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Linkages between snow ablation and atmospheric boundary-layer conditions in a semi-arid basin of Western Canada

Scott I. Jackson *, Terry D. Prowse, Barrie R. Bonsal

Water and Climate Impacts Research Centre (W-CIRC), Environment Canada, Department of Geography, University of Victoria, Victoria, British Columbia V8W 3R4, Canada

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SUMMARY

High-elevation snowpacks provide critical inputs to the hydrological system of mountainous semi-arid regions where summer precipitation is insufficient to maintain adequate discharges for ecological and economic needs. The Okanagan Basin in Western Canada is an example of such a system, as most of the summer streamflow is derived from snowmelt. To better understand how snowmelt events vary as a result of atmospheric conditions, this study developed statistical models using upper-air atmospheric data for evaluating changes in snowpack ablation. Specifically, radiosonde data were statistically linked with detailed ground-based measurements of snowmelt and associated streamflow. Statistical models were developed based on data from the 2007 ablation season and concurrent data from the 850 hPa geopotential height. These models explained 57–68% of the variance in snowmelt for 2007, and were extended to predict snowmelt for the radiosonde period of record (1972–2012). Time-series analyses showed significant trends toward higher winter and spring temperatures, vertical temperature gradients in the atmospheric boundary layer in spring, and earlier dates for snowmelt and freshet initiation. Significant negative trends were also found towards decreasing spring precipitation. More broadly, ablation-season climatic and hydrological variables were significantly positively correlated with the winter and spring Multivariate El Niño Southern Oscillation and Pacific Decadal Oscillation indices, in which the positive (negative) phase was associated with higher (lower) magnitude and frequency of melt events. This combination of strong correlations and significant temporal trends indicates that with projected air-temperature increases, the magnitude and duration of melt events are likely to increase, particularly during favourable phases of the above teleconnections.

1. Introduction

Water resources in semi-arid regions with high-elevation snowpacks, are highly susceptible to changes in snowmelt timing and volume as this process maintains stream flows throughout the dry summer months (Barnett et al., 2005). Given the strong reliance of these regions on vulnerable high-elevation snowpacks, it is critical that snow ablation processes and their links to the controlling meteorological conditions are better understood. This is particularly true for the Okanagan Basin in south-central British Columbia, where the stress on fresh-water supplies is increasing due to increasing population and a changing climate (Fig. 1). The Okanagan Basin is already undergoing substantial hydro-climatic change. Over the past century, in the Coldstream sub-basin both winter and spring temperatures and winter, spring, autumn and annual precipitation have increased significantly (Taylor and Barton, 2004). This coincides with a shift towards a two days/decade (1901–2012) earlier occurrence of the spring 0 °C isotherm at the Vernon Coldstream Ranch station in the northern portion of the Okanagan Basin (Bonsal and Prowse, 2003). Future climate projections indicate that over the next century as winter temperature and precipitation increase, less precipitation will fall as snow and the snowmelt season will occur 4–6 weeks earlier, resulting in “considerable reductions” in annual and spring flow volumes (Merritt et al., 2006).

Further compounding stress on the hydrologic regime are the extensive forest cover changes resulting from a mountain pine-beetle epidemic. In particular, snow accumulation and ablation patterns are projected to change as openings in the forest become larger and more interconnected, thereby increasing snow accumulation, fetch lengths and melt rates (Carroll et al., 2006; Boon, 2009).

Information about snow energy and mass exchanges at higher elevations in the Okanagan is limited, making evaluation of

* Corresponding author. Present address: BC Ministry of Environment, Bag 5000, 3726 Alfred Avenue, Smithers, BC V0J 2N0, Canada. Tel.: +1 250 847 7507; fax: +1 250 847 7591.

E-mail address: Scott.Jackson@gov.bc.ca (S.I. Jackson).

