Appendix S2: SnowModel Simulations

Navigating snowscapes: scale-dependent responses of mountain sheep to snowpack properties

Mahoney et al. Ecological Applications

Model description

a. SnowModel

Model simulations were performed using SnowModel (Liston and Elder 2006a), a spatially-distributed snow-evolution modeling system designed for application in all landscapes, climates, and conditions where snow occurs. It is an aggregation of four sub-models: EnBal (Liston 1995; Liston et al. 1999) calculates surface energy exchanges and snowmelt; SnowPack (Liston and Hall 1995; Liston and Mernild 2012) is a multi-layer snowpack sub-model that simulates snow depth and water-equivalent evolution; SnowTran-3D (Liston and Sturm 1998; Liston et al. 2007) accounts for snow redistribution by wind; and SnowAssim (Liston and Hiemstra 2008) is available to assimilate field and remote sensing datasets.

SnowModel is designed to run on grid increments of 1-m to 500-m and temporal increments of 10-minutes to 1-day. It can be applied using much larger grid increments (up to 10s of km) if the inherent loss in high-resolution (subgrid) information (Liston 2004) is acceptable. Processes simulated by SnowModel include snow precipitation; blowing-snow redistribution and sublimation; interception, unloading, and sublimation within forest canopies; snow-density evolution; and snowpack ripening and melt. SnowModel incorporates first-order physics required to simulate snow evolution within each of the global snow classes (i.e., Ice, Tundra, Taiga, Warm Forest [or Alpine], Prairie, Maritime, and Ephemeral) defined by Sturm et al. (1995) and G. E. Liston and M. Sturm (2018, *unpublished manuscript*). Required SnowModel inputs include temporally-variant precipitation, wind speed and direction, air temperature, and relative humidity obtained from meteorological stations and/or an atmospheric model located within or near the simulation domain. Spatially-distributed, time-invariant topography and land cover are also necessary.

b. MicroMet

Meteorological forcings required by SnowModel are provided by MicroMet (Liston and Elder 2006b), a quasi-physically-based, high-resolution (e.g., 1-m to 10-km horizontal grid increment), meteorological distribution model. MicroMet is a data assimilation and interpolation model that utilizes meteorological station datasets and/or gridded atmospheric model or (re)analyses datasets. MicroMet minimally requires near-surface air temperature, relative humidity, wind speed and direction, and precipitation data. The model uses known relationships among meteorological variables and the surrounding landscape (primarily topography) to distribute those variables over any given landscape in physically plausible and computationally efficient ways (Liston and Elder 2006b). MicroMet performs two kinds of adjustments to the meteorological data; 1) all available data fields, at a given time, are spatially interpolated over the domain, and 2) physically based sub-models are applied to each MicroMet variable to quantify topographic, elevation, and vegetation effects at any given point in space and time. At each time step, MicroMet simulates and distributes air temperature, relative humidity, wind speed, wind direction, incoming solar radiation, incoming longwave radiation, surface pressure, and precipitation, and makes them accessible to SnowModel.

MicroMet and SnowModel constitute a physically-based modeling system that creates value-added snow information (e.g., snow depth, snow density, snow melt rate, snow thermal properties, snow cover duration, sublimation) from basic meteorological variables (e.g., air temperature, humidity, precipitation, wind). The products yielded are based on our physical understanding of snow-evolution processes and features, and their interactions with the atmosphere and surrounding land surface. MicroMet and SnowModel have been used to distribute observed and modeled meteorological variables and evolve snow distributions over complex terrain in Colorado, Wyoming, Idaho, Oregon, Alaska, Arctic Canada, Siberia, Japan, Tibet, Chile, Germany, Austria, Svalbard, Norway, Greenland, and Antarctica as part of a wide variety of terrestrial modeling studies (e.g., Liston and Sturm 1998, 2002; Greene et al. 1999; Liston et al. 2000, 2002, 2007, 2008, 2016; Prasad et al. 2001; Hiemstra et al. 2002, 2006; Hasholt et al. 2003; Bruland et al. 2004; Liston and Winther 2005; Mernild et al. 2006, 2008, 2009, 2010, 2011, 2014, 2015; Liston and Hiemstra 2008, 2011a, b; Mernild and Liston 2010; Suzuki et al. 2011, 2015a, b; Fletcher et al. 2012; Gascoin et al. 2012; Liston and Mernild 2012; Stuefer et al. 2013; Hoffman et al. 2014, 2016; Pedersen et al. 2015).

Model simulation

a. Model configuration and simulation domain

SnowModel simulations were performed for the period 1 September 2005 through 31 August 2008 (1096 days) over a spatial domain that covered an 80-km by 120-km area in southwest Alaska. Model simulations were performed using a 25-m horizontal grid increment over the domain (3200 and 4800 grid cells in the x and y directions, respectively; or ~15 million grid cells). This 25-m grid increment strikes a balance between available computer resources and the need to accurately represent the driving snow-distribution processes found within the simulation domain, and it created a dataset that was integer divisible by the other grid resolutions used in this study (100-m, 500-m, 2-km, and 10-km). In addition, the simulations used a 1-day time increment to keep computational requirements within acceptable limits.

Topographical data (30-m horizontal resolution) for the domain were obtained from the United States Landfire database and regridded to the 25-m simulation grid (Fig. S1). Vegetation data (30-m horizontal resolution) were obtained from the United States National Land Cover Data database and regridded to the 25-m grid and reclassified to match SnowModel's defined vegetation classes (Fig. S2) (Liston and Elder 2006a).

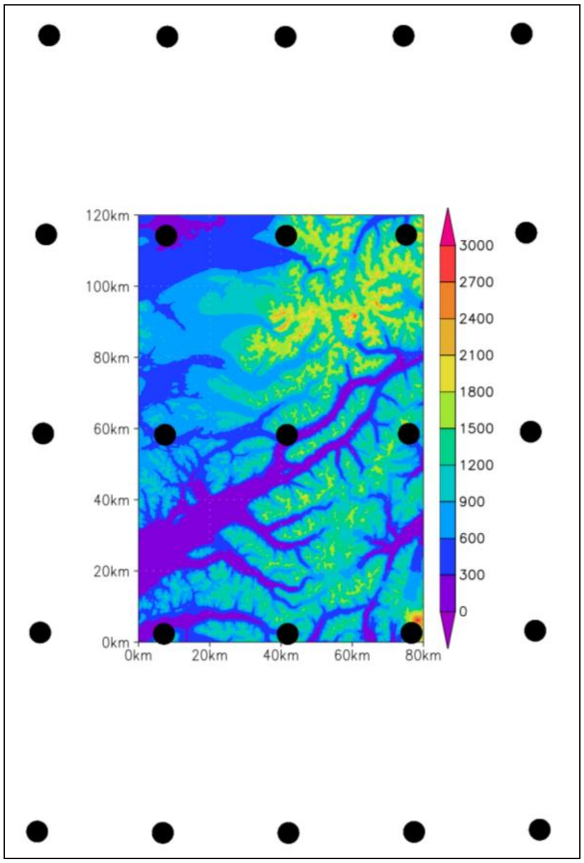

Fig. S1: 80-km by 120-km simulation domain (color shades are topography; m), and MERRA-2 atmospheric forcing locations (black dots).

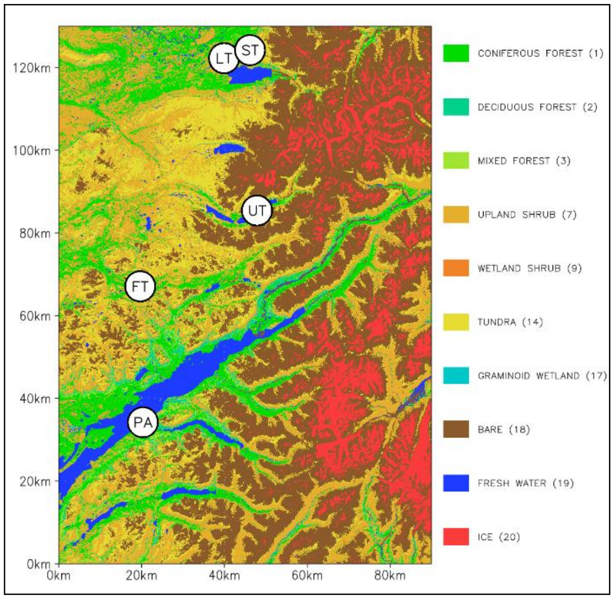

Fig. S2: Land-cover distribution (see Liston and Elder 2006a for the available land-cover classes). Also shown are the meteorological stations (large circles with ID letters) used in the analyses. The RAWS stations Port Alsworth (PA) and Stoney (ST) were used in the air temperature and wind speed analyses, and the SNOTEL stations PA and Lake Telaquana (LT) were used in the precipitation and snow depth analyses.

b. Meteorological forcing

Atmospheric forcing data were provided by NASA Modern Era Retrospective-Analysis for Research and Applications (MERRA) products (Bosilovich et al. 2008; Cullather and Bosilovich 2011; Rienecker et al. 2011; Lindsay et al. 2014). This reanalysis program has the specific goal of improving the representation of water cycle processes and features within the analyses while taking advantage of modern satellite era datasets. The latest version of the MERRA reanalysis used herein (MERRA-2) covers the period 1980-present, on a 5/8° longitude by 1/2° latitude global grid. Hourly surface atmospheric forcing variables were available. The MERRA-2 reanalysis assimilates a wide range of satellite observations in addition to more conventional radiosonde, dropsonde, aircraft, and surface observations. Bosilovich et al. (2008) analyzed precipitation outputs from an early version of the MERRA reanalysis system, and concluded the MERRA precipitation fields were an improvement over the previous generations of reanalyses.

In preparation for the model simulations, hourly, MERRA-2 10-m air temperature, specific humidity, and u and v wind components, and surface pressure and precipitation variables were aggregated to daily values. Locations of the 25 MERRA-2 grid points used to force the MicroMet - SnowModel simulations are included in Fig. S1. MicroMet then used these to create the daily, 25-m atmospheric forcing distributions required by SnowModel (air temperature, relative humidity, wind speed and direction, precipitation, and incoming solar and longwave radiation); see Liston and Elder (2006b) for additional details. Water-equivalent precipitation was provided from MERRA-2, and MicroMet's temperature threshold parameterization was used to define whether rain or snow fell on each model grid cell. MicroMet ingested the MERRA-2 atmospheric variables and created the atmospheric forcing conditions on the 25-m SnowModel grid. The resulting 25-m atmospheric fields were ingested by SnowModel to simulate the daily time evolution and spatial distribution of water and energy fluxes and states. SnowModel-simulated variables included: surface (skin) temperature, albedo, outgoing longwave radiation, latent heat flux, sensible heat flux, liquid precipitation, solid precipitation, snowmelt, sublimation, snowmelt runoff, and snow water equivalent. In addition, we generated secondary products such as the timing and distribution of rain-on-snow events, changes in snow and growing season lengths, hydrologic budgets, and changes in surface energy exchanges.

As part of these simulations, SnowAssim was used to assimilate available SNOTEL snow depth data (Liston and Hiemstra 2008). This assimilation imposed a correction to the MERRA-2 water-equivalent precipitation inputs such that the SnowModel simulated snow water equivalent closely matched the SNOTEL observations. As part of the model integrations, the SNOTEL snow depths were converted to snow water equivalent using the Sturm et al. (2010) snow-classification snow-density sub-model. The resulting snow water equivalent was used to correct the water equivalent precipitation inputs. Then, because of this project's specific interest in snow depth, SnowModel's snow water equivalent evolution was converted to snow depth evolution using Sturm et al. (2010). The data assimilation was performed using the Port Alsworth and Lake Telaquana SNOTEL sites (PA and LT in Fig. S2, respectively), using data available late in the snow accumulation season (Table S1), and assumed to be representative of snowscapes within a 5-km radius (in the absence of a high density of SNOTEL stations). As part of the data assimilation, the MERRA-2 precipitation forcing was decreased by approximately 2/3 in order to reproduce the SNOTEL observations.

c. Additional SnowModel parameterizations

A wind increase with elevation was implemented in the SnowModel simulations. This was required in order to have blowing snow on the highest ridges (when driven with the relatively low-elevation MERRA-2 wind speeds). The presence of glaciers on lee slopes indicates this is an important component of the system. The wind speed increase is represented the same way that precipitation increases with elevation in the modeling system (using different parameters, of course). In this context, a general wind speed increase of 25% per 1-km elevation gain was applied in the absence of ridge-top meteorological stations. In addition, a moist lapse rate was applied to the simulation.

d. Results

Table S1: Late-winter SNOTEL snow-depth data used in the precipitation-correction assimilations. The snow-water-equivalent values were obtained by applying the Sturm et al. (2010) taiga snow density (217 kg·m^{-3}) to the SNOTEL snow-depth observations.

		SNOTEL		**SnowModel**	
Station	*Date*	*Snow Depth (cm)*	*Snow Water Equivalent (cm)*	*Snow Depth (cm)*	*Snow Water Equivalent (cm)*
LT	4/5/2006	54.61	11.85	47.76	10.36
PA	4/7/2006	37.08	8.05	43.16	9.37
LT	4/2/2007	16.38	3.56	15.74	3.41
PA	4/3/2007	22.99	4.99	20.17	4.38
LT	3/13/2008	46.74	10.14	44.34	9.62
PA	3/14/2008	54.19	11.76	60.23	13.07

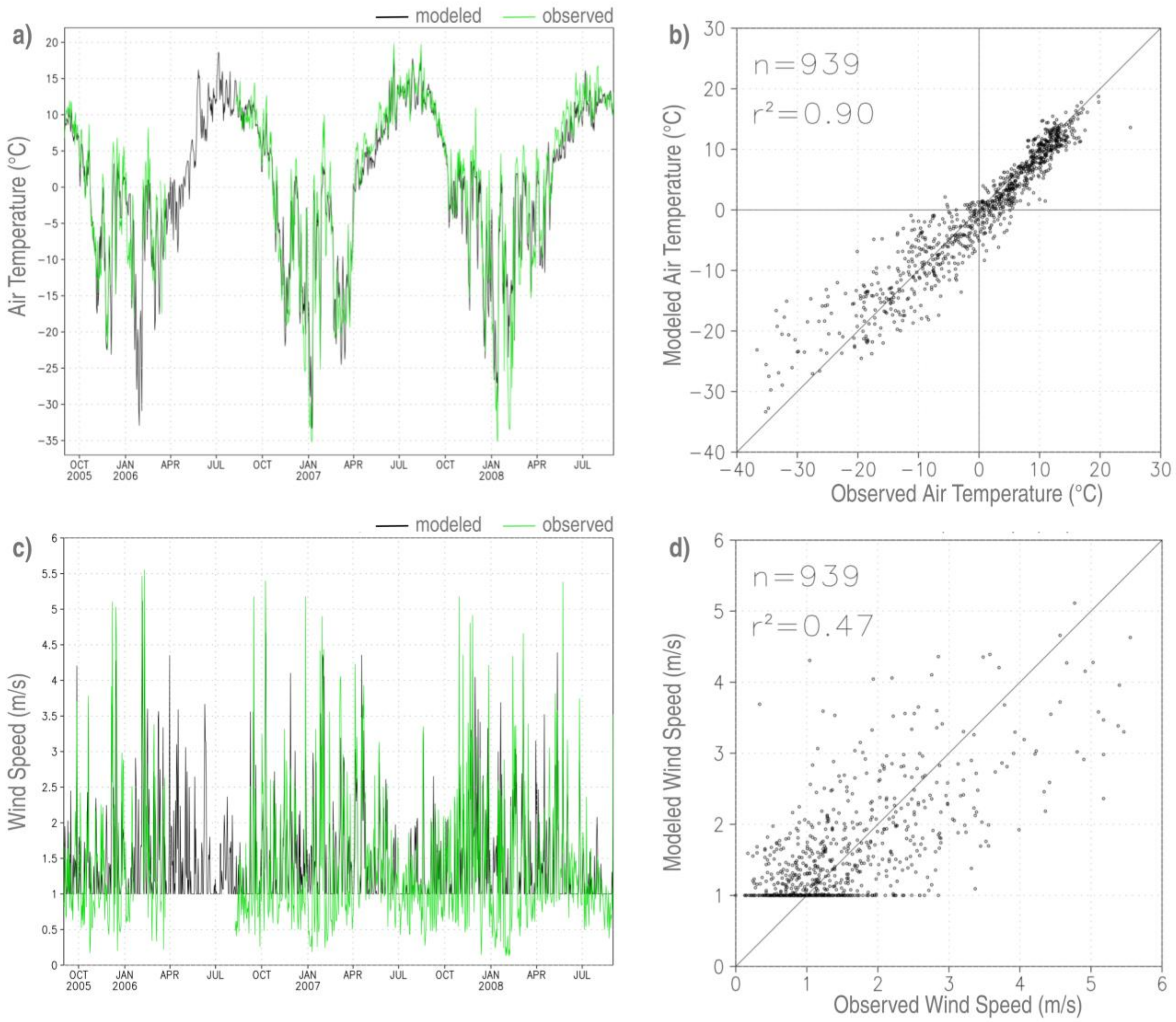

Figure S3: The model-predicted (black) and observed (green) air temperatures (a,b) and wind speeds (c,d) at the Port Alsworth (PA) SNOTEL site as measured on a 25-m grid. Wind speeds are constrained at or above 1-m/s because low wind speeds violate turbulent wind field assumptions within model equations in MicroMet. Results are similar to the Lake Telaquana SNOTEL site.

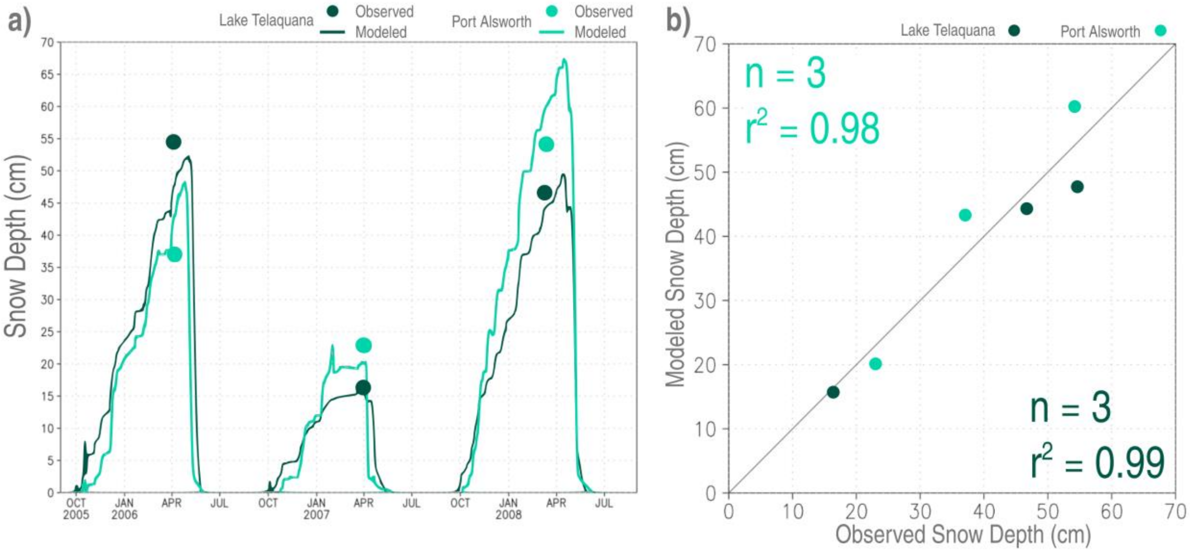

Fig. S4: The model-predicted (line) and observed (circle) snow depths at the Port Alsworth (light green) and Lake Telaquana (dark green) SNOTEL sites as measured on a 25-m grid. SnowModel's data assimilation sub-model (SnowAssim) pushes snowpack simulations toward snow depth observations in order to accurately replicate snow physics and conditions in space and time.

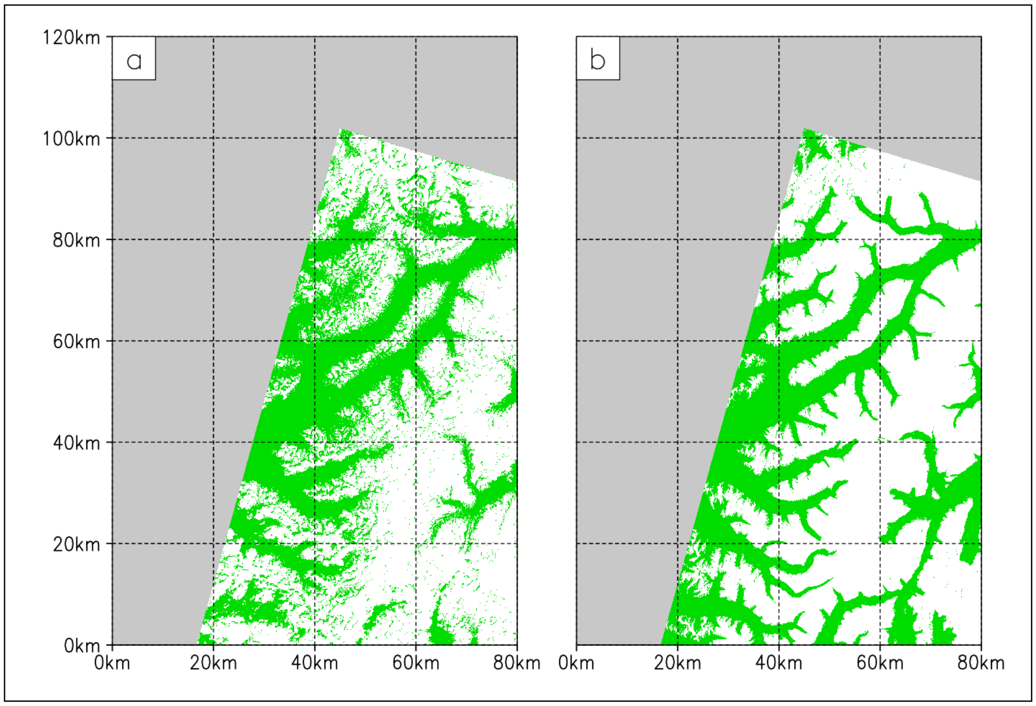

Figure S5: Landsat image LT50710182008170GLC00 from 18 June 2008 was used to compare the snow-covered area simulated by SnowModel on this same date. The western half of the Landsat image had considerable cloud cover, so it was not used in the analysis (grey areas). Green is snow-free, white is snow-covered. (a) is the Landsat image, and it is 38% snow-free; (b) is the SnowModel output, and, for the area coincident with the Landsat image, 36% of the area is snow-free.

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