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Blowing Snow Fluxes in the Cariboo Mountains of British Columbia, Canada

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Abstract

The Cariboo Mountains form the northern extension of the Columbia Mountains, spanning a distance of about 300 km in central British Columbia (BC), Canada. Cool air temperatures, abundant snowfall, and strong winds (especially above treeline and along exposed ridges) would suggest frequent and intense blowing snow events. The occurrence of intense blowing snow episodes is confirmed by automated wind and snow depth measurements at several sites in the area. Simulations conducted with a numerical model forced by meteorological observations recorded from 2006 to 2009 reveal a high frequency of blowing snow episodes at three high-elevation sites in the Cariboo Mountains. This process is especially prominent on the exposed ridge of Browntop Mountain (elevation of 2031 m a.s.l.) where snow transport by wind is calculated to occur as much as two-thirds of the time during some winter months. Simulated blowing snow fluxes remain high at this site with monthly transport and sublimation rates reaching 5301 Mg m^{-1} and 31 mm snow water equivalent (SWE), respectively. Blowing snow is also shown to be a dominant process in snow accumulation at the upper Castle Creek Glacier site (elevation of 2105 m a.s.l.), with strong winds generating sharp declines in snow depth and the erosion of more than 200 cm of snow depth during two successive winters. The results presented in this study suggest that blowing snow contributes significantly to snow accumulation and the mass balance of glaciers in BC's Cariboo Mountains.

Introduction

The Cariboo Mountains form the northern extension of the Columbia Mountains, between the interior plateau and the Rocky Mountain Trench in British Columbia (BC), Canada (Fig. 1). They span over 300 km and culminate at Mt. Sir Wilfrid Laurier with an elevation of 3520 m a.s.l. The vegetation, soils and climate vary greatly with the steep elevation gradients that arise from the surrounding Fraser River Valley to the spine of the Cariboo Mountains. In the valley bottoms, rich soils and a relatively warm climate preserve extensive forests, including old-growth cedars and hemlocks. At intermediate altitudes, shallow soils and cooler conditions typically support lodgepole pine, Engelmann spruce, and subalpine fir. Above treeline, the rocky terrain and harsh climate sustain only a variety of shrubs, alpine meadows, and lichens. River runoff and precipitation exhibit strong spatial gradients owing to the steep rise toward the highest elevations in the area. For instance, river runoff increases by 1.26 mm yr^{-1} for each meter of elevation gain in the region's watersheds (Burford et al., 2009). Similarly, precipitation at the town of Quesnel, BC, on the western periphery of the region, is $\approx$500 mm yr^{-1} and increases eastward to reach 2500 mm yr^{-1} around 150 km further east in the Cariboo Mountains. Snow forms a considerable proportion of the total precipitation in the region, and its relative amount increases with altitude (Burford et al., 2009).

The relatively cool air temperatures and abundant snowfall favor the development of numerous glaciers in the Cariboo Mountains. Several large glacier systems exist here including those of the Mt. Lunn Massif and Mt. Sir Wilfrid Laurier, as well as many other smaller glaciers. These glaciers store freshwater and consequently are now recognized as an important economic resource. For example, in 2007 almost 90% of BC's power was generated from hydroelectric projects and provided 85% of the province's generating capacity (Statistics Canada, 2007; BC Hydro, 2009, http://www.bchydro.com). They are also useful climate change indicators, as they respond to varying precipitation and air temperature (e.g., Oerlemans, 2005).

Concerns about the impacts of climate change on glaciers in western Canada has led to enhanced research on processes affecting glacier mass balance including blowing snow. Given its prevalence at high elevations, blowing snow is a contributing factor in the mass balance of glaciers and ice fields (Gallée et al., 2001; Jaedicke, 2002; van den Broeke et al., 2004; Mernild et al., 2006). Snowdrift moves mass around glaciers and across their equilibrium line altitudes, increasing the spatial heterogeneity of snowpack characteristics and altering the melt process from the case with no wind and uniform snow conditions (Mott et al., 2008). Numerical modeling of wind flows on Spitsbergen, Svalbard, suggests that areas of wind deceleration (acceleration) are well correlated to glacierized (glacier-free) regions (Jaedicke and Gauer, 2005). Mass balance processes include positive terms such as precipitation and negative terms such as melting; blowing snow is unusual in that it can appear both as a loss (erosion on windward slopes) and a gain (deposition on leeward slopes), depending on local wind regimes.

Few efforts to date have been devoted to assessing the importance of blowing snow fluxes in mountainous terrain such as western Canada. Previous studies on blowing snow fluxes have focused on prairie or tundra environments (e.g., Pomeroy et al., 1993; Déry and Yau, 2001). Nonetheless, some studies in mountainous terrain do exist in the literature. For instance, Föhn (1980) measured snow mass gains of 87.5 kg m^{-2} from wind

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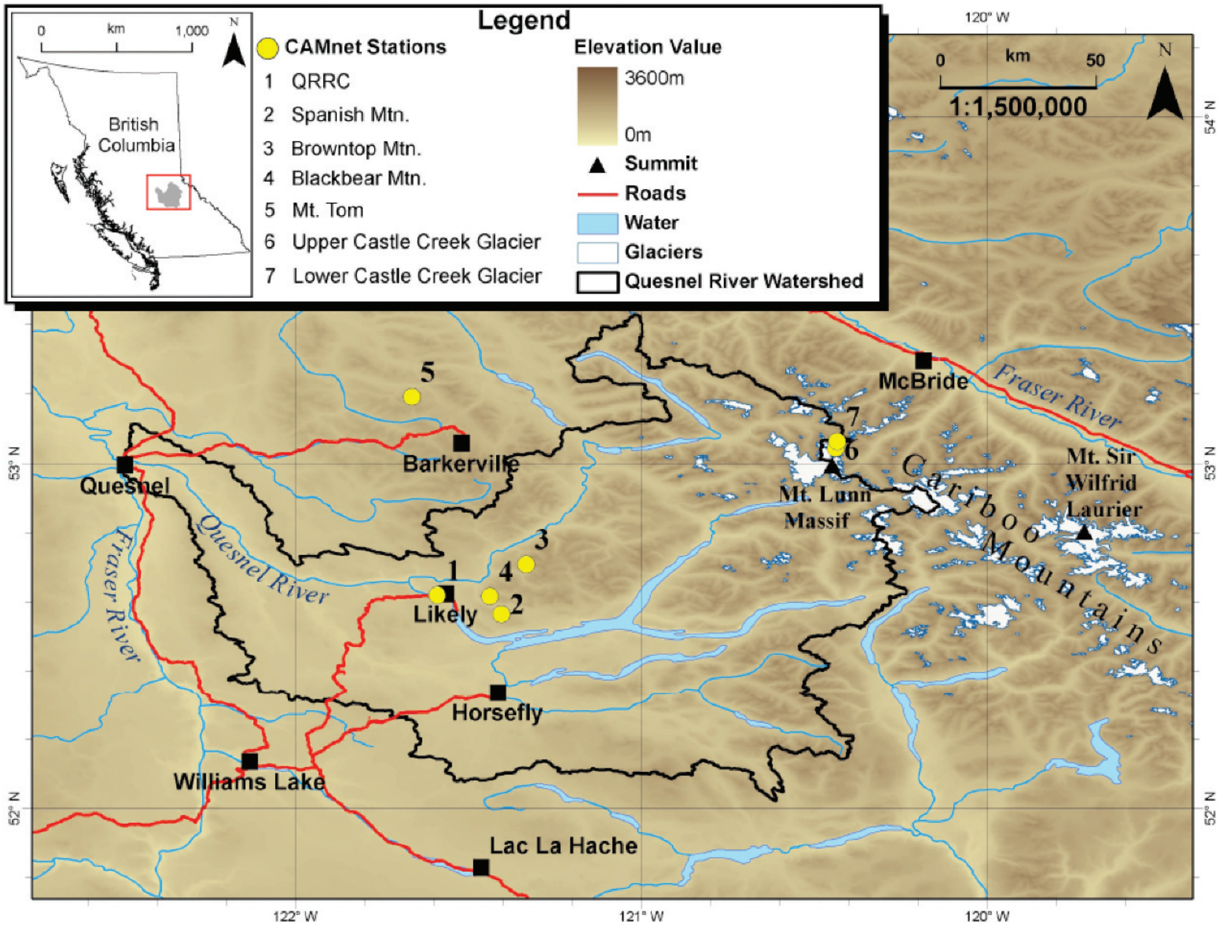

FIGURE 1. **Map of the Cariboo Mountains of British Columbia including the location of CAMnet stations (numbered as in Table 1).**

transport on the leeward slope of Gaudergrat Ridge in the Alps (compared to annual precipitation in the area of 2000 mm or 2000 kg m^{-2}). More recent simulations showed the potential of computationally intensive approaches to modeling snow redistribution around that ridge during a storm (Lehning et al., 2008), but at a resolution which is probably impractical for the Cariboo Mountains. Berg (1986) established that blowing snow occurs over half of the time during winter at Niwot Ridge (elevation of ≈3500 m a.s.l.), Colorado. Greene et al. (1999) and Hiemstra et al. (2002, 2006) simulated snowdrift processes and snow distribution at upper treelines in mountainous terrain of Colorado and Wyoming, respectively. Liston and Sturm (2002) established snowfall patterns in Alaska's Brooks Range from snow depth observations and a blowing snow model. Sublimation of suspended snow has also been shown to be important in the water balance of Niwot Ridge (Hood et al., 1999) and of a high alpine region of southern Germany (Strasser et al., 2008).

These studies suggest that mass movement of snow by wind could also play an important role in the hydrological cycle in some high-elevation, mountainous drainage basins. Indeed, Tong et al. (2009) hypothesized that blowing snow may explain differences of the distribution and persistence in snow cover between windward and leeward slopes of the Cariboo Mountains, but did not quantify its role in snow cover development. The present work builds on the previous efforts that have examined this process in mountainous terrain by quantifying the frequency and fluxes of blowing snow in the Cariboo Mountains of western Canada. The application of a numerical model of blowing snow driven by meteorological observations at three sites in the Cariboo Mountains provides an important step in determining the potential contribution of this process to snow accumulation, glacier mass balance, and the hydrology of watersheds in this remote area.

Data and Methods

METEOROLOGICAL DATA

The Cariboo Alpine Mesonet (CAMnet; MacLeod and Déry, 2007) has been in operation since the summer of 2006 and provides meteorological measurements across a range of elevations (744 to 2105 m a.s.l.) in the Cariboo Mountains (Table 1 and Fig. 1). Instruments at each station measure atmospheric pressure, air and soil temperature, relative humidity (with respect to water), wind speed and direction, liquid precipitation, and snow depth (among other variables; details of the instrumentation are found in MacLeod and Déry, 2007). Data are typically sampled every minute and averaged over 15-min intervals. Gaps exist in some of the time series, most notably for the Browntop Mountain site where the tower and/or meteorological equipment has failed repeatedly during storms in the fall or early winter. This loss of data occurred in the seasons of 2006, 2007, and 2008. Typically, the anemometers are set about 3 m above the surface; however, changing snow depths will influence the relative intensity of the measured wind speeds. We adjust our wind values to a reference height z_{10} of 10 m above the surface assuming a logarithmic profile

TABLE 1

Details of the CAMnet sites.

Site	Name	Latitude (N)	Longitude (W)	Altitude (m a.s.l.)	Terrain	Date of Deployment
1	QRRC[a]	52°37′06″	121°35′24″	744	Flat short grass	Aug. 2006
2	Spanish Mtn.	52°33′44″	121°24′35″	1511	Sloped forest regrowth	June 2006
3	Browntop Mtn.	52°42′48″	121°20′02″	2031	Alpine ridge	Aug. 2006
4	Blackbear Mtn.[b]	52°36′54″	121°26′18″	1590	Sloped forest regrowth	Aug. 2006
5	Mt. Tom[c]	53°11′32″	121°39′49″	1490	Sloped cutblock	Sept. 2007
6	upper Castle Creek Glacier	53°02′36″	120°26′18″	2105	Bedrock ridge	Aug. 2007
7	lower Castle Creek Glacier	53°03′45″	120°26′04″	1803	Flat moraine	Aug. 2008
8	Ancient Forest	53°46′21″	121°13′44″	774	Old-growth forest	Oct. 2009

[a] Quesnel River Research Centre.

[b] The Blackbear Mtn. AWS was dismantled in July 2007 and moved to upper Castle Creek Glacier (site 6) in August 2007.

[c] The Mt. Tom AWS was dismantled in September 2009 and relocated to the Ancient Forest (site 8), ≈100 km east of Prince George, British Columbia, during October 2009 (north of the domain shown in Fig. 1).

in neutral conditions (Oke, 1987) such that:

$$U_{10} = \frac{U_a \ln(z_{10}/z_0)}{\ln((z_a - z_s)/z_0)}, \qquad (1)$$

where z_a (m) is the height of the anemometer above bare ground, z_s (m) denotes snow depth, and z_0 (m) is the roughness length for momentum, taken as 1 mm for flat, uniform snow surfaces (although it may vary by ±1 order of magnitude; Oke, 1987, and Clifton et al., 2006). From this relationship, we estimate the 10-m wind speed U_{10} (m s^{-1}) above the snow surface from the anemometer measurements U_a (m s^{-1}) at the sites of interest. Although values of U_{10} are not highly sensitive to the prescribed z_0 (U_{10} varies by about ±3% with z_s = 0 m and z_0 ranging over two orders of magnitude), improved estimates of z_0 and then U_{10} would be obtained with wind speed measurements at two or more heights.

Air temperature and humidity are gauged ≈2 m above bare ground but these measurements are not modified to a reference height in spite of snow depth changes. The relative humidity with respect to ice (RH_i) is computed using standard relations between water and ice saturation when air temperatures are below freezing (Stull, 2000). Previous work has shown that sublimation fluxes are directly proportional to (RH_i − 1) (see Déry and Yau, 1999a) and hence it is important to correctly define the humidity at temperatures below 0 °C.

Quantitative measurement of the mass flux of blowing snow has proved elusive. We are unaware of any sensor or combination of sensors that allows reliable, unattended, quantitative measurements of drifting snow over the range of heights that are relevant to blowing snow. Particle counters such as the SPC S-7 drift sensor (e.g., Clifton et al., 2006) allow localized measurements of grain size and frequency, and multiple units can be combined into a profile, but the high unit cost prohibits this. Aerodynamic samplers such as Mellor's (1960) are too large, expensive, and prone to clogging for use in this application.

NUMERICAL MODEL

As blowing snow is not routinely measured at the CAMnet sites, the PIEKTUK model is adopted to estimate blowing snow fluxes in the Cariboo Mountains. Various incarnations of the model exist (Déry et al., 1998; Déry and Yau, 1999a; Déry and Tremblay, 2004; Yang and Yau, 2008). Here we employ its double-moment version (PIEKTUK-D), which performs with similar accuracy to other numerical models of drifting and blowing snow (Xiao et al., 2000).

Only a brief summary of PIEKTUK-D is given here since details of the numerical model are provided elsewhere (Déry and Yau, 1999a, 2001). The model integrates four prognostic equations over time to resolve the vertical profiles of air temperature, humidity, blowing snow particle numbers, and mixing ratio. The model is run in time-dependent mode to simulate the vertical profiles of the four prognostic quantities using 24 levels with an upper model boundary at 1 km above the surface. The competing processes of turbulent diffusion, settling, and sublimation influence the blowing snow quantities while only turbulent diffusion and sublimation affect the thermodynamic variables. Based on the simulated profiles of blowing snow, the model provides estimates of the column-integrated rates of blowing snow transport Q_t (kg m^{-1}) and sublimation Q_s (mm d^{-1} snow water equivalent or SWE). These two variables form important components of the water budget of high-latitude or high-elevation regions (Déry and Yau, 2002).

NUMERICAL SIMULATIONS

A series of simulations are conducted with PIEKTUK-D to compute the blowing snow transport and sublimation fluxes at three high-elevation sites in the Cariboo Mountains of BC. Initial simulations suggest limited occurrence of snow transport at sites below treeline (<1700 m a.s.l.), which agrees well with anecdotal evidence from field work in the region. The model is applied to the Browntop Mountain (September to December 2006 and 2008), the upper Castle Creek Glacier (September 2007 to June 2009), and the lower Castle Creek Glacier (September 2008 to June 2009) sites. These are the three CAMnet sites with the strongest winds and longest snow season (Tong et al., 2009), suggesting the largest potential for snowdrift. The model is forced at 15-min intervals with the observed atmospheric pressure, air temperature, relative humidity, 10-m wind speed, and snow depth (when and where available). Short (<1 day) gaps in the meteorological time series are infilled through linear interpolation of the observed data at the start and end of the interval. Longer (≥1 day) gaps in the meteorological time series at Browntop Mountain are not infilled, and the corresponding results are therefore not presented in this study (i.e. January to June 2007 and 2009, September 2007 to June 2008). Apart from wind speeds, evolving snow depths influence the effective height above the snowpack at which air temperature and humidity are measured. In the model, the air column is initially taken as isothermal such that no adjustments are necessary in this case. However, the moisture profile is assumed to decrease a)

b)

FIGURE 2. Photographic evidence of blowing snow events at Browntop Mountain. (a) Photo taken on 30 June 2007 facing south from the AWS showing cornices on the leeward side of a ridge extending from Browntop Mountain. (b) Photo taken on 16 September 2008 facing east showing two extensive snowdrifts (≈500 m in length) on the leeward (north) side of Browntop Mountain. The arrow indicates the location of the AWS. Photos taken by S. Déry.

logarithmically from saturation at the surface to the value measured at $z \approx 2$ m, and constant above this level (Garratt, 1994; Déry and Yau, 1999a) such that the initial conditions for humidity consider the effective height of the hygrometer above the snowpack.

Three criteria are usually required to initiate blowing snow transport (Déry and Yau, 1999b): air temperatures must be ≤ 0 °C, wind speeds at the reference height must surpass a given threshold, and snow must be present at the surface. Air temperatures are measured directly. In the absence of more information about the state of the snowpack and the friction velocity acting on the surface, we apply the simple threshold model of Li and Pomeroy (1997), which was developed for similar circumstances. The presence of snow is inferred from the snow depth sensor. The snow depth sensor failed during the fall of 2008 at Browntop Mountain and so we ignore the snow requirement for that case only. We track the times when these criteria are satisfied and report the frequency of blowing snow events and the associated transport and sublimation fluxes at all sites. When the conditions for blowing snow are not met, the transport and sublimation fluxes are taken as zero for that 15-min interval, and the model moves forward to the next set of meteorological observations.

The model is integrated using 5 s time steps, and the blowing snow fluxes are summed over time to provide daily, monthly, and seasonal totals. Comparisons between the different seasons and sites are then provided as well as a discussion of the potential implications of the results on glacier mass balance in the Cariboo Mountains.

TABLE 2

Mean monthly values of the observed air temperature, relative humidity with respect to ice (RH_i), snow depth (z_s), 10-m wind speed and of the simulated blowing snow frequency, transport rate (Q_t), and sublimation rate (Q_s) at Browntop Mountain during the fall of 2006.

	Climate Data				Blowing Snow Fluxes		
Month (2006)	Temperature (°c)	RH_i (%)	z_s (cm)	Wind Speed (m s^{-1})	Frequency (%)	Q_t (Mg m^{-1})	Q_s (mm SWE)
September	6.8	86.9	1.1	7.2	6.6	20.9	2.3
October	−1.4	92.7	1.3	6.0	12.1	90.0	1.1
November	−9.2	97.7	2.4	11.7	54.0	3928.0	5.9
December	−7.7	93.4	0.5	13.8	66.8	5301.0	21.5
Mean	−2.9	94.4	1.3	9.7	34.9		
Total						9339.9	30.7

Results and Discussion

BROWNTOP MOUNTAIN

The automatic weather station (AWS) at Browntop Mountain is situated on an exposed ridge and experiences the windiest conditions of all CAMnet sites (Fig. 2). During the fall seasons of 2006 and 2008, the mean wind speed (adjusted to a reference height of 10 m above the snow surface) reached 9.7 and 9.1 m s^{-1}, respectively (Tables 2 and 3). Blowing snow occurs about one-third of the time during the snow onset season at Browntop Mountain, with monthly values of blowing snow frequency reaching 67% in December of 2006. Blowing snow transport rates varied non-linearly with wind speed and reached a monthly maximum of 5301 Mg m^{-1} during the windy December 2006. Although transport rates diminished considerably in 2008, the modeled 2008 blowing snow sublimation rates surpassed those estimated in 2006 by 8 mm SWE. This is in part owing to the relatively drier conditions experienced during November 2008 when the modeled monthly blowing snow sublimation rates reached 31 mm SWE.

Table 2 reveals that negligible accumulation (mean monthly snow depth $<$2.5 cm) was seen at the Browntop Mountain site during the fall of 2006. This is in sharp contrast to the heavy accumulation of snow at neighboring sites. For instance, the Spanish Mountain AWS, situated below treeline, measured a mean monthly snow depth of 82.3 cm for December 2006 while less than 1 cm was recorded at Browntop Mountain the same month, only 17 km away. This suggests that the abundant snowfall in the region is continuously being eroded from the ridge-top site and deposited on the leeward side of Browntop Mountain. A late spring 2007 visit to Browntop Mountain showed large residual cornices on leeward slopes near the AWS, evidence of significant scouring over the ridge and subsequent deposition (Schweizer et al., 2003). Furthermore, a snow field has persisted through the 2007–2009 ablation seasons on the leeward side of Browntop Mountain (Fig. 2), suggesting increased density or depth of snow in this area. The simulations, AWS data, and observations on-site show that wind transport, along with topographical factors, drastically changes the spatial distribution and duration of the snowpack in the region, particularly above treeline.

Two cases of high winds and blowing snow observed at Browntop Mountain during 2006 are highlighted in Figure 3. The first event occurred over 18–19 November 2006 with peak 15-minute-average wind speeds of over 40 m s^{-1}. The air temperature remained stable at -5 °C and RH_i at saturation during the first day of the event as the atmospheric pressure began to decrease with the approaching storm. Air temperatures then rose to near the freezing point and RH_i dropped to around 85% before the passage of a cold front. Application of the PIEKTUK-D model to this case study shows increasing blowing snow transport fluxes as the wind speeds rose. However, there was a marked reduction in the simulated 15-min blowing snow transport fluxes (to about 10 Mg m^{-1}) on day 1.25 of the event despite the increasing wind speeds (see further discussion below). Blowing snow sublimation fluxes remained negligible and became apparent only when $RH_i <$ 100%.

On 20–21 December 2006, another winter storm affected the area, with peak 15-min winds comparable to the previous event. In this case, however, 15-min blowing snow transport fluxes reached nearly 40 Mg m^{-1}, or about twice the maximum amount simulated for the other case study. In this case, RH_i remained nearly constant at 100% throughout the event, limiting blowing snow sublimation fluxes despite the strong winds.

UPPER CASTLE CREEK GLACIER

Castle Creek Glacier is a 9.4 km^2 mountain glacier, about 5 km long on a SW–NE axis, and 2 km wide. The glacier terminus is at 1810 m a.s.l. and the accumulation area rises to 2827 m a.s.l. (Beedle et al., 2009). The first AWS deployed at Castle Creek

TABLE 3

Mean monthly values of the observed air temperature, relative humidity with respect to ice (RH_i), 10-m wind speed and of the simulated blowing snow frequency, transport rate (Q_t), and sublimation rate (Q_s) at Browntop Mountain during the fall of 2008. Snow depth data are unavailable during this period at Browntop Mountain.

	Climate Data			Blowing Snow Fluxes		
Month (2008)	Temperature (°c)	RH_i (%)	Wind Speed (m s^{-1})	Frequency (%)	Q_t (Mg m^{-1})	Q_s (mm SWE)
September	5.8	94.7	6.4	3.7	59.0	0.5
October	−1.9	90.4	11.3	29.8	553.4	6.3
November	−4.3	90.0	12.2	46.7	1025.2	30.9
December	−13.7	96.1	6.8	38.6	629.6	1.0
Mean	−3.4	92.6	9.1	29.4		
Total					2267.3	38.6

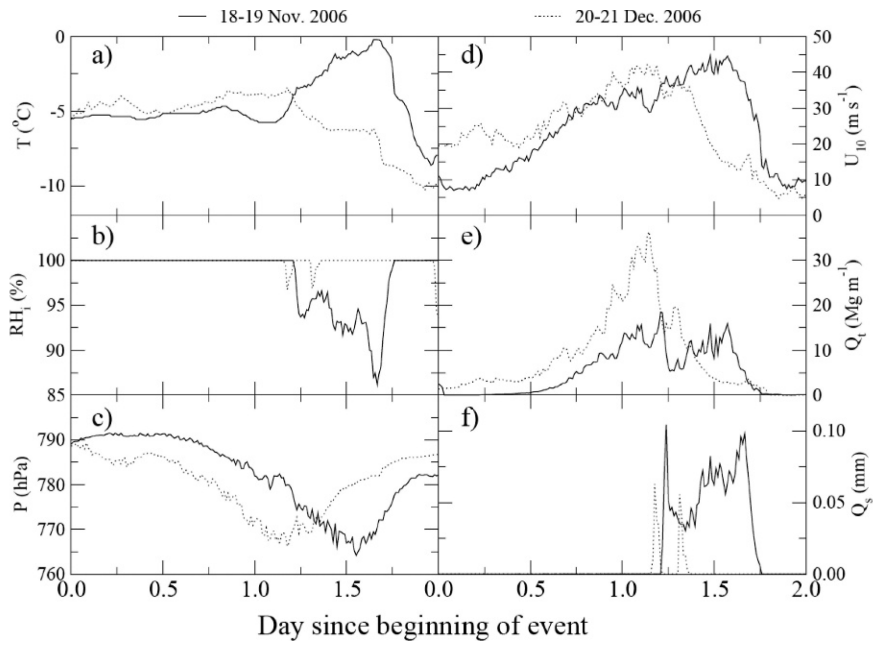

FIGURE 3. Temporal evolution of the observed 15-min (a) air temperature (T), (b) relative humidity with respect to ice (RH_i), (c) atmospheric pressure (P), (d) 10-m wind speed (U_{10}), and the simulated 15-min blowing snow (e) transport (Q_t) and (f) sublimation (Q_s) fluxes at Browntop Mountain during two extreme events in 2006.

Glacier in 2007 is situated at an altitude of 2105 m a.s.l. on a bedrock ridge approximately 1 km east of the glacier. The meteorological station is located on the lee side of this ridge. Wind speeds show little monthly variation and peaked at 5.1 m s^{-1} during the snow accumulation season of 2007–2008 (Table 4). This site is therefore not as exposed to strong winds as the Browntop Mountain site. The snowdrift frequency, however, shows a pronounced seasonal cycle with a maximum blowing snow frequency of 17.4% in January. The greatest monthly estimates of transport at 53.0 Mg m^{-1} are up to two orders of magnitude less than those simulated at Browntop Mountain. Despite drier conditions, the blowing snow sublimation rates remain low owing to the reduced frequency and intensity of wind events at this site. This suggests that snow is redeposited locally, rather than being transported as water vapor and precipitating elsewhere.

Meteorological conditions during the winter of 2008–2009 were quite similar to those of the previous winter. Although the mean November wind speeds were relatively high at 5.6 m s^{-1}, the blowing snow transport rates peaked at 42.6 Mg m^{-1} in January when mean monthly wind speeds reached 5.2 m s^{-1}. The frequency of blowing snow occurrence and total transport from September to June inclusively changed by only 0.8% and −7.8 Mg m^{-1}, respectively, during the most recent snow season. Sublimation fluxes remained low with a total of 6.5 mm SWE despite moderately drier conditions during the winter of 2008–2009.

It is interesting to note that mean monthly snow accumulation peaked at 136.7 cm in April 2008 while it reached a much lower value of 91.1 cm in April 2009 (Tables 4 and 5). This occurred despite an increase (of about 100 mm SWE relative to 2007–2008) in maximum snow accumulation as measured by a nearby snow pillow (McBride Upper, 53°18′N, 120°19′W, elevation = 1608 m a.s.l.) during the winter of 2008–2009. The temporal evolution of observed daily mean snow depth and simulated blowing snow frequency at the upper Castle Creek Glacier site provides insights on the possible causes for these discrepancies between the two snow accumulation seasons (Fig. 4). In 2007–2008, early winter storms led to rapid accumulation of snow (≈45 cm) by early October, prior to any significant episodes of snow transport. Successive storms then augmented snow accumulation, but high winds then led to abrupt decreases in snow depth. This pattern continued throughout the

TABLE 4

Mean monthly values of the observed air temperature, relative humidity with respect to ice (RH_i), snow depth (z_s), 10-m wind speed and of the simulated blowing snow frequency, transport rate (Q_t), and sublimation rate (Q_s) at upper Castle Creek Glacier during the fall, winter, and spring of 2007–2008.

Month (2007–2008)	Climate Data				Blowing Snow Fluxes		
	Temperature (°c)	RH_i (%)	z_s (cm)	Wind Speed (m s^{-1})	Frequency (%)	Q_t (Mg m^{-1})	Q_s (mm SWE)
September	2.0	91.5	4.4	4.3	0.8	0.7	0.0
October	−2.5	88.4	35.1	4.9	4.1	5.9	0.2
November	−7.7	85.1	49.6	5.1	14.5	29.4	0.6
December	−11.3	90.7	65.7	4.6	10.8	23.7	0.6
January	−10.9	89.9	78.5	4.9	17.4	53.0	0.7
February	−8.0	85.9	103.8	5.1	16.5	33.3	1.0
March	−8.6	85.0	128.4	4.9	13.2	25.0	1.1
April	−7.6	85.9	136.7	4.8	8.6	11.5	0.5
May	1.6	87.7	110.3	4.0	0.4	0.3	0.0
June	3.7	90.7	10.2	3.8	0.2	0.2	0.0
Mean	−3.3	87.7	63.2	4.6	7.5		
Total						183.2	4.7

TABLE 5

Mean monthly values of the observed air temperature, relative humidity with respect to ice (RH_i), snow depth (z_s), 10-m wind speed and of the simulated blowing snow frequency, transport rate (Q_t), and sublimation rate (Q_s) at upper Castle Creek Glacier during the fall, winter, and spring of 2008–2009.

Month	Climate Data				Blowing Snow Fluxes		
(2008–2009)	Temperature (°c)	RH_i (%)	z_s (cm)	Wind Speed (m s^{-1})	Frequency (%)	Q_t (Mg m^{-1})	Q_s (mm SWE)
September	4.9	89.2	0.5	3.9	0.0	0.0	0.0
October	−2.2	82.3	6.2	5.1	8.7	17.9	1.2
November	−4.7	86.0	14.0	5.6	14.3	35.9	1.5
December	−14.7	88.9	30.8	4.4	12.6	26.0	0.5
January	−7.7	85.2	36.1	5.2	17.5	42.6	1.4
February	−9.6	81.1	42.2	3.9	8.8	12.9	0.6
March	−10.9	88.2	66.6	5.0	13.5	26.3	0.7
April	−4.8	78.5	91.1	4.4	7.3	11.9	0.5
May	0.2	84.6	97.9	4.2	1.0	1.1	0.0
June	4.3	79.4	14.7	4.2	0.6	0.8	0.0
Mean	−4.5	84.5	40.2	4.5	8.3		
Total						175.4	6.5

winter with a decline in blowing snow frequency in March and April that coincided with the maximum daily accumulation of nearly 150 cm. In contrast, snow accumulation began later during the winter of 2008–2009 as periods of accumulation were frequently accompanied or followed by episodes of strong winds that eroded snow. The 2008–2009 data show more variability in snow depth than the steadier, upward pattern observed in 2007–2008.

To quantify the potential impacts of wind transport on snow accumulation at the upper Castle Creek Glacier site during these two winters, we integrate the changes in snow depth (within resolution of the instrument, i.e. ±1 cm) over time (September to April, inclusively) during blowing snow events as detected by PIEKTUK-D. This provides a measure of the total erosion/deposition of snow at the AWS attributed to wind transport, although other processes such as snow densification and snowfall may contribute further to changes in snow depth during high wind episodes (e.g., DeWalle and Rango, 2008). During 2007–2008 there was a loss of 219 cm of snow depth through wind transport, whereas in 2008–2009 this amounted to the erosion of 340 cm of snow depth. Snow surveys conducted on the center line of the glacier at elevations similar to the AWS, and near the period of peak seasonal accumulation, recorded 349 cm and 368 cm of snow depth in early May 2008 and 2009, respectively. This amounted to 211 cm and 264 cm more snow depth than at the AWS, matching the relative amounts of snow erosion simulated by PIEKTUK-D. The difference in snow depth over a small distance (the AWS is less than 1 km from the glacier measurement point) illustrates how the timing of snowfall and blowing snow events is critical in establishing maximum accumulations observed in windy environments such as upper Castle Creek Glacier. It also suggests that snow accumulation on the exposed sections of the glacier may be highly influenced from one year to the next by the timing and intensity of winter storms. Mass balance measurements typically utilize a limited number of data points distributed along the center line of a glacier. These points likely do not account for snow erosion and deposition, especially for glaciers with large areas exposed to winter storms. Further work is necessary to determine the extent of snow erosion and deposition, and its cumulative impact on glacier mass balance, especially considering that the magnitude of such redistribution may be in excess of 200 cm of snow depth.

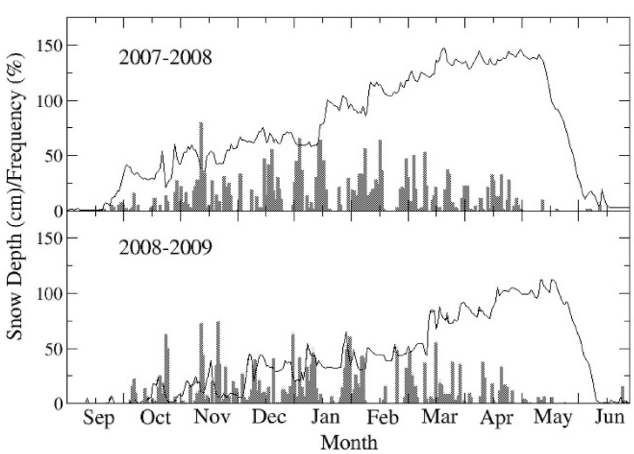

FIGURE 4. Temporal evolution of the observed daily mean snow depth and of the simulated daily frequency of blowing snow occurrence (bars) at the upper Castle Creek Glacier site during the winters of 2007–2008 and 2008–2009.

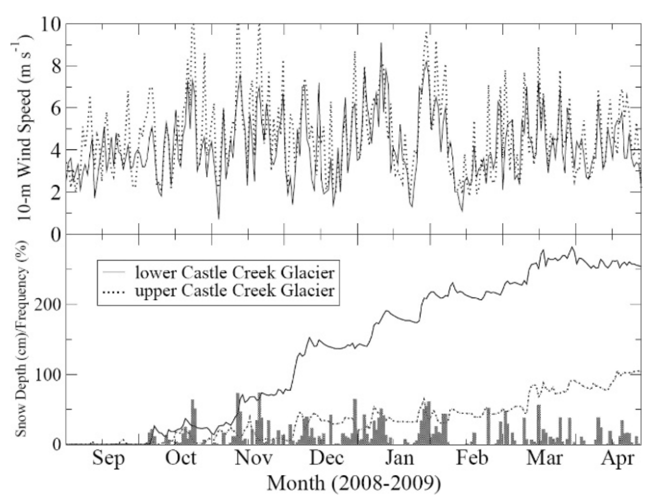

FIGURE 5. Temporal evolution of the observed daily mean 10-m wind speed and snow depth at Castle Creek Glacier, and of the simulated daily frequency of blowing snow occurrence (bars) at the upper Castle Creek Glacier site during the winter of 2008–2009.

TABLE 6

Mean monthly values of the observed air temperature, relative humidity with respect to ice (RH_i), snow depth (z_s), 10-m wind speed and of the simulated blowing snow frequency, transport rate (Q_t), and sublimation rate (Q_s) at lower Castle Creek Glacier during the fall, winter, and spring of 2008–2009.

Month	Climate Data				Blowing Snow Fluxes		
(2008–2009)	Temperature (°c)	RH_i (%)	z_s (cm)	Wind Speed (m s^{-1})	Frequency (%)	Q_t (Mg m^{-1})	Q_s (mm SWE)
September	6.1	88.5	0.0	3.5	0.0	0.0	0.0
October	−0.8	82.2	18.3	4.2	1.4	2.0	0.1
November	−3.2	87.9	54.6	4.6	4.9	9.1	0.1
December	−14.5	91.5	130.5	3.7	7.2	16.7	0.1
January	−7.5	87.8	174.9	5.1	10.7	20.7	7.0
February	−9.2	84.1	214.6	3.7	2.2	2.5	1.2
March	−9.3	85.7	249.2	4.6	4.9	5.6	3.6
April	−3.1	78.0	258.9	4.0	1.1	1.3	1.9
May	1.5	86.5	222.6	3.8	0.0	0.0	0.0
June	5.2	77.8	101.3	3.1	0.0	0.0	0.0
Mean	−3.4	85.7	142.2	4.0	3.3		
Total						57.9	14.1

LOWER CASTLE CREEK GLACIER

The AWS at the lower Castle Creek Glacier site was installed in the glacier forefield about 1 km from the glacier terminus during August 2008, providing meteorological data only for the 2008–2009 winter season. Nonetheless, it yielded an interesting comparison with the conditions observed at the upper elevation site, adjacent to the glacier. The most notable differences were reduced wind speeds (difference of 0.5 m s^{-1}) and much higher snow accumulation than at the upper Castle Creek Glacier site (Table 6 and Fig. 5). The lower wind speeds induced fewer episodes of blowing snow and reduced transportation fluxes. However, sublimation fluxes were about twice those modeled at the upper Castle Creek Glacier site owing in part to the warmer conditions at lower elevations. The reduced blowing snow fluxes led to higher snow accumulation at the lower Castle Creek Glacier site than the upper. The mean monthly snow depth for April reached 259 cm at this site, nearly 170 cm more than observed at the upper Castle Creek Glacier site. The profile of snow accumulation at the lower site showed few abrupt decreases in snow depth that would be indicative of blowing snow events, whereas at the upper site, these occurred much more frequently. Hence, although the two AWSs are just over 2 km apart, the evolution of snow accumulation was considerably different during the winter of 2008–2009 and the simulations suggest that this was largely due to snow transport by wind. These results highlight the need to consider blowing snow when estimating or assessing snow accumulation and glacier mass balance in windy environments.

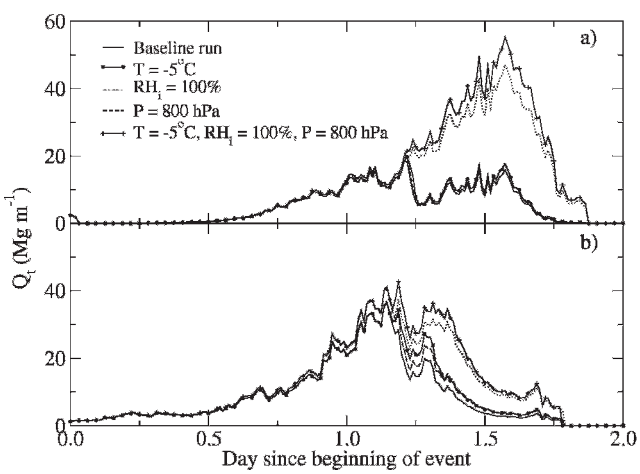

FIGURE 6. Temporal evolution of the simulated 15-min blowing snow transport fluxes (Q_t) for various sensitivity tests at Browntop Mountain during two extreme events that occurred on (a) 18–19 November 2006 and (b) 20–21 December 2006.

Sensitivity Tests

Simulations with the PIEKTUK-D model provide estimates of the blowing snow fluxes at various locations in the Cariboo Mountains. The results for Browntop Mountain during two selected events during 2006, however, illustrate some sensitivities, and perhaps limitations, of the model. Despite the similar wind speeds observed during the two intense storms discussed above, the 2-day blowing snow transport rates during the December event exceeded those simulated in the November storm by more than 50%. To better understand the factors leading to these simulation results, several sensitivity tests using PIEKTUK-D were conducted. For both case studies, four additional simulations with the original meteorological forcing were performed while using (1) a constant air temperature of −5 °C; (2) a constant RH_i = 100%; (3) a constant atmospheric pressure of 800 hPa; and (4) a combination of the previous three factors. These variables were selected for the sensitivity tests owing to their thermodynamic impacts on the blowing snow transport and sublimation fluxes (see Déry et al., 1998).

Figure 6 shows the blowing snow transport rates for each of the sensitivity tests for both events. Transport rates are not highly sensitive to air temperature or atmospheric pressure; however, in both cases, they are more sensitive to atmospheric moisture content. During the 18–19 November 2006 winter storm, the intrusion of drier air ($RH_i \approx 90\%$) near the surface induced a sharp decline in the transport fluxes in the latter half of the event. In air that is less than saturated (with respect to ice), sublimation erodes snow mass from the air column, reducing the blowing snow particle numbers and mixing ratio, and hence the vertically-integrated transport fluxes. However, when air is saturated with respect to ice, blowing snow sublimation is set to zero and blowing snow transport fluxes are maximized. There is a similar but less intense response in the 20–21 December 2006 case study as RH_i did not decline as much as in the other case. These supplemental simulations illustrate the numerical model's sensitivity to the observed moisture profiles, particularly during high wind events.

Conclusion

The Cariboo Mountains of BC, particularly those regions above treeline, have a snow cover that can last for more than half the year and experience periods of extreme winds during winter. These conditions would suggest that blowing snow is a contributing factor in snow accumulation and glacier mass balance in the region. Simulations conducted with the PIEKTUK-D model show a high frequency of blowing snow episodes at three sites in the Cariboo Mountains, particularly on the exposed ridge of Browntop Mountain where this process is modeled as occurring as much as two-thirds of the time during some winter months. Blowing snow fluxes are high at this exposed site with monthly transport and sublimation rates reaching 5301 Mg m^{-1} and 31 mm SWE, respectively. Blowing snow is also shown to be a dominant process in snow accumulation at the upper Castle Creek Glacier site, with winds leading to rapid declines in snow depth and the erosion of more than 200 cm of snow depth during two successive winters. This amounts to more than 50% of the snowpack in this location. The results presented in this study strongly suggest that snowdrift forms an important part of the mass balance of glaciers in the Cariboo Mountains, with strong evidence of mass redistribution from windward to leeward slopes.

The frequency and fluxes of blowing snow reported in this work are similar to those measured in other cold, windy environments. For instance, the frequency of drifting snow at Browntop Mountain from September to December 2006 and 2008 is comparable to that observed at Niwot Ridge, Colorado, where it occurred more than 50% of the time during two successive winters from 1973 to 1975 (Berg, 1986). The complete erosion of snow by wind at the Browntop Mountain ridge matches observations over similar topography in Spitsbergen (Jaedicke and Gauer, 2005) and in the Alps (Föhn, 1980; Gauer, 2001). Sublimation of blowing snow remains lower than in other regions such as Niwot Ridge (Hood et al., 1999) and the Alps (Strasser et al., 2008), perhaps owing in part to the relatively wetter climate of the Cariboo Mountains. Our results agree with those from previous studies that suggest blowing snow forms an important process in the evolution of the snowpack over complex terrain.

Despite the agreement of our findings with those from previous research, the picture obtained from our weather station observations and the PIEKTUK-D blowing snow model may be over-simplified. Snowdrift is a complex process, and the amount of snow that can be transported and sublimated is strongly influenced by the local wind field (not purely wind speed), the properties of the snow cover, and model sensitivities. For this reason, additional investigations of the contribution of blowing snow to glacier mass balance and basin-scale hydrology using a mesoscale atmospheric model have been initiated to simulate the high-resolution wind field over the complex terrain of the Cariboo Mountains. In conjunction with the PIEKTUK-D model and continuing expansion and improvement of CAMnet, these simulations will provide a better understanding of the complex nature of snow transport by wind and its contribution to glacier mass balance and the hydrology of British Columbia's Cariboo Mountains.

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