Influence of Sub-grid Variability on Snow Deposition and Ablation in North American Mountain Environments: Implications for Upscaling to Meso-scale Representations

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Abstract

A measurement and modeling evaluation of how snow distribution and melt are influenced by vegetation and topographic structure at three different experimental catchments in western North America (two in the western U.S. and one in western Canada) has been undertaken. This ongoing research investigates variations in the critical interactions between vegetation, topography and snowcover in different snow-dominated basins, how these variations impact upscaling site- and basin-scale processes for watershed and regional scale analyses, and how these differences are incorporated in transferable methods to account for the effects of sub-grid variability. By uniquely covering a transect of cordilleran research sites from 35 to 61° N and from 1,000 to 2,700 m asl, it provides a true 'Western Cordilleran baseline' for snowmelt runoff prediction for North America that will substantially benefit model development and testing.

Keywords: snow, watershed hydrology

Introduction

Forest snow scaling

The influence of forest canopy cover and variable melt energetics on depletion of snowcover was investigated following earlier work in open environments. The results can be stratified into that variability within the forest stand and that between forest stands. Within stands, Faria et al. (2000) found the frequency distribution of snow water equivalent (SWE) under boreal forest canopies fit a log-normal distribution. Within-stand covariance between the spatial distributions of snow water equivalent and melt energy promoted an earlier depletion of snowcover than if melt energy were uniform. This covariance was largest for the most heterogeneous stands (usually medium density). Stand scale variability in mean SWE and mean melt energy resulted in more rapid snow covered area (SCA) depletion for stands with lower leaf area. Because of the heterogeneity in the spatial distributions of SWE and melt energy in forest environments, it is necessary that these variations be included in calculations of SCA depletion (Faria et al. 2000).

Forest snowmelt energetics

Recent studies of energetics of forest snowmelt (Davis et al. 1997, Hardy et al. 1997, Pomeroy and Granger 1997, Link and Marks 1999a, Link and Marks 1999b, Hardy et al. 2000) have focused on sub-canopy radiative exchange. Sub-canopy insolation is roughly one order of magnitude less than that incoming to a mature pine forest during melt. Snow albedo below forest canopies is lower than that of typical open snowfields (Harding and Pomeroy 1996) and is subject to a premelt decay due to deposited leaf litter from forest canopies (Hardy et al. 2000). Melt simulations that include a litter decay algorithm are vastly improved over those with traditional albedo assumptions (Link and Marks 1999b, Hardy et al. 2000).

Few studies have considered in detail the contribution of sub-canopy longwave radiation, despite the relatively warm canopy temperatures (10 to 20 °C above that of snow) measured during melt.

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Measurements in a boreal pine forest by the authors of this paper (Figures 1 and 2) suggest that net sub-canopy longwave radiation can be a significant component of melt energy (Figure 1), and canopy air temperatures are poor predictors of sub-canopy longwave radiation (Figure 2). The implications of these suggestions are that research should focus on improving longwave radiation parameterizations for snowmelt under forest canopies.

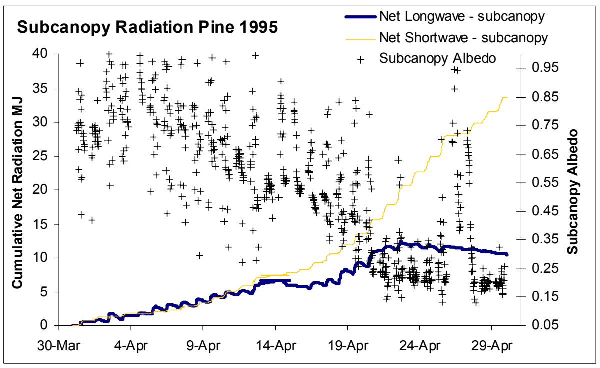


Figure 1. Radiation under a pine canopy 1995. Cumulative net longwave is within 2/3 of net shortwave until the snowpack is largely depleted (albedo < 0.25).

