Quantifying low rates of summertime sublimation for buried glacier ice in Beacon Valley, Antarctica

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Abstract: A remnant of Taylor Glacier ice rests beneath a 40–80 cm thick layer of sublimation till in central Beacon Valley, Antarctica. A vapour diffusion model was developed to track summertime vapour flow within this till. As input, we used meteorological data from installed HOBO data loggers that captured changes in solar radiance, atmospheric temperature, relative humidity, soil temperature, and soil moisture from 18 November 2004–29 December 2004. Model results show that vapour flows into and out of the sublimation till at rates dependent on the non-linear variation of soil temperature with depth. Although measured meteorological conditions during the study interval favoured a net loss of buried glacier ice (~0.017 mm), we show that ice preservation is extremely sensitive to minor perturbations in temperature and relative humidity. Net loss of buried glacier ice is reduced to zero (during summer months) if air temperature (measured 2 cm above the till surface) decreases by 5.5°C (from -7°C to -12°C); or average relative humidity increases by 22% (from ~36% to 58%); or infiltration of minor snowmelt equals ~0.002 mm day⁻¹. Our model results are consistent with the potential for long-term survival of buried glacier ice in the hyper-arid stable upland zone of the western Dry Valleys.

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Introduction

Interest in buried glacial ice has gained considerable attention in recent years due to its potential as an archive for long-term climate change. Geochemical analyses of ice stored in stagnant debris-covered glaciers in the western Dry Valleys region of Antarctica may ultimately extend records back into the Miocene, well beyond that now possible from analyses of ice at Vostok and Dome C (e.g. Petit et al. 1999, EPICA 2004). At issue, however, is whether these stagnant debris-covered glaciers can maintain a core of glacier ice for millions of years, or whether ice sublimation would remove all traces of original glacier ice over these time scales (e.g. Sugden et al. 1995, Hindmarsh et al. 1998, Schaefer et al. 2000, Ng et al. 2005).

In order to address the question of the longevity of buried glacier ice in the Dry Valleys, we modelled summertime vapour flow through an ancient sublimation till that caps a buried glacier in central Beacon Valley (Fig. 1). The age of this underlying glacier ice is debated (van der Wateren & Hindmarsh 1995), with published ages ranging from ~300 ka (Ng et al. 2005), to > 2.3 Ma (Schaefer et al. 2000, Marchant et al. 2002), to > 8.1 Ma (Sugden et al. 1995). In this paper we outline the range of climate conditions necessary to preserve the buried ice for millions of years. Our approach is to first calculate rates of summertime sublimation and vapour flow under existing climate conditions (atmospheric temperature and relative humidity, solar radiance, soil temperature and moisture) and then calculate sublimation rates for a range of plausible climate scenarios that may have occurred in this sector of Antarctica over the last several million years.

Geologic setting

The buried ice in central Beacon Valley is stagnant (zero horizontal motion, Rignot et al. 2002) and contains 3 wt% debris; it rests beneath a thin sublimation till that is on average 50 cm thick. Debris within the ice is commonly concentrated in bands up to 10 cm-thick and includes clay-to-cobble-sized clasts of Ferrar Dolerite, Beacon Heights Orthoquartzite, and granite erratics foreign to Beacon Valley (Marchant et al. 2002). Sublimation of the ice has thus far produced the thin protective cap of sublimation till that mantles the ice (Fig. 1). Schaefer et al. (2000) showed ice sublimation decreases with increasing till thickness and Marchant et al. (2002) found that the development of high-centred polygons at the till surface also exerts a strong control on ice sublimation. Initially rates of sublimation are highest at immature polygon troughs, but as troughs deepen via sublimation, they become preferred sites for wind-blown snow; this snow cover reduces underlying ice sublimation and in many cases leads to the formation of secondary ice. To a first order, then, ice sublimation is controlled by the rate of ice loss at polygon centres (see also Fig. 2). Hence we have focused our analyses on sublimation processes at polygon centres.
Methods

We deployed a series of HOBO Micro Station data loggers and “Smart Sensors” (manufactured by Onset Computer Corporation) along a vertical profile at the centre of a well-formed polygon in central Beacon Valley. The diameter of the polygon is ~17 m and the nearest trough from the profile is about ~6 m distant. Data for solar radiance, relative humidity, atmospheric and soