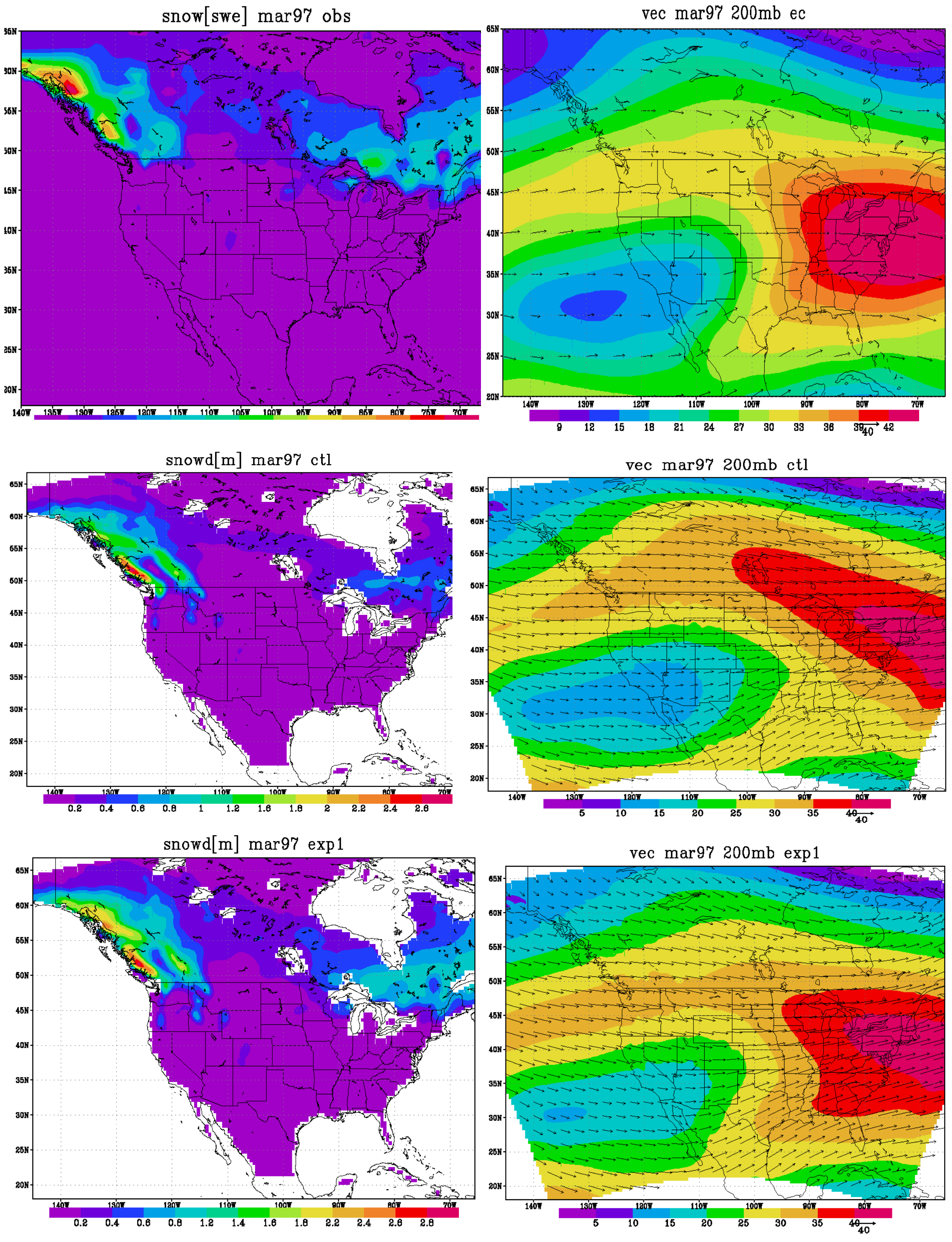

Fig. 2: Left: Observed (top) and simulated snow depth from CTL and EXP1. Right: Monthly mean of 200 hPa wind vector for March 1997 from ECMWF (top), CTL (middle) and EXP1 (bottom), respectively.

