Estimating surface sublimation losses from snowpacks in a mountain catchment using eddy covariance and turbulent transfer calculations

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Abstract:

Sublimation is a critical component of the snow cover mass balance. Although sublimation can be directly measured using eddy covariance (EC), such measurements are relatively uncommon in complex mountainous environments. The EC measurements of surface snowpack sublimation from three consecutive winter seasons (2004, 2005 and 2006) at a wind-exposed and wind-sheltered site were analysed to characterise sublimation in mountainous terrain. During the 2006 snow season, snow surface and near-surface air temperature, humidity and wind were also measured, permitting the calculation of sublimation rates and a comparison with EC measurements. This comparison showed that measured and simulated sublimation was very similar at the exposed site but less so at the sheltered site. Wind speeds at the exposed site were nearly four times than that at the sheltered site, and the exposed site yielded measured sublimation that was two times the magnitude of that at the sheltered site. The time variation of measured sublimation showed diurnal increases in the early afternoon and increased rates overall as the snow season progressed. Measured mean daily sublimation rates were 0.39 and 0.15 mm day\(^{-1}\) at the exposed and sheltered sites, respectively. At the exposed site, measured sublimation accounted for 16% and 41% of the maximum snow accumulation in 2006 and 2005, respectively. At the sheltered site, measured seasonal sublimation was approximately 4% in 2004 and 2006 and 8% in 2005 of the maximum snow water equivalent. Simulated sublimation was only available for 2006 and suggested smaller but comparable percentages to the sublimation estimated from observations. At the exposed site, a total of 42 mm sublimated for the snow season, which constituted 12% of the maximum accumulation. At the sheltered site, 17 mm (2.2% of maximum accumulation) was sublimated over the snow season. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS eddy covariance; snow; sublimation

Received 30 September 2010; Accepted 12 October 2011

INTRODUCTION

Net radiation, sensible and latent heat fluxes are the primary components of the snow cover energy balance (Price and Dunne, 1976; Marks and Dozier, 1992; Marks et al., 2002; Pomeroy et al., 2006; Nayak et al., 2010). Even in complex mountainous terrain or under vegetation, radiation has been reliably measured and modelled with robust sensors, supported by an extensive body of research presenting both methods and well-validated modelling approaches (Marks and Dozier, 1979; Wiscombe, 1983; Anderson, 1985; Dozier and Frew, 1990; Marks and Dozier, 1992; Dubayah, 1994; Pomeroy and Dion, 1996; Hardy et al., 2004; Link et al., 2004; Pohl et al., 2006; Sicart et al., 2006; Bewley et al., 2007; Essery and Marks, 2007). There are, however, few direct measurements of sublimation in complex terrain using eddy covariance (EC).

The two primary energy contributions to snow ablation are radiant and turbulent energy fluxes. Although radiant transfer is frequently the dominant process, the contribution of turbulent transfer can be episodically important. The contribution from turbulent transfer to the ablation of the snow cover varies between 5% and 40% (Marks et al., 1992; Marks et al., 1998; Marks et al., 2001a; Pomeroy et al., 2002; Pomeroy et al., 2006). Several studies have reported losses from the surface snowpack because of sublimation ranging from approximately 20% at an alpine site in the Sierra Nevada of California to 45% in a subalpine forest in the Rocky Mountains of Colorado (Marks and Dozier, 1992; Molotch et al., 2007).

In dry environments, sensible and latent heat fluxes tend to offset each other, so that the net turbulent flux (\( H + L_{\varepsilon}E \)) is relatively small although the individual terms may be large (Marks and Dozier, 1992; Link and Marks, 1999; Marks et al., 1999; Marks et al., 2001b; Marks et al., 2002; Garen and Marks, 2005). These studies show that while sublimation from the snow surface rarely exceeds 1 mm day\(^{-1}\), this loss of water to the atmosphere can be hydrologically important in dry regions, over thin snow covers or during drought conditions. During specific events, rain-on-snow (ROS) or high wind speeds coupled with a humid atmosphere, \( H \) and \( L_{\varepsilon}E \) may be out of balance...
(both large and positive), with significant effect on the snow cover energy balance. Under sparse shrub canopies, sensible heat to snow can be large and positive and can contribute significantly to the snow energy balance (Lee and Mahrt, 2004). During ROS conditions, latent heat flux can be positive, and sensible heat is large and positive so that net turbulent flux contributions can be as high as 60% to 90% of energy to snow (Marks et al., 1998), increasing the potential for rapid melt and flooding (Marks et al., 1998; Marks et al., 2001b). The sublimation of intercepted snow is a large term in the water balance that can cause reduced snow accumulation beneath conifer canopies (Pomeroy et al., 1998).

Climate warming may increase the uncertainty associated with modelling turbulent fluxes between the snow cover and the atmosphere. For instance, Nayak et al. (2011) showed that with warmer temperatures and higher humidity, a greater frequency of winter rain and ROS events is expected at a study site in the intermountain western USA. To model snow dynamics for such conditions, it is critical that we improve our understanding of turbulent exchange at the snow surface. EC technology can provide reliable validation data for models used to simulate the snow cover energy and mass balance.

