10.14 MODELING SNOWCOVER HETEROGENEITY IN POLAR REGIONS

Stephen J. Déry,[1,*] Wade T. Crow,[2,3] Marc Stieglitz[1] and Eric F. Wood[3]

[1]Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York
[2]Hydrology and Remote Sensing Laboratory, ARS/USDA, Beltsville, Maryland
[3]Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey

1. INTRODUCTION

In polar regions, snow processes are especially crucial to accurately model the high-latitude hydrological cycle given their ubiquitous presence throughout the year. With its radiational and thermal properties, a snowpack greatly affects the overlying air and the evolution of the underlying ground temperatures. For instance, Stieglitz et al. (2003) demonstrated that about half of the 1983-1998 warming of Alaskan permafrost temperatures at a 20-m depth could be explained by a recovery of snowpack conditions in the region. Through sublimation processes, a snowpack constitutes a sink of energy near the surface and a source of atmospheric moisture (Déry and Yau 2002). During the spring transition period, water retained in this temporary reservoir is quickly released to the environment, yielding high runoff rates that contribute as much as 80% of the yearly discharge rates of some Arctic streams and rivers (McNamara et al. 1998).

In many northern regions such as the Alaskan North Slope, the snowcover exhibits considerable heterogeneity (Figure 1). This situation arises due to several factors, including topographic control of precipitation, solar insolation and temperature. In the open and windswept Arctic tundra regions, frequent high wind episodes promote the transport of snow that leads to a substantially heterogeneous snowpack (Déry and Yau 1999). In fact, snowdrifts in the region attain thicknesses and water contents 3-20 times larger than observed in non-drift areas (Sturm et al. 2001). Despite occupying a small fraction of the Arctic landscape, these features nevertheless govern the timing and intensity of the spring melt (Stieglitz et al. 1999). Unfortunately, few conventional land surface models are able to resolve these subgrid-scale features in the evolution of a snowpack and this may, in turn, lead to significant errors in the generation of meltwater at high latitudes (Stieglitz et al. 1999). To remedy some of these deficiencies, we incorporate a parameterization for subgrid-scale snow in a state-of-the-art land surface model and examine its effects on simulations of the snowmelt period in the Upper Kuparuk River Basin, a 142 km^2 watershed on the North Slope of Alaska.

Figure 1: Photograph showing the end-of-winter snowcover distribution at Toolik Lake on the North Slope of Alaska, with the Brooks Range in the background. The photo was taken on 28 May 1996 facing southward by Dr. George W. Kling, University of Michigan.

2. DATA AND NUMERICAL MODEL

The Upper Kuparuk is selected as our primary test bed since unlike most other northern catchments, it has been the subject of intense field experiments (Kane et al. 2000). To force the numerical model, meteorological data from 13 sites located in the vicinity of the Upper Kuparuk Basin are therefore available and utilized in this study. The period chosen for the simulations begins on 1 January 1996 and terminates on 31 December 1997, with emphasis on the 1997 spring melt period. Standard meteorological variables of the near-surface air temperature, the relative humidity and wind speed are available at hourly intervals for nearly all stations. Other required meteorological fields for the numerical simulations are the surface atmospheric pressure, the precipitation rate, the incoming solar radiation and the

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[*] *Corresponding author address:* Stephen J. Déry, Lamont-Doherty Earth Observatory, Columbia University, 61 Route 9W, Palisades, NY, 10964; e-mail: dery@ldeo.columbia.edu

incoming longwave radiation. All of these fields are averaged based on a least-squares weighting scheme from the measurement sites to the geographical center of the Upper Kuparuk Basin. This approach yields a continuous time series in each of the required forcing variables at hourly intervals while eliminating the gaps during which data were unavailable from certain locations. It also provides a dataset representative of the wide range of elevations (from 570 to 1490 masl) in the Upper Kuparuk Basin. Daily snowfall data from the Imnavait Creek Wyoming snow gauge, operated by the Natural Resources Conservation Service (NRCS), are added to supplement liquid precipitation measurements from the tipping rain buckets.

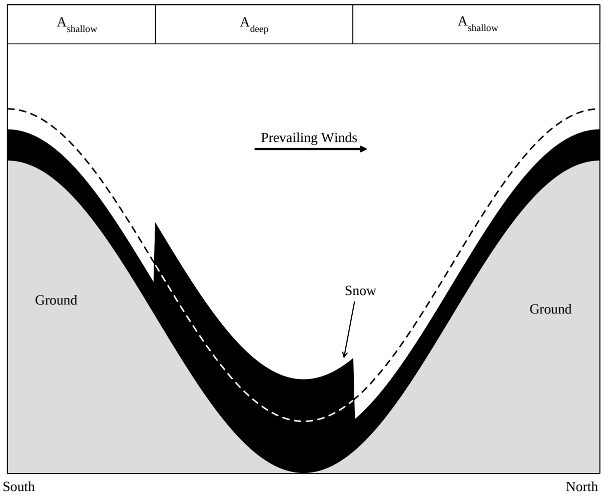

Figure 2: The CLSM representation of the end-of-winter, nonuniform snowpack that arises due to wind redistribution of snow over the Upper Kuparuk Basin. Blowing snow carried by the prevailing southerly winds (here from left to right) is transported from erosion areas, leaving a shallow snowpack (of area $A_{shallow}$) at hilltops and windward slopes while mass accumulates in valleys and on lee slopes into a deep snowpack (of area A_{deep}). The basin mean snow water equivalent, denoted by the dashed line, represents standard CLSM conditions with a uniform snowpack.

The model we use to simulate land surface processes in the Upper Kuparuk is NASA's Seasonal-to-Interannual Prediction Project (NSIPP) Catchment-based Land Surface Model (CLSM; Koster et al. 2000). In opposition to traditional land surface schemes, the CLSM employs TOPMODEL concepts that define the watershed as the fundamental hydrological unit and not a rectangular grid cell. The CLSM is also coupled to a permafrost dynamics model that determines the heat transfer and freeze/thaw cycle of the underlying ground and to a snow physics model that prognosticates the heat content, snow water equivalent and snow depth for each of 3 snow layers in the CLSM (Stieglitz et al. 2001). This snow model considers most processes that lead to the formation and ablation of the snowpack, including precipitation, sublimation, snowmelt, compaction, liquid water infiltration and refreezing.

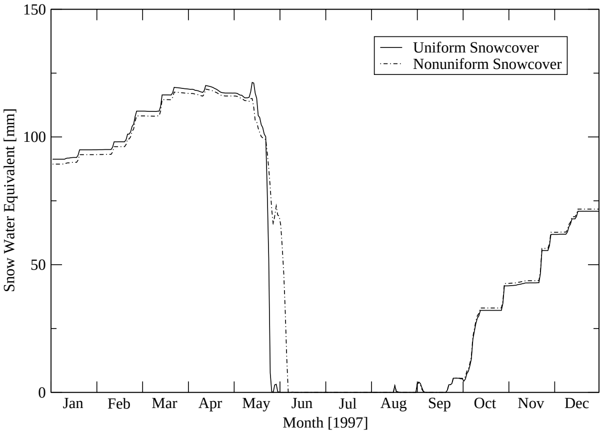

Figure 3: Daily values of the snow water equivalent simulated by the CLSM with a uniform and nonuniform snowpack for the Upper Kuparuk River in 1997.

The standard CLSM snow module considers the snowpack to exhibit uniform characteristics across each watershed. Figure 1 clearly illustrates, however, that the snowpack in the vicinity of the Upper Kuparuk Basin displays considerable small-scale heterogeneity. Thus for the CLSM, a simple subgrid-scale snow parameterization has been formulated (Déry et al. 2003). It divides the snowpack into two regions: one depicting a shallow snowpack (of area $A_{shallow}$) in erosion zones, and another representing a deep snowpack (of area A_{deep}) in accumulation zones (Figure 2). In the following section, results from two sets of simulations are presented: one using the standard CLSM snow model with spatially uniform characteristics and the second that includes the parameterization for subgrid-scale snow.

3. RESULTS

The evolution of the simulated snowpacks during 1997 in each of the two numerical experiments is shown in Figure 3. In the non-uniform snowcover simulation, we have partitioned the shallow and deep snowpacks such that $A_{shallow} = 2/3$ and $A_{deep} = 1/3$. Furthermore, we impose 10 times more precipitation onto the deep snowpack than on the shallow one. These values derive from observations of snowpack conditions

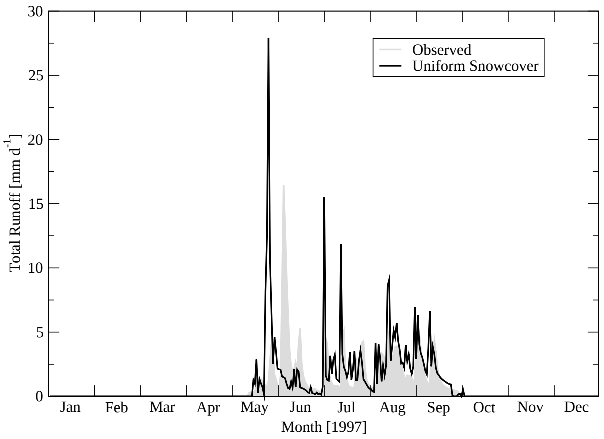

Figure 4: Daily values of the observed runoff rates and those simulated by the CLSM with a uniform snowpack for the Upper Kuparuk River in 1997.

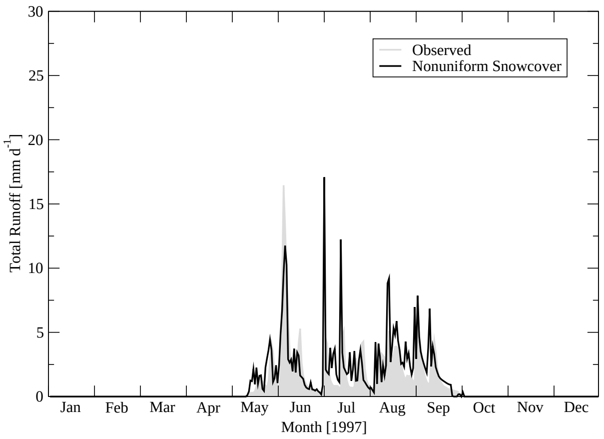

Figure 5: Daily values of the observed runoff rates and those simulated by the CLSM with a nonuniform snowpack for the Upper Kuparuk River in 1997.

on the North Slope of Alaska (König and Sturm 1998; Sturm et al. 2001) and on results from a blowing snow model (Déry and Yau 2001; Déry et al. 2003). On average over the entire Upper Kuparuk watershed, the growth of the snowpack in both experiments is similar during its formation period; however, discrepancies between the two simulations become prominent during late May and early June as the snowpack is ablating. At this time, the snowpack collapses rapidly in the model with the uniform snowpack whereas the subgrid-scale snowcover simulation displays a more gradual depletion of the snowpack with persistent snows for an additional 10 days.

Figure 4 depicts the temporal evolution of the daily streamflow recorded by a weir on the Upper Kuparuk versus that simulated by the CLSM during 1997. Clearly, the standard version of the CLSM model has difficulty representing the melt period where simulated runoff rates attain 28 mm d^{-1} on 26 May, 70% larger than the 16 mm d^{-1} observed on 5 June. In this experiment, the CLSM retains a uniform snowpack that melts rapidly and evenly across the Upper Kuparuk watershed. In turn, this leads to an early (and unrealistic) peak in the simulated hydrograph.

The next CLSM simulation uses the same experimental design as the previous experiment, with the exception that subgrid-scale variations in the snowcover are now included in the CLSM. Figure 5 reveals the improvement in the simulated runoff during the spring melt period when this additional physical process is incorporated by the means of a simple parameterization into the CLSM. By extending the ablation period by 10 days, the magnitude and the timing of the spring melt are now realistically captured by the model.

4. CONCLUDING DISCUSSION

In this study, we have demonstrated that the consideration of small-scale variations in snowcover within a land surface model provides a more accurate representation of the spring meltwater discharge peak of the Upper Kuparuk River. Apart from runoff generation, Déry et al. (2003) demonstrate that, in fact, a whole range of other processes, including the components of the surface energy and water budgets, are also affected by the subgrid-scale variations in snowcover for this Alaskan watershed. Given that up to 40% of the northern hemisphere is covered by seasonal snowcover (Hall 1988), a corruption of regional or global climate simulations may arise if such effects remain unresolved (Lynch et al. 1998). This is especially true for a patchy snowcover since land/atmosphere interactions and feedbacks are tightly coupled during the spring transition period (Lynch et al. 1998; Liston 1999). This work suggests that a simple parameterization for subgrid-scale snow improves the simulation (at low computational costs) of land surface/atmosphere processes and interactions during the spring transition period. Despite its simple formulation, however, the application of the subgrid-scale snow parameterization is not straightforward as it requires the areas covered by shallow and deep snowpacks within a CLSM catchment unit. These areal fractions must therefore be obtained through a combination of field observations, remote sensing data, blowing snow and distributed snow models.

5. ACKNOWLEDGMENTS

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