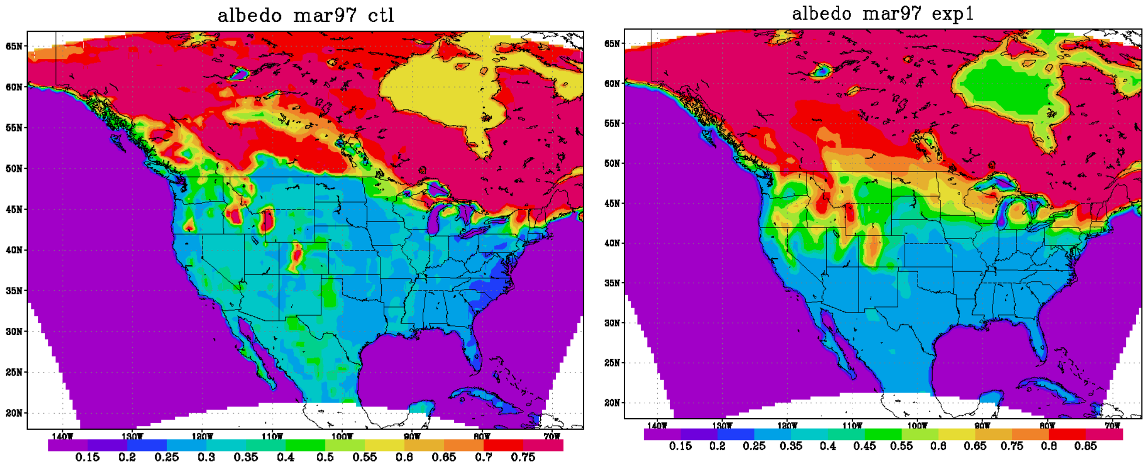

Fig. 3: Simulated mean albedo in March 97 from CTL and EXP1.

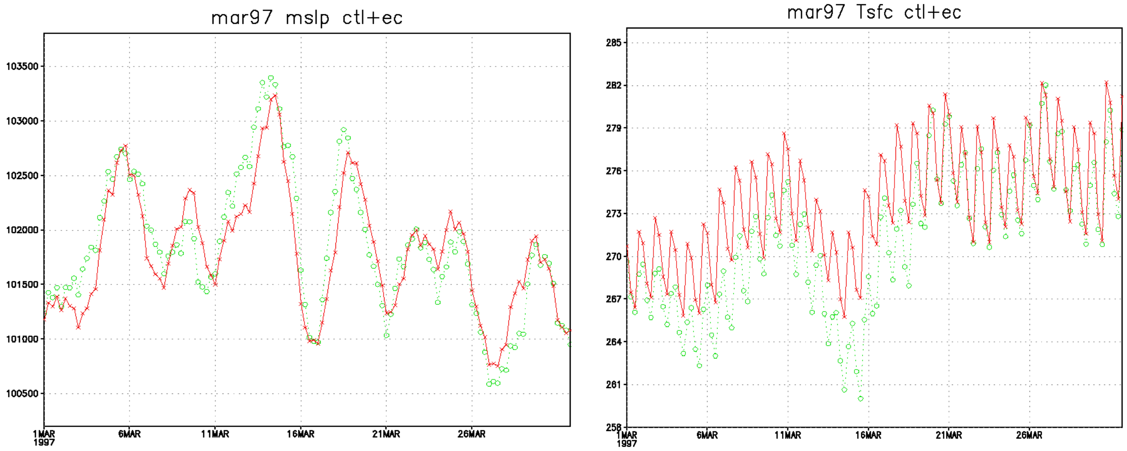

Fig. 4: Comparison between ECMWF (green dots) and CTL simulations (red lines) for mean sea-level pressure (MSLP) and surface air temperature (Tsfc) in box 2 of Fig. 1.