In the past decade, the application of EC to measure fluxes of heat, water and carbon has been extended to more complex sites (Baldocchi et al., 2000a; Pomeroy et al., 2003; Turnipseed et al., 2003; Marks et al., 2008; Reba et al., 2009). EC measurements over vegetated surfaces typically show energy balance (EB) closure discrepancies of 10% to 30% (Twine, 2000; Wilson et al., 2002). Energy balance closure discrepancies are often attributed to differences in measurement scale of the energy balance components, systematic bias in instrumentation and loss of low- and/or high-frequency contributions (Wilson et al., 2002). Instrumentation that is more robust has increased the application of EC technology over snow in mountain basins. Because the EC method assumes a constant flux layer such that fluxes measured at some height in the atmosphere reflect surface fluxes, the use of the method still restricts sites to those with adequate uniform fetches to permit the development of a fully developed boundary layer at the measurement height (>1.5 m). Many complex terrain locations do not meet this requirement. Despite the challenges associated with EC in complex terrain, the technology has been used over snow in several studies (Harding and Pomeroy, 1996; Nakai et al., 1999; Arck and Scherer, 2002; Pomeroy et al., 2003; Turnipseed et al., 2003; Lee and Mahrt, 2004; Mahrt and Vickers, 2005; Molotch et al., 2007; Marks et al., 2008; Reba et al., 2009). EC has been used in additional studies over snow below a forested canopy (Harding and Pomeroy, 1996; Launainen et al., 2005), where vegetation and intercepted snow in the canopy clearly influenced snow deposition and ablation patterns and moderated meteorological conditions. Findings from Molotch et al. (2007) suggest the need for additional studies of snow sublimation rates, particularly those that integrate subcanopy processes. Findings below a forested canopy but over a snow-free forest floor found the method capable of accurately quantifying fluxes after thorough validation (Baldocchi et al., 2000b).

In general, most over-snow EC applications have been for short periods and rarely for full snow seasons or multiple years (Cullen et al., 2007; Molotch et al., 2007; Marks et al., 2008). Studies of multiple years over different sites could facilitate our understanding of the interannual and intersite sublimation variability. Furthermore, additional measurements of sublimation rates at sites in different regions of North America can improve our understanding of how site conditions influence measured sublimation rates.

EC-measured sublimation from two contrasting sites typical of long-term snow observation stations for three consecutive snow seasons (2004, 2005 and 2006) were analysed to determine (i) interannual, seasonal and diurnal variability in measured and simulated sublimation rates and (ii) how site characteristics, season and meteorological conditions influenced measured sublimation rates.

METHODS

Site description

Data for this analysis were collected at two long-term snow mass balance measurement sites within the Reynolds Creek Experimental Watershed (RCEW). RCEW is a research watershed located in the Owyhee Mountains, approximately 80 km southwest of Boise, ID, USA (Figure 1). RCEW is typical of mountain ranges in the interior western USA, which are characterised by moderate relief and seasonal snow cover for approximately 4 to 6 months of the year. Elevations range from 1101 m above mean sea level (m.s.l.) at the outlet to 2241 m above m.s.l. Water year (WY) precipitation ranges from 236 mm at the lower elevations in the northern part of the watershed to 1123 mm at the higher elevations in the southwestern portion of the watershed. The study area, Reynolds Mountain East (RME), is a small (0.38 km²) catchment in the southwestern corner of RCEW, ranging in elevation from 2028 to 2137 m above m.s.l. (Slaughter et al., 2001) (Figure 1). The average WY wind-corrected precipitation is 997 mm (Hanson, 2001), approximately 70% of which falls as snow. The long-term average peak snow water equivalent (SWE) is 560 mm at the sheltered site (Marks et al., 2001a). The catchment is characterised by small patches of vegetation with 34% of the catchment area in fir and aspen (Marks and Winstral, 2001).

The two EC measurement sites used for this study are located within RME. The sites are representative of the two major landscape units in the catchment and have been the focus of intensive, long-term climate and snow observations and modelling to characterise the hydrology of RME. The wind-exposed location (Figure 2a) is dominated by mixed sagebrush. The wind-sheltered location is below an aspen canopy in a small grove (Figure 2b). Hereafter, the

WY is defined as starting 1 October and finishing 30 September. The year number corresponds to the calendar year at the end of the WY.
sites will be called exposed and sheltered, respectively. The aspen canopy intercepts minimal amounts of snow, and so all reference to sublimation at this site is for surface snow sublimation. Neither site was ideal for flux measurements because they are located in complex terrain with variable upwind fetch conditions. However, they are typical of the long-term snow and climate monitoring sites (Snopack Telemetry) in the mountainous west of the USA. For that reason, evaluating sublimation at these research locations should lend insight into sublimation rates at similar sites.