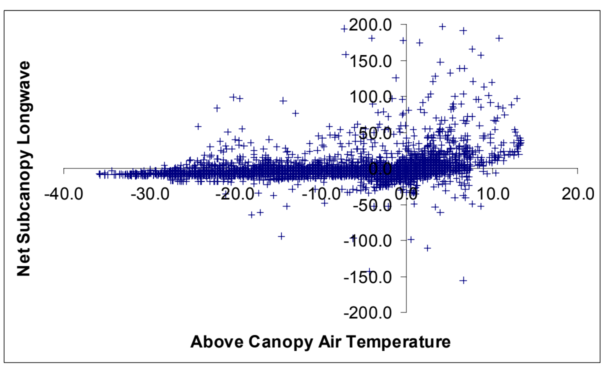


Figure 2. Sub-canopy longwave radiation vs. air temperature under pine canopy, 1995 showing poor predictive relationship.

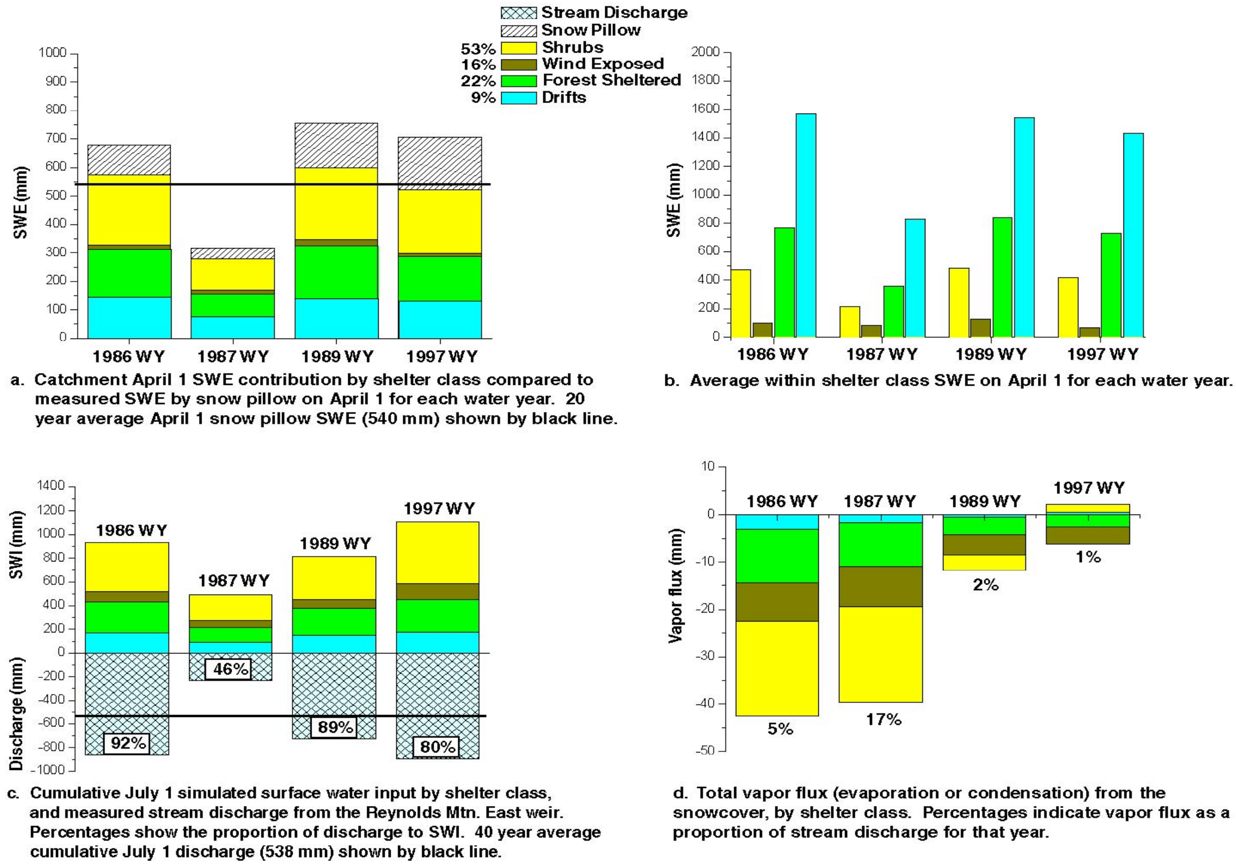
High mountain accumulation and ablation

Marks et al. (2001a, 2002) showed that in mountain catchments, the degree of vegetation and terrain shelter could account for patterns of snow deposition and melt. Figures 3a-3d show how the degree of shelter in a small headwater catchment in the Reynolds Creek Experimental Watershed, Idaho, impacts snow deposition, sublimation, melt and runoff generation. This work suggests that: 1) drift areas represent only a small portion of mountain catchments, but hold a significant portion of catchment SWE; and 2) wind scoured areas may account for a large part of catchment area, but hold hardly any catchment SWE. Furthermore, SWE stored in large drifts persists into late spring and early summer, providing water to ecosystems well into the growing season, while wind exposed areas melt early and are generally snow-free by late winter or early spring.

This prior research suggests that forest SWE mean and variability is controlled by canopy structure, that the below canopy solar and thermal radiation to snow is influenced by canopy type and structure, and that to account for these effects we must improve our understanding of litter, shading and thermal structure of different canopy types. It is also clear that the coupled effects of terrain structure and vegetation in mountain catchments significantly affect the degree of shelter from wind and solar radiation. The degree or shelter determines patterns of drifting, snow deposition, and scour, and alters snowcover energetics causing exposed regions to melt early, and more sheltered regions to melt later in the spring and early summer. In mountainous regions, all of these effects vary at scales much smaller than 1 km.

Background

The processes controlling the rates and magnitude of snow deposition and ablation over complex topography and in and under vegetation canopies remain one of the greatest uncertainties in the operation of land surface schemes and hydrological models over mountainous regions. For instance, very few hydrological or land surface models distinguish between snow intercepted in forest canopies, and the surface snowpack sheltered under forest canopies (Pomeroy et al. 1998). No climate or water model includes the effects of exposed shrubs in collecting wind-blown snow in the alpine zone or the development of large drifts in topographically sheltered areas; these effects transform shortwave and longwave radiative exchange above the snowpack and moderate turbulent exchange between the atmosphere and underlying snowpack. Land surface schemes have at best an ad hoc representation of snow cover development and depletion that does not well represent wind redistribution of snow or actual areal albedo decay during melt and results in significant errors in surface energy balance calculations (Pomeroy et al. 1998). Complex mountain



a. Catchment April 1 SWE contribution by shelter class compared to measured SWE by snow pillow on April 1 for each water year. 20 year average April 1 snow pillow SWE (540 mm) shown by black line.

b. Average within shelter class SWE on April 1 for each water year.

c. Cumulative July 1 simulated surface water input by shelter class, and measured stream discharge from the Reynolds Mtn. East weir. Percentages show the proportion of discharge to SWI. 40 year average cumulative July 1 discharge (538 mm) shown by black line.

d. Total vapor flux (evaporation or condensation) from the snowcover, by shelter class. Percentages indicate vapor flux as a proportion of stream discharge for that year.

Figure 3. Snow Water Equivalent (SWE), Surface Water Input (SWI) and Vapor Flux by Shelter Class, Reynolds Mountain East Catchment, Reynolds Creek Experimental Watershed.

terrain includes combined effects due to slope, aspect, terrain shelter, and vegetation structure (Marks and Winstral 2001) that largely control both snow redistribution and drifting during the development of the snowcover, and variable patterns of snowcover energetics during melt. These effects are either poorly described or ignored in regional and global scale climate and hydrological models.

For larger scale models the processes governing snowmelt energetics have been most fully considered for idealized ‘plane’ surfaces that meet the uniform, level fetch requirements for steady-state atmospheric boundary layer development and for straightforward radiation fluxes as a function of solar angle and latitude. Refinements to these considerations include the calculation of incoming direct and diffuse shortwave radiation on slopes (Garnier and Ohmura 1968), calculation of longwave fluxes from neighboring slopes (Marks and Dozier 1979) and consideration of the effects of vegetation on radiative transfer (Hardy et al. 1997, Link and Marks 1999b, Marks et al. 2001b). Recent progress has considered the important effect of discontinuous snow cover on advective turbulent exchange and snow energy balance (Shook and Gray 1997) but has still employed level terrain assumptions.

Most models of snow energetics, snow hydrology and snow-atmosphere interactions still employ the uniform planar snow cover assumption with the most sophisticated now including modifications for radiation based on solar angle, slope, aspect and skyview (e.g. Marks et al. 1999) and for advection (Shook and Gray 1997). At the catchment scale, over grids of 100m or less, the processes controlling both snow deposition and melt have been fully accounted for in the applications of the ISNOBAL model (Marks et al. 2002), and effectively accounted for over larger areas using grids as large as 250m (Garen and Marks 2003). In considering the usefulness of snowmelt calculations for mountain hydrology, it is important to realize that hillslopes form the most critical and distinctive part of the catchment contributing area. During snowmelt in alpine locations they are particularly important because snow drifts on lee-side slopes provide an inordinately large proportion of basin SWE accumulation (Woo and Marsh 1978, Marks et al. 2002) and contribute to streamflow generation for an extended period after other landscape types have become depleted of snow (Marsh and Pomeroy, 1996). The influence of slope and aspect are very important for hillslope snowmelt calculations as they affect snow accumulation, snowmelt energetics, the resulting meltwater fluxes and runoff contributing area. The impact of slope and aspect on the energetics of snowmelt may need to be considered comprehensively with snow accumulation and snow cover state for a discrete slope within a landscape type because the energy and mass balance processes are coupled through the evolving state of the snow cover and non-snow- covered surfaces. The variability in the microclimate of these slopes and of the atmospheric exchange occurring on slopes is of interest to better understand and describe land-snow-atmosphere interactions during snow deposition and melt in mountain environments. Critical parameters to consider are the spatial variability of snow mass, components of the snowcover energy balance, and the association between these terms. In particular, land cover characteristics and topographic shape of snow deposition areas where large drifts develop and scour areas where wind exposure and scrub height limit the maximum snow depth must be accounted for.

Approach

Research sites

This research effort relies on three world-class experimental basins: Wolf Creek Research Basin (WCRB) in the Yukon Territory (Canada), the Reynolds Creek Experimental Watershed (RCEW) in Idaho, and the Fraser Experimental Forest in Colorado (Fraser) (Figure 4). These sites form a continental-scale transect that is representative of northern cordilleran mountains, semi-arid mountainous rangelands, and high-elevation Rocky mountain regions that comprise the headwaters of western North American river systems. All sites are extensively instrumented, have a significant historical hydrometeorological and vegetation/ topographic data records, and are currently supported by intensive local experiments that provide the basic infrastructure and local collaborators with which to conduct research (USDA in RCEW, CLPX and USFS in Fraser, and CFCAS/Northern Affairs Canada in WCRB).

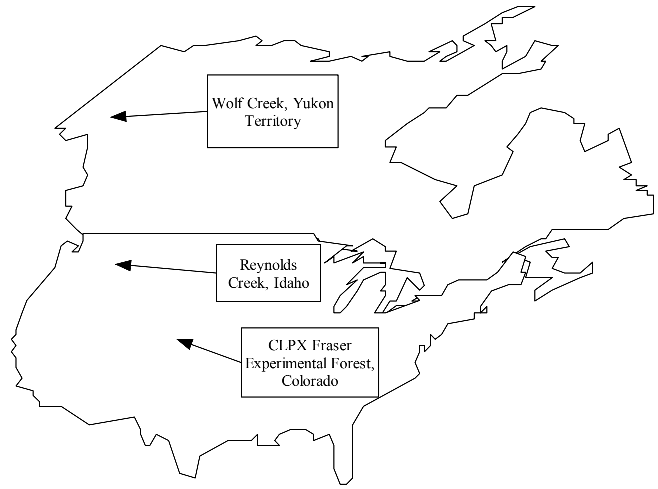


Figure 4. Field experiment sites in the Western Cordillera of North America.

Wolf Creek Research Basin (WCRB), Yukon Territory, Canada

The Wolf Creek Research Basin is located in the northern cordillera of northern Canada near the city of Whitehorse, Yukon Territory at 61° N latitude. The basin is 195 km^2, spans an elevation range from 800 to 2,250 m asl, and contains boreal forest, sub-alpine taiga, and alpine tundra ecosystems. The WCRB provides uniquely simple access to high-altitude sites with a distinct snow season, both forest and shrub-tundra and some degree of complex topography. Whitehorse Airport has a full reference climate and upper air sounding station. WCRB was established as a GEWEX research basin in 1993. WCRB has grown to host a number of hydrological, atmospheric and ecological studies (Pomeroy and Granger 1999) and its physical attributes are well documented with DEM, vegetation and soils maps, NDVI, and LAI. The proponents have established nine hydro-meteorological towers at various elevations/vegetation zones (alpine, shrub tundra, forest) in the catchment that continuously measure WMO standard meteorological variables as well as net and solar radiation, soil temperature, snow depth and soil moisture.

Reynolds Creek Experimental Watershed (RCEW)

The Reynolds Creek Experimental Watershed is located in the Owyhee Mountains of southwestern Idaho, in close proximity to Boise, ID (Marks 2001).