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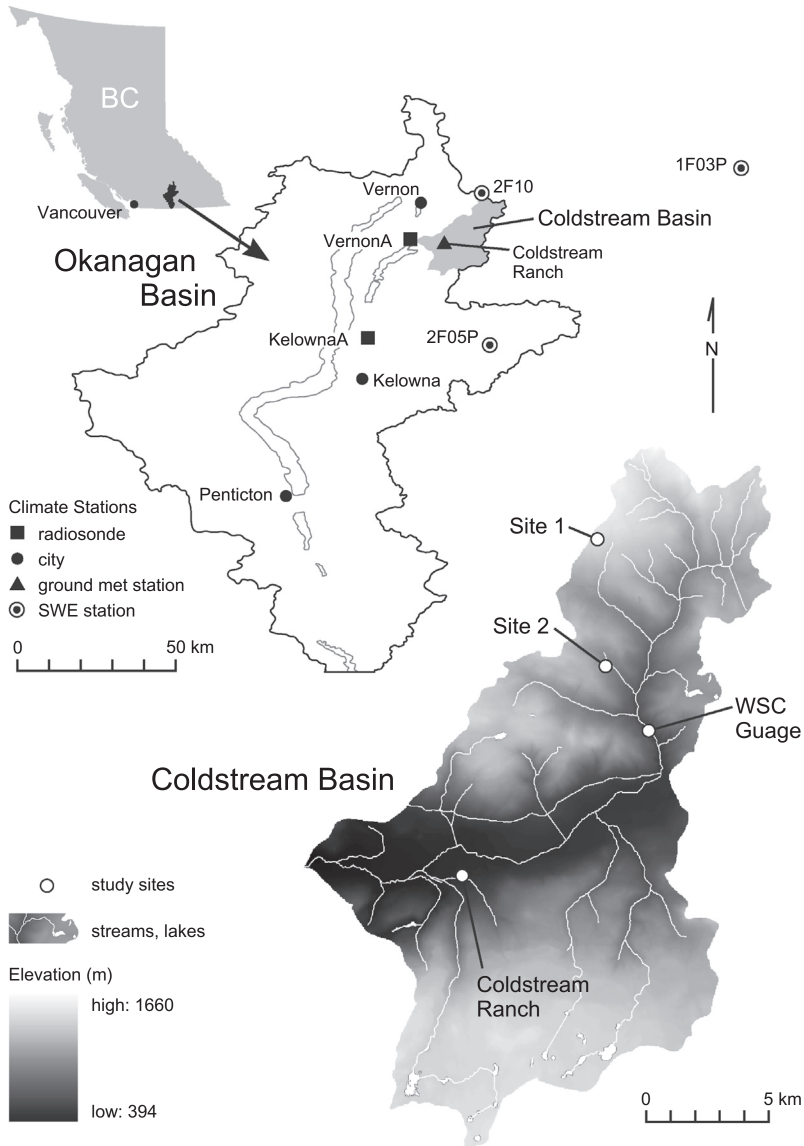

Fig. 1. Location of Coldstream Basin within British Columbia, Canada, and climate stations used in the analysis.

atmospheric-change effects challenging (Merritt et al., 2006). The lack of information partly stems from the high cost of long-term maintenance of high-elevation climate stations. As an alternative, this study explored the use of upper atmosphere climate data obtained from operational radiosonde flights, to evaluate long-term changes in the ablation-season snow energy balance. This required detailed ground-level information on snow melt processes from which statistical relationships with atmospheric data could be established. Such information was available from a previously published study (Jackson and Prowse, 2009) in which snow ablation processes were investigated along a four-site elevational transect in a high-elevation basin situated at the north end of the larger Okanagan Basin.

The issue of scale is paramount in snow hydrology, and in particular, the scaling up of site-specific data to accurately represent basin-wide responses (Blöschl, 1999). Given the operational impracticality of conducting snow ablation measurements at multiple sites for many years, it is necessary to find alternative methods to estimate snow melt over larger spatial and temporal scales. Radiosonde flights take measurements throughout the atmospheric boundary layer (ABL) profile, which mitigates some of the influence of site-specific factors such as vegetation and topography. Above a certain elevation (dependant on the depth of the boundary layer), the influence of spatial variation in topography and vegetation at the micro- and meso-scale becomes muted, and the conditions measured in the ABL integrate the effects of the composition of the earths surface on the atmosphere over a much wider area. Therefore, the radiosonde data provide an excellent source of high-quality data that can be considered representative of the northern Okanagan Basin.

Although the literature regarding use of radiosonde data to characterise surface energy balance is limited, there are several studies that have examined the utility of this approach. For example, Granger and Male (1978) reported that sensible heat flux over a melting snowpack in Saskatchewan was more closely related to the 850 hPa height temperature than near-surface temperature. This was due to advection from the air mass dominating the ground level sensible heat flux instead of local radiative heating and advection (e.g., from snow free areas). Additional studies have shown that evaporation estimates derived from radiosonde data provided good agreement with ground based measurements over a wide area, in both simple (Mawdsley and Brutsaert, 1977;