**Measurements**

Reba et al. (2009) report on the data quality and postprocessing steps associated with the data collected at the two EC sites described for this study. Only the data deemed of high-quality, based on stationarity and integral turbulence characteristics, were used for the analysis presented here (Reba et al., 2009). Two-dimensional rotation (Kaimal and Finnigan, 1994), wind direction filtering, sonic temperature correction (Schotanus et al., 1983), density correction (Webb et al., 1980) and sensor heating correction (Burba et al., 2008) were applied to the data. Covariances were calculated using a 10-min averaging period that satisfied stationarity requirements. The computed 10-min fluxes were averaged over an hour to reduce flux sampling errors (Vickers and Mahrt, 1997). Available EC data during the study period were not serially complete, and although several methods are available for gap filling of data (Baldocchi, 2003), no gap filling was applied to complete the data set. This was performed to retain the focus of this study on the measurements rather than the quality of gap-filling procedures.

Sensor specifics for both EC systems and associated measurements are given in Table I. The infrared gas analyser (IRGA), the wind speed and the direction and temperature/
relative humidity sensors were located at 5 and 4.5 m above the ground surface at the exposed and sheltered sites, respectively. The height of the EC system (IRGA and wind speed and direction sensors) at each site was dictated by site and operational conditions (shrubs and forest canopy structure) and the need to maintain adequate distance between the surface and the EC system to account for snow depth fluctuation through the snow season.

Only data from snow cover initiation to melt out (mid-November through late April or early May) were analysed. EC-measured sublimation is presented only for days in which a full 24 h of measured data was available and a complete snow cover existed upwind. As transpiration ceases in winter in this environment, the water vapor source for sublimation is presumed to be almost entirely the snow surface. The usable snow season ended on 11 April 2004, 26 April 2005 and 3 May 2006 at the exposed site and 25 April 2004, 1 May 2005 and 9 May 2006 at the sheltered site.

**Simulation approach**

Turbulent transfer terms, $H$ (W m$^{-2}$) and $L_a E$ (W m$^{-2}$), were calculated using a method adapted by Marks and Dozier (1992) from Brutsaert (1982) as a system of nonlinear equations that simultaneously solve for the Obukhov stability length $L$ (m), the friction velocity $u^*$ (m s$^{-1}$), the sensible heat flux $H$ (W m$^{-2}$) and the mass flux by sublimation from or condensation to the snow surface $E$ (kg m$^{-2}$ s$^{-1}$):

$$L = \frac{u^3 \rho}{kg \left[ \frac{H}{v_{a}} + 0.61E \right]} \quad \text{(1)}$$

$$u^* = \frac{uk}{\ln \left[ \frac{z_a - \delta}{\delta} \right] - \frac{\Psi_{sm}}{2}} \quad \text{(2)}$$

$$H = \frac{(T_a - T_s) \alpha_k u^* \rho C_p}{\ln \left[ \frac{z_a - \delta}{\delta} \right] - \frac{\Psi_{sh}}{2}} \quad \text{(3)}$$

$$E = \frac{(q - q_s) \alpha_k u^* \rho}{\ln \left[ \frac{z_a - \delta}{\delta} \right] - \frac{\Psi_{sv}}{2}} \quad \text{(4)}$$

where $\rho$ is the density of the air, $k$ is the von Karman constant (~0.40), $g$ is the acceleration of gravity (9.81 m s$^{-2}$), $C_p$ is the specific heat of dry air at constant pressure (1005 J kg$^{-1}$ K$^{-1}$), $E$ is the mass flux by sublimation from or condensation to the snow surface (kg m$^{-2}$ s$^{-1}$), $u$ is the wind speed (m s$^{-1}$), $d_0$ is the zero-plane displacement height (m, $\sim$2/3 $z_0$), and $\alpha_k$ and $\alpha_e$ are the ratio of eddy diffusivity for heat and water vapor to eddy viscosity, respectively. Brutsaert (1982) suggested that, in the absence of other information, $\alpha_k = \alpha_e = 1.0$. $\Psi_{sm}$, $\Psi_{sh}$ and $\Psi_{sv}$ are stability functions for mass, heat and water vapor based on stability and expanded below (Brutsaert, 1982) (Marks and Dozier, 1992).