The RCEW is typical of semiarid rangelands that cover large regions of intermediate elevation lands in the western U.S. The RCEW is a 239 km^2 watershed ranging in elevation from 1,101 to 2,241 m asl. Mean annual precipitation ranges from about 230 mm at the lower elevations to over 1,100 mm at the higher elevations, where 75% or more of the annual precipitation occurs as snowfall. A mix of shrub, deciduous forest and coniferous forest communities are found at the more mesic, snow-dominated, higher elevation areas.

RCEW has been operated since 1960 by the USDA Agricultural Research Service, Northwest Watershed Research Center (NWRC). Intensive precipitation measurements are completed throughout the watershed with 28 precipitation sites composed of paired shielded and unshielded gauges. Snow cover and snow water equivalent (SWE) at RCEW is monitored bi-weekly. Meteorological data are collected at 11 sites and include solar and thermal radiation, air temperature, humidity, wind speed and direction, barometric pressure, and soil temperature. Hourly streamflow records are present for nested watersheds ranging from 1 ha to 23,866 ha. Spatial data sets for RCEW include a high-resolution (10 m grid) digital elevation model (DEM), vegetation coverage, soils, and geology.

Fraser Experimental Forest, Colorado

The Fraser Experimental Forest is located approximately 60 miles northwest of Denver, CO on the western slope of the Front Range. Fraser is a topographically complex, forested area, with a mean elevation is 3,066 m asl. Fraser is the site of the Cold Land Processes Field Experiment (CLPX) (Cline et al. 2001), designed to advance our understanding of the terrestrial cryosphere. CLPX is being conducted over an area 4.5^o x 3.5^o centered over the mountains of western central Colorado. Within this area, nine 25 km x 25 km regions have been selected for intensive snow surveys. During winter and spring of 2002, 2003, and 2004 pairs of surveys of depth and SWE will be conducted each time generating over 560 samples within each of the nine study areas, and over 5,000 over the CLPX region.

This data set will become the primary model testing and verification data set for snow simulation over large regions. Installed as part of the CLPX, the 1-ha Local Scale Observation Site (LSOS) was designed to investigate fine-scale snow processes and properties. The LSOS consists of a dense pine stand and an open pine stand. This site is comprehensively instrumented with full energy and mass balance meteorological stations by the USFS RMS and NASA GSFC and intensively snow surveyed at both fine and long scales.

Coordinated site data collection

Observational strategies at the three sites are harmonized according to an assessment of 'best practices' developed for a number of studies such as GEWEX-GAPP, MAGS, CLPX and ARS watershed hydrology programs at RCEW, to provide consistent, high quality datasets for model development and testing. Automated data collection efforts are coordinated so that key hydro-meteorological variables are measured using comparable equipment at vertical and lateral positions within vegetation canopies, and within similar terrain positions at all three sites. Specific variables measured at all sites include snow depth, snow water equivalent, total solar radiation, diffuse solar radiation, thermal radiation, air and soil temperature, sensible and latent heat fluxes, wind speed and direction, and relative humidity. Spatially intensive manual sampling of snow and vegetation properties is also coordinated at all three sites during a series of focused field campaigns.

Focused field campaigns

Focused field campaigns are designed to improve multi-dimensional process representations of snow dynamics for complex terrain, reduce uncertainty in model runs and assess the transferability of improved small to medium scale models of snow accumulation and ablation. The focused field campaigns provide the following key data: 1) continuous measurements of vertical and horizontal distributions of radiation and climate variables within and above forest and shrub canopies, 2) eddy covariance measurements of sensible and latent heat fluxes above forest canopies and from open snowfields, and 3) periodic, spatially distributed, measurements of snow properties over topographically complex catchments with a variety of shrub and forest covers.

Field experiments at RCEW focus on the shrub, coniferous and deciduous forest zones. Field experiments at WCRB focus on the forest and the shrub tundra zone, and field experiments at Fraser focus on the dense and open coniferous forests at the LSOS site.

Conclusions

This coordinated multi-watershed research effort will permit an assessment of the key fine-scale snow processes operating across the complex cordilleran environments, and the transferability of process upscaling methodologies in the various mountain environments. It will produce datasets that can be used for further basin-scale model validation, suggest methods to deal with the effect of sub-grid variability and provide the inputs needed to suggest faithful representations of snow deposition and ablation at larger scales.

Acknowledgments

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