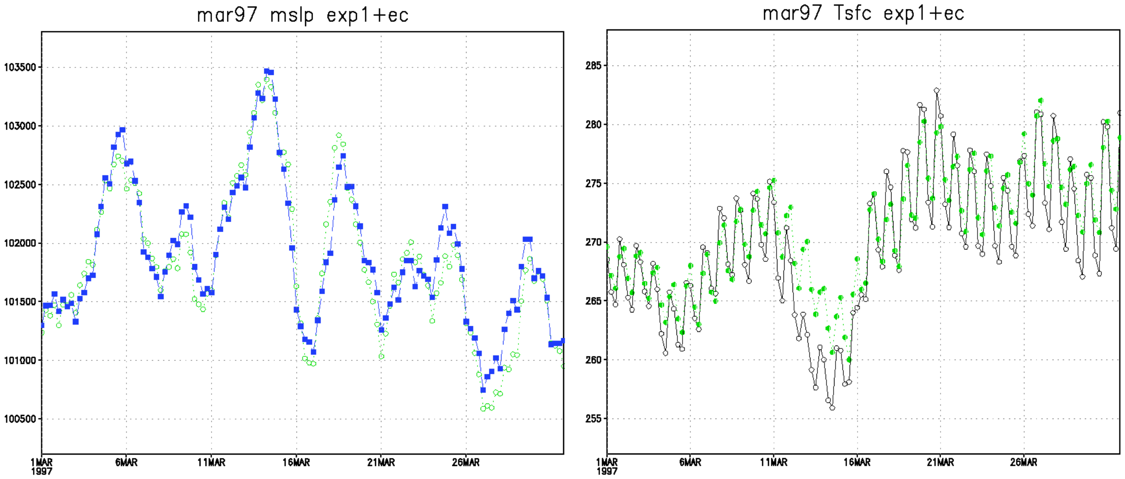

Fig. 5: Sames as Fig. 1 except for EXP1 simulations (blue and gray lines).

and in turn changes the location of synoptic weather systems passing over the cold land region. Remarkable improvement is also found over the geopotential and wind field even at 200 hPa-level from the new SSM compared with the previous simple snow-soil parameterization (LSS), as shown in Fig. 2. Hence, it indicates that the detailed snow-soil parameterization is important to weather prediction models. It can affect not only in the lower atmosphere and the upper atmosphere but also large scale weather systems (Min 2005).

3.2 *Vertical Profile*

Figures 6 and 7 show the monthly averaged vertical profile of temperature and mixing ratio of CTL (open circle) and EXP1 (green line), and the geopotential height difference for March and April over the entire model domain (box 1 in Fig. 7). In general, a significant impact of cold land processes appears in the mid-to-lower atmosphere for both temperature and moisture. Higher surface albedo and initial frozen soil in EXP1 cool and dry the lower atmosphere over the whole domain. Geopotential height difference also shows a significant reduction of the height field for EXP1. In a hydrostatic model atmosphere, the variation of geopotential depends on the temperature, and geopotential height decreases more rapidly in a cold layer than in a warm layer. Therefore, there is a gradual decrease in EXP1 height field up to 200 hPa because the air column below is colder when compared to CTL.

With the additional moisture of CTL in the lower atmosphere and increased precipitation in the central United States, excessive latent heat release heats the mid-to-upper level atmosphere. This decreases the column averaged meridional temperature gradient of CTL; and the speed of upper-level jet stream is reduced and has more curvature than ECMWF data for March (figures not shown). Intensification of the subtropical jet in April EXP1 can be understood in a similar way. Although the northward retreat and weakening of the polar jet stream is well simulated in both CTL and EXP1, the inclusion of cold season processes (EXP1) results in a stronger column averaged temperature gradient near 30° ~ 40° N latitude and colder mid-to-upper level temperatures further up to 250 hPa than CTL. Overall, the effect of cold season processes intensifies both the Canadian high pressure system and the low pressure systems over the Pacific Northwest and the south.