**Stable** ($\zeta = z/L > 0$)

$$\Psi_{sm}(\zeta) = \Psi_{sv}(\zeta) = \Psi_{sh}(\zeta) = -\beta_5 \zeta \quad 0 < \zeta \leq 1 \quad \beta_5 = 5.2 \quad \beta_5 = 5.2$$

**Unstable** ($\zeta = z/L < 0$)

$$x = (1 - \beta_u \zeta)^{1/4} \quad \beta_u = 16$$

$$\Psi_{sm} = 2 \ln \left[ \frac{1 + x}{2} \right] + \frac{\ln \left[ \frac{1 + x^2}{2} \right]}{2} - 2 \arctan \frac{x}{2} + \frac{\pi}{2}$$

$$\Psi_{sh}(\zeta) = \Psi_{sv}(\zeta) = 2 \ln \left[ \frac{1 + x^2}{2} \right]$$

The measurement heights for temperature, humidity and wind (m), $z_T$, $z_q$ and $z_u$, were determined from the individual sensor setup at the two sites. Roughness length $z_0$ (m) was set at 0.003 for the sheltered site and 0.0001 for the exposed site and was assumed equal to $z_{0T}$ and $z_{0q}$. Air temperature $T_a$ (K), wind speed $u$ (m s$^{-1}$) and vapor pressure $e_a$ (Pa) were measured, and specific humidity $q$ (g kg$^{-1}$) was calculated from $e_a$ and site atmospheric pressure. Snow surface layer temperature $T_{s,0}$ (K) was estimated from measured long-wave radiation exitance from the surface and the Stefan–Boltzmann relationship. The latent heat flux $L_n E$ (W m$^{-2}$) is $L_n \times E$, where $L_n$ is the latent heat of vapourisation or sublimation (J kg$^{-1}$), which varies with temperature and state of the water (liquid or solid) from 2.501 $\times$ 10$^6$ J kg$^{-1}$ for liquid water at 0°C (vapourisation), or 2.834 to 2.839 $\times$ 10$^6$ J kg$^{-1}$ for ice between 0°C and −30°C (sublimation) (see Appendix C; Byers, 1974).

The turbulent transfer equations described are used in a snow cover energy balance model, Isonobal (Marks and Dozier, 1992; Marks et al., 1999). Using a long-term...
record at RME, the model was shown to be accurate under varied meteorological conditions, with an average model efficiency of 0.90 when comparing simulated and measured SWE at a measurement site (Reba et al., 2011).

RESULTS

Meteorological conditions

Seasonal trends. Snow cover and weather during the 2004, 2005 and 2006 WY spanned a range of conditions. Average WY wind-shielded precipitation was 557 mm at the exposed and 832 mm at the sheltered site, but when blowing snow erosion and redistribution were taken into account, snow accumulation at the exposed site was only 57% of that deposited at the sheltered site (Marks et al., 2002). Generally, the snow cover is established 2 to 3 weeks earlier and remains 4 to 6 weeks later at the sheltered site compared with the exposed site. Snow season precipitation was average (99%) in 2004, below average (90%) in 2005 and above average (128%) in 2006. SWE on 1 April was 98% of average in 2004 and 118% of average in 2006; it was only 64% of average in 2006. SWE on 1 April was 98% of average in 2004 and above average (128%) in 2006 with only 79% of average in 2005.

For the three-snow seasons analysed, average air temperature was −1.9°C and −1.6°C at the exposed and sheltered sites, respectively (Table II). Although the sheltered site was systematically warmer than the exposed site, the difference was only slightly larger than the ±0.25°C accuracy of the data. Mean vapor pressure measurements for the snow seasons analysed were 377 and 391 Pa for the exposed and sheltered sites, respectively, which is within the ±25-Pa accuracy of the measurement. The average snow season wind speeds were two to three times greater, and the maximum daily wind speeds were three to five times greater at the exposed than at the sheltered site (Table II).

However, larger temperature differences between the sites were measured for the diurnal range, midday values and maximum and minimum daily values (Table III). The diurnal temperature range was calculated as the daily difference between the maximum air temperature and the minimum air temperature. Midday temperature was defined as the average air temperature calculated from hourly measurements taken between 1300 and 1500 h. Mean midday temperature for the years analysed was −0.4°C at the exposed site and 1.1°C at the sheltered site. The exposed site mean diurnal air temperature range was 5.4°C, whereas the sheltered site was 7.0°C. Table III shows that the sheltered site daily minimum air temperature was 1.6°C colder and the maximum air temperature was 2.5°C warmer than the exposed site.

The monthly averages of temperature and vapor pressure from December through April for each of the snow seasons analysed are presented in Figure 4. These indicate that overall, the 2004 snow season was cool, 2005 was warm and dry and 2006 was warm and wet compared with typical conditions.

Monthly variation in diurnal patterns. The diurnal patterns in air temperature and vapor pressure at both sites are shown in Figure 4 for the months of the three seasons studied. The 2005 mean monthly temperatures for December, January and February were nearly a degree warmer at both sites than the other study years. However, March and April 2005 were much cooler than 2004, which had the warmest spring of the years analysed. Spring came later in 2006, as March was cold, April was nearly 8°C warmer. For nearly every month during the years analysed, the exposed site had colder mean air temperatures than the sheltered site.

As shown in Figure 4, humidity generally follows the temperature trends at the two sites. Although humidity was systematically higher at the sheltered site, the difference was seldom larger than the ±25-Pa measurement accuracy. Humidity was lower during winter and higher in spring.

Table II. Mean snow season $T_a$ (°C), vapor pressure (Pa), horizontal wind speed (m s$^{-1}$) and mean daily maximum wind gust (m s$^{-1}$) at the exposed and sheltered sites during the 2004, 2005 and 2006 snow seasons.

<table>
<thead>
<tr>
<th></th>
<th>Mean snow season $T_a$ (°C)</th>
<th>Mean vapor pressure (Pa)</th>
<th>Mean wind speed (daily maximum) (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exposed</td>
<td>Sheltered</td>
<td>Exposed</td>
</tr>
<tr>
<td>2004</td>
<td>−1.7</td>
<td>−1.5</td>
<td>393</td>
</tr>
<tr>
<td>2005</td>
<td>−1.5</td>
<td>−0.9</td>
<td>364</td>
</tr>
<tr>
<td>2006</td>
<td>−2.4</td>
<td>−2.3</td>
<td>374</td>
</tr>
</tbody>
</table>
Sublimation

EC-measured sublimation. Reba et al. (2009) showed that it was possible to measure sublimation using EC at these two measurement sites. Only EC-measured sublimation from complete 24-h periods with high-quality observations was considered in this analysis. For the purposes of this article, these will be called complete days.

Table III. Mean diurnal $T_a$ range ($^\circ$C), mean midday (1300–1500 h) $T_a$ ($^\circ$C), maximum daily $T_a$ ($^\circ$C) and minimum daily $T_a$ ($^\circ$C) at the exposed (Ex) and sheltered (Sh) site during the 2004, 2005 and 2006 snow seasons

<table>
<thead>
<tr>
<th></th>
<th>Mean diurnal $T_a$ range</th>
<th>Mean midday $T_a$ (1300–1500 h)</th>
<th>Maximum daily $T_a$</th>
<th>Minimum daily $T_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ex</td>
<td>Sh</td>
<td>Ex</td>
<td>Sh</td>
</tr>
<tr>
<td>2004</td>
<td>4.9</td>
<td>6.8</td>
<td>-0.3</td>
<td>1.2</td>
</tr>
<tr>
<td>2005</td>
<td>5.3</td>
<td>7.0</td>
<td>0.1</td>
<td>1.9</td>
</tr>
<tr>
<td>2006</td>
<td>5.9</td>
<td>7.2</td>
<td>-0.9</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Figure 4. Mean diurnal air temperature and vapor pressure at the exposed and sheltered sites for December, January, February, March and April for (a) air temperature 2004, (b) vapor pressure 2004, (c) air temperature 2005, (d) vapor pressure 2005, (e) air temperature 2006 and (f) vapor pressure 2006.

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DOI: 10.1002/hyp
analysis include times of instrument failure and under-developed turbulence characterised by low wind speeds and nonstationarity.

The measured sublimation on complete days is given in Table IV. In contrast to the year-to-year differences in boundary layer climatology (Table II), sublimation does not vary greatly from year to year (excluding the exposed site during WY 2004). The larger value reported in 2004 at the exposed site was due to the majority of the complete days coming from the late snow season months of March and April, when energy inputs and hence sublimation rates are higher than mid-winter. The exposed site snowpack, excluding WY 2004, sublimated (0.33 mm day\(^{-1}\)) at twice the rate of the sheltered site (0.15 mm day\(^{-1}\)). The maximum measured daily sublimation rates showed similar differences, ranging from 1.00 to 1.25 mm day\(^{-1}\) and from 0.61 to 0.93 mm day\(^{-1}\) at the exposed and sheltered sites, respectively. The minimum daily sublimation rates at both sites were small with the values at the sheltered site being ten times smaller than those at the exposed site.

Simulated sublimation. During WY 2006, data were available to simulate the sublimation for the entire snow season. The full snow season of simulated sublimation values is shown in Figure 5. The mean values of measured and simulated sublimation for complete days are given in Table V. Figure 6 shows measured and simulated sublimation values for complete days. The exposed site values were very similar, with a mean difference of 0.05 mm day\(^{-1}\), a correlation coefficient of 0.85 and an RMS difference of 0.15 mm. At the sheltered site, mean differences were smaller (0.01 mm day\(^{-1}\)), but the variance in the difference was relatively large, with a correlation coefficient of 0.41 and an RMS difference of 0.15 mm. The simulated daily sublimation rate over the snow season and the measured mean daily sublimation rate for complete days were within 0.04 mm day\(^{-1}\) at the both sites, suggesting that the analysis of complete days is comparable with that of seasonal simulated sublimation. The total simulated snow season sublimation at the exposed site was 2.5 times that at the sheltered site.

Meteorological conditions. To further evaluate meteorological conditions that influence sublimation, the relationships between hourly sublimation measured on complete days to vapor pressure difference, wind speed and air temperature were examined (Table VI). Vapor pressure difference was defined as the difference between vapor pressure of air near the snow surface and at approximately 4.5 to 5 m above the ground. Vapor pressure difference and the measured sublimation were weakly correlated with correlation coefficients ranging from 0.68 to 0.76 and from 0.37 to 0.57 at the exposed and sheltered sites, respectively. Correlation coefficients between sublimation and wind speed and air temperature exhibited a larger range than did vapor pressure differences and ranged from weak to moderate. In WY 2006, the correlation coefficient between the air temperature and the measured sublimation was approximately 0.5 at both sites. A negative and weak correlation was found at both sites between relative humidity and measured sublimation during all years studied except for WY 2004 at the exposed site.

Specific weather conditions were analysed to further evaluate the sensitivity of measured sublimation. The periods selected were only from complete days of data at

Table IV. Measured mean, maximum and minimum sublimation rates (mm day\(^{-1}\)) for the exposed and sheltered sites for WY 2004, 2005 and 2006

<table>
<thead>
<tr>
<th></th>
<th>Exposed site</th>
<th>Sheltered site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured mean daily sublimation rate for complete data for 24-h periods (mm day(^{-1}))</td>
<td>0.32</td>
<td>0.34</td>
</tr>
<tr>
<td>Measured maximum daily sublimation rate for complete days (mm day(^{-1}))</td>
<td>1.25</td>
<td>1.00</td>
</tr>
<tr>
<td>Measured minimum daily sublimation rate for complete days (mm day(^{-1}))</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Number complete measurement days</td>
<td>29</td>
<td>23</td>
</tr>
</tbody>
</table>
both exposed and sheltered sites from WY 2006, which was the most complete year.

Figure 7 presents a dry mid-winter event with large sublimation rates at both sites and the largest daily sublimation event at the sheltered site of WY 2006. The conditions at both sites were generally similar, with strong vapor pressure differences between the relatively drier air (measured at approximately 5 and 4.5 m above the ground surface at the exposed and sheltered sites, respectively) and the wetter air just at the snow surface (approximately 0.8 and 1.9 m above the ground surface at the exposed and sheltered sites, respectively, at peak accumulation). At the exposed site during the highest sublimation rates (greater than 0.05 mm h\(^{-1}\)), wind speeds were higher than 8 m s\(^{-1}\) and the vapor pressure difference was more than 250 Pa. These wind speeds are consistent with blowing snow conditions, and so blowing snow sublimation may have contributed to these high values (Pomeroy and Essery, 1999). On 6 January 2006, the third-largest daily sublimation amount for the WY at the exposed site at 1.06 mm was yielded. The maximum hourly sublimation rate during this period at the exposed site was 0.067 mm h\(^{-1}\). At the sheltered site, the maximum daily sublimation rate for WY 2006 was 0.61 mm day\(^{-1}\) and occurred with wind speeds ranging from 1.1 to 1.6 m s\(^{-1}\) and vapor pressure differences ranging between 124 and 242 Pa. Although winds were slight in the early hours of 5 January, the vapor pressure difference did not strengthen until after 6:00 AM at the sheltered site. This resulted in a delay in sublimation losses until after approximately 9:00 AM on 5 January.

Figure 8 illustrates a damp mid-winter, 2-day period with temperatures well below freezing and small vapor pressure differences resulting in little sublimation. At the exposed site, wind speeds were moderate and on 20 February 2006, and ranged between 5.0 and 7.7 m s\(^{-1}\) and peaked at 9.6 m s\(^{-1}\) on 21 February 2006. On 20 February, more sublimation from the exposed site was exhibited (0.18 mm) than that on 21 February (0.03 mm) because of a larger vapor pressure difference coupled with sustained winds on the 20th. At the sheltered site, wind speeds did not exceed 2.5 m s\(^{-1}\) and vapor pressure differences were small, resulting in daily sublimation rates during this 2-day period less than 0.1 mm day\(^{-1}\). The vapor pressure difference reversed at both sites (the vapor pressure difference of the air was larger than the snow surface) in the early hours of 20 February 2006 and in the late hours of 21 February 2006, resulting in condensation to the snowpack.

Figure 9 illustrates dry, warm and windy late-season conditions. The air temperature at both sites was near zero, with a steady warming over the 3-day period. The steady warming of the air temperature coincided with an increase in wind speed and vapor pressure differences. Maximum wind speed at the exposed site during this period occurred midday on 24 March 2006 and was 10.7 m s\(^{-1}\), whereas the sheltered site maximum wind speed was 4.3 m s\(^{-1}\), which occurred late afternoon on 23 March 2006. With such warm conditions, blowing snow is unlikely despite these high wind speeds (Li and Pomeroy, 1997). The winds during this period were more fluctuated compared with the mid-winter events and resulted in more variability in sublimation. The 24th of March yielded the second largest daily sublimation value at the exposed site of WY 2006 and was characterised by high winds and a large vapor pressure difference that ranged from 115 to 230 Pa. The total sublimation from the

<p>| Table V. Measured and simulated sublimation (mm) at the exposed and sheltered sites for WY 2006 |
|---------------------------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Exposed site</th>
<th>Sheltered site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured mean daily sublimation rate for complete days (mm day(^{-1}))</td>
<td>0.32</td>
</tr>
<tr>
<td>Simulated mean daily sublimation rate for complete days (mm day(^{-1}))</td>
<td>0.37</td>
</tr>
<tr>
<td>Number days of complete days</td>
<td>28</td>
</tr>
<tr>
<td>Simulated snow season sublimation (mm)</td>
<td>42.5</td>
</tr>
<tr>
<td>Simulated mean daily sublimation rate for the snow season (mm day(^{-1}))</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Figure 6. Measured and simulated sublimation (mm) from complete days at (a) exposed site and (b) sheltered site for WY 2006.
Table VI. Correlation coefficients calculated for given parameter and measured sublimation for exposed and sheltered sites for WY 2004, 2005 and 2006

<table>
<thead>
<tr>
<th>WY</th>
<th>Vapor pressure difference</th>
<th>Air temperature</th>
<th>Wind speed</th>
<th>Relative humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposed site</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>0.76</td>
<td>0.50</td>
<td>0.20</td>
<td>−0.54</td>
</tr>
<tr>
<td>2005</td>
<td>0.75</td>
<td>0.44</td>
<td>0.38</td>
<td>−0.54</td>
</tr>
<tr>
<td>2004</td>
<td>0.68</td>
<td>0.31</td>
<td>0.64</td>
<td>−0.17</td>
</tr>
<tr>
<td>Sheltered site</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>0.57</td>
<td>0.51</td>
<td>0.30</td>
<td>−0.44</td>
</tr>
<tr>
<td>2005</td>
<td>0.37</td>
<td>0.32</td>
<td>0.37</td>
<td>−0.41</td>
</tr>
<tr>
<td>2004</td>
<td>0.53</td>
<td>0.39</td>
<td>0.39</td>
<td>−0.46</td>
</tr>
</tbody>
</table>

Figure 7. Measured sublimation, wind speed, vapor pressure (blue, snow surface; red, air) and temperature (blue, snow surface; red, air) for the early season period of 5–7 January 2006 at (a) exposed site and (b) sheltered site.

Figure 8. Measured sublimation, wind speed, vapor pressure (blue, snow surface; red, air) and temperature (blue, snow surface; red, air) for the early season period of 20–22 February 2006 at (a) exposed site and (b) sheltered site.
exposed site for this period was 2.1 times larger than the sheltered site. This difference can be attributed to the large differences in wind speed and hence turbulent transfer.

Overall, a strong vapor pressure difference and at least low to moderate wind speeds were necessary for nonnegligible sublimation to occur. Conditions with high winds and low vapor pressure differences (damp periods at the exposed site) did not generate as much sublimation as conditions with large vapor pressure differences and low to moderate winds (dry conditions at sheltered site). Conversely, even with very high winds but little vapor pressure difference, a minor amount of sublimation was produced. Exceptionally high sublimation rates were found with high winds and strong vapor pressure differences and cold conditions for which blowing snow sublimation is likely to have contributed to total sublimation rates in the exposed site.

**Sublimation.** Because of the incomplete seasonal measurements of sublimation, the seasonal sublimation was estimated from the average daily sublimation rate multiplied by the number of days with snow cover. This value was then compared with the maximum SWE at the site for the snow season to evaluate the effect of sublimation on seasonal snow accumulation. Seasonal sublimation as a percentage of the maximum SWE at the sheltered site was approximately 4% in 2004 and 2006 and 8% in 2005. At the exposed site, sublimation accounted for 16% and 41% of the maximum SWE in 2006 and 2005, respectively. The value for 2004 was not used because of the disproportionate number of complete days from the end of the season. Simulated sublimation was only available for 2006 and suggested smaller but comparable percentages with the sublimation estimated from observations. At the exposed site, a total of 42 mm was sublimated for the snow season, which constituted 12% of the maximum SWE. At the sheltered site, 17 mm (2.2% of maximum SWE) was sublimated over the snow season.

**DISCUSSION**

The influence of wind speed differences due to sheltering by forest structure had a strong effect on observations; the exposed site yielded sublimation rates approximately twice those at the sheltered site. There was little interannual variability in sublimation rates at either site. Therefore, during below-average snowfall years, sublimation becomes a larger percentage of the annual snowfall and more important to the water balance. These results validate a simulated outcome shown by Marks and Winstral (2001) and Marks et al. (2001b), in which during a low WY, a larger percentage of the snow cover is lost to sublimation, and hence less total snow is available for melt. These findings are consistent with the relative importance of sublimation losses in dry environments such as the Canadian Prairies (Pomeroy and Gray, 1995).

Measured sublimation is likely enhanced by in-transit sublimation during blowing snow events because of increased snow surface area and greater ventilation (Pomeroy and Essery, 1999; Mahrt and Vickers, 2005). Sublimation associated with blowing snow events has been found to return 10% to 50% of seasonal snowfall back to the atmosphere in North American prairie and arctic environments (Pomeroy and Gray, 1995; Pomeroy and Li, 2000). The amount of sublimation during blowing snow events increases roughly with the fifth power of wind speed and is additionally influenced by air temperature, vapor pressure, snow cover particle cohesion and bonding resistance, fetch and land cover characteristics (Li and Pomeroy, 1997; Pomeroy and Essery, 1999; Pomeroy and Li, 2000; Liston and Sturm, 2002). However, an attempt to isolate blowing snow sublimation from that of the snow

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**Figure 9.** Measured sublimation, wind speed, vapor pressure (blue, snow surface; red, air) and temperature (blue, snow surface; red, air) for the early season period of 22–25 March 2006 at (a) exposed site and (b) sheltered site.
surface illustrated little difference between sublimation that occurred directly after a snow event, when greater entrainment of particles would be expected, and during nonstorm or poststorm periods. Therefore, findings are discussed in the context of surface snow sublimation, but it is quite possible that a portion of measured sublimation occurred from blowing snow particles.

The three snow seasons analysed represent a range of conditions. The snow season of 2004 was cool with average precipitation, 2005 was warm and dry with below-average precipitation and 2006 was warm and wet with the second-highest precipitation in the 47-year history of data collection at the site. However, climate variability at the two study sites only mildly influenced the magnitude of measured sublimation. Overall, the sheltered site had a larger diurnal temperature range, slightly warmer temperatures and higher vapor pressures than the exposed site. However, there was little variability in the daily sublimation rates measured at either site. Given the large variability in the amount of snowfall during the three study years, the importance of sublimation to the seasonal water balance varied widely.

Site condition had a greater influence on the boundary layer meteorology and the measured sublimation rates than did interannual variability. Mean wind speeds at the exposed site were 3.8 times those measured at the sheltered site. Higher maximum air temperatures, lower minimum temperatures, nearly two degrees greater diurnal temperature range and warmer midday temperatures were recorded at the sheltered site compared with the exposed site. The measured sublimation rate at the exposed site was approximately twice that measured at the sheltered site.

Diurnally, sublimation peaked in early afternoon, which coincides with the largest vapor pressure difference and often sustained high wind speeds. Sublimation rates increased as the season progressed, with the largest rates occurring during the spring months. Average sublimation rates during the period between 1 March and 10 April ranged from 0.37 to 0.53 mm day$^{-1}$ and from 0.17 and 0.28 mm day$^{-1}$ at the exposed and sheltered sites, respectively (excluding the exposed site during WY 2004).

The mean sublimation rate (0.15 mm day$^{-1}$) from the sheltered site is low compared with published values of measured sublimation of 0.41 mm day$^{-1}$ at a subcanopy site in the Rocky Mountains of Colorado (Molotch et al., 2007). The exposed site mean sublimation rate (0.39 mm day$^{-1}$) was low compared with sites dominated by blowing snow with reported values of 1.2 to 1.8 mm day$^{-1}$ (Pomeroy and Essery, 1999) and 0.75 mm day$^{-1}$ (Fassnacht, 2004). A mean value of 0.15 mm day$^{-1}$ was calculated from a 4-day period at a Canadian Prairie site with a range of 0.02 to 0.30 mm day$^{-1}$ (Male and Granger, 1979). A wide range of sublimation rates was measured at a Russian boreal forest open site and forested site, and average values were 0.19 and 0.12 mm day$^{-1}$, respectively, during mid-winter and 0.40 and 0.14 mm day$^{-1}$, respectively, in the spring (Gelfan et al., 2004).

The sublimation rates measured for this study were most like those in the Gelfan et al. (2004) and Male and Granger (1979) studies, with a similar difference between open and forested sites to that found by Gelfan et al. (2004).

**CONCLUSIONS**

Measured sublimation using EC for three snow seasons at two contrasting sites yielded results that provide valuable information for the water balance of snow-dominated, semiarid mountain watersheds and can also be used to evaluate the effect of land use on hydrology and for hydrological model testing. Comparing measured sublimation between two sites supports the idea that sites well exposed to wind yield larger sublimation rates and total sublimation over a season than do sheltered sites. The mean sublimation rates were 0.39 and 0.15 mm day$^{-1}$ at the exposed and sheltered sites, respectively, and sublimation rates increased as the season progressed from low energetics in winter to high energetics in spring.

Sublimation from snow accounted for 12% of maximum snow accumulation at the exposed site and 2.2% of maximum snow accumulation at the sheltered site. Because sublimation from snow is difficult to measure and often a neglected component of the water balance, the findings in this study better define the magnitude and variation of this term. The measured sublimation values, trends and comparisons from two contrasting sites can be used as a guide for modelers and researchers.

**ACKNOWLEDGEMENTS**

Funding from the USDA-Agricultural Research Service, the University of Idaho, the DeVlieg Foundation, the IP3 Network and the NSF EPSCoR made this research possible. Field assistance from Zane Cram and Ron Hartzman and data support from Dean Vickers, Russell Scott and Steve Van Vactor are greatly appreciated.

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