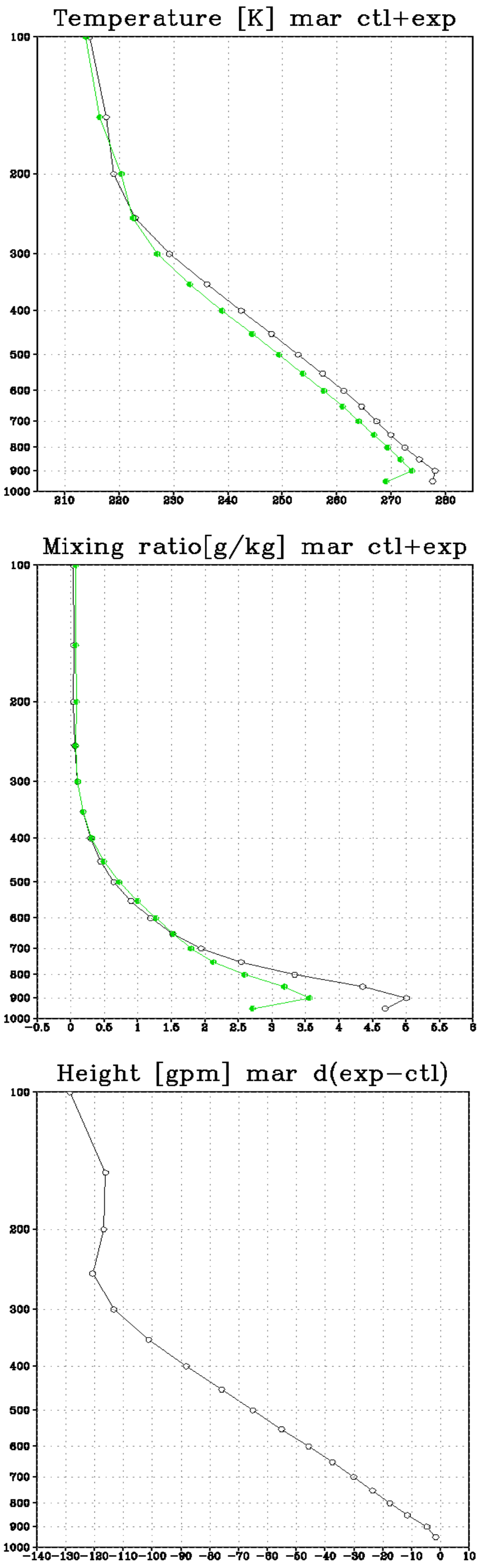

Fig. 6 Vertical profile of temperature and mixing ratio of CTL (open circle) and EXP1 (green line), and the geopotential height differences for March over the entire model domain.

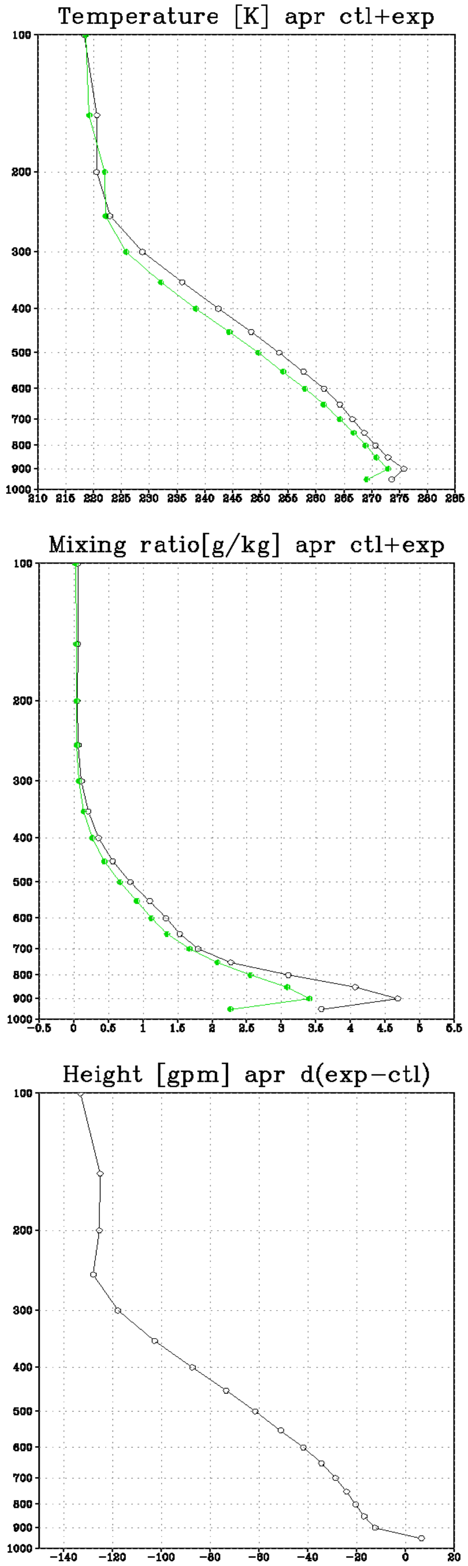

Fig. 7 Same as Fig. 6 except for April 1997.

The strengthening of the pressure gradient force between the two systems increases the surface wind, which stimulates low-level mixing of temperature and moisture. The cooling and drying of the lower atmosphere further enhance the reduction of the height field in the mid-to-upper level by hydrostatic balance and increase the meridional temperature gradient. These subsequent processes strengthen the upper-level wind, thus changing the governing dynamics and atmospheric circulation over the Northern Plains and the North America.

In addition, the strengthening of cold Canadian high pressure system increases the snowfall amount over the Northern Plains when compared with CTL in March and in early April. Increased snowfall also increases the surface albedo, which further cools the surface temperature by reducing the solar radiation reaching ground. We consider this feature as a direct effect of the cold season processes. On the other hand, increase in precipitation over the major storm pathways can be considered as an indirect effect of cold season processes since the shift in synoptic weather patterns locate the storm systems in a more favorable position with respect to upper-level dynamics.

4. CONCLUSION

The multi-layer Soil-Snow Model (SSM) has been successfully coupled with the Purdue Regional Climate Model (PRCM) to simulate the spring snowmelt floods over the Northern Plains during spring 1997. The current PRCM includes a land-surface scheme (LSS), which does not include the detailed physics needed to model snow and frozen soil. In order to extend the model's capability to simulate the accumulation and thermodynamics of snow on the ground, and freezing and thawing inside the soil, a newly developed multi-layer SSM has replaced the former LSS in PRCM. This change is required since the surface energy budget is strongly affected by the presence of snow and frozen soil. Due to snow's high albedo the amount of shortwave radiative energy available at the surface is dramatically reduced, and snow's low thermal conductivity significantly restricts the exchange of heat between soil and the atmosphere. Thus, snow and frozen soil physics are essential processes to model snow covered surface hydrology and its interaction with the atmosphere.

Compared with the current LSS (Bosilovich and Sun 1995), the SSM shows marked differences in surface and ground temperature, precipitation, and albedo calculations. In general, the intensity and location of precipitation over the Northern Plains region was in better agreement with PRCM-SSM. Overall, the regional climate simulation of March and April 1997 with the inclusion of the detailed frozen soil and snow processes improves the synoptic and local circulations during the cold season. Both spatial and temporal analyses of PRCM-SSM indicate that the coupling of this processes are important when simulating cold season surfaces with frozen soil and snow cover.

The effect of including cryosphere model physics lowers the surface temperatures due in part by the initial frozen soil conditions and by the reduction of incoming solar radiation at the surface due to higher albedo over the snow covered region. These affect the horizontal temperature gradients, and in turn change the location of synoptic weather systems passing over the cold land region. In addition, the partitioning of incoming radiative energy into the sensible and latent heat fluxes is sensitive to snowmelt and soil freeze/thaw conditions during the early stages of the model simulations. Further detailed and more sensitivity studies are left for future research that will lead us to better understand past and future regional climate.

When observational data are limited, numerical models become a major tool in studying the physics and interactions of land-surface phenomena. This is especially true during the cold season and at high latitudes. With more accurate descriptions of atmosphere-land interactions and the use of high-resolution land-surface initial conditions, we expect to better predict snowmelt flooding and decrease its damage to agriculture, property, and human life. The broader impact of this coupled modeling system is to help identify the important factors that influence late winter to early spring regional scale water and energy cycles at different spatial and time scales. This study shows promise that quantitative forecasting of precipitation and flooding caused by winter to spring snowmelt can also be improved with cold-land physics.

REFERENCES

Bosilovich, M. G., and W. Y. Sun, 1995: Formation and verification of a land surface parameterization for atmospheric models. *Boundary Layer Meteor.*, **73**, 321-341.

______, and ______, 1998: Monthly simulation of surface layer fluxes and soil properties during FIFE.. *J. Atmos. Sci.* **55**, 1170-1183.

______, and ______, 1999: Numerical simulation of the 1993 Midwestern Flood: Local and remote sources of water. *J. Geophys. Res.* **104**, D16, 19,415-19,423.

Chern, J. D., 1994: *Numerical simulations of cyclogenesis over the western United States*. Ph.D. Thesis, Dept. of Earth and Atmospheric Sciences, Purdue University, 178 pp.

Gutzler, D. and J. Preston, 1997: Evidence for a relationship between spring snow cover in North America and summer rainfall in New Mexico, *Geophys. Res. Let.*, **24**, 2207-2210.

Houser, P. R., 2000: Land Data Assimilation Systems, *NASA Tech. Memo*, 5pp.

Koster, R. D. and M. J. Suarez, 1995: Relative contributions of land and ocean processes to precipitation variability, *J. Geophys. Res.*, **100**, 1375-1390.

Min, K. H., 2005: Coupled Cryosphere Model Development For Regional Climate Study And The Initialization Of Purdue Regional Model With The Land Data Assimilation System. Ph.D. Thesis, Dept. of Earth and Atmospheric Sciences, Purdue Univ., W. Lafayette, IN 47907, 149pp.

Small, E. E., 2001: The influence of soil moisture anomalies on variability of the North American Monsoon System. *Geophy. Res. Let.*, **28**, 139-142.

Stieglitz, M., A. Ducharne, R. Koster, and M. Suarez, 2001: The impact of detailed snow physics on the simulation of snow cover and subsurface thermodynamics at continental scales, *J. Hydrometeor.*, **2**, 228-242.

Sun, W. Y., and J-D. Chern, 2005: One dimensional snow-land surface model applied to Sleepers experiment, *Boundary-Layer Meteorology,* **116***, 95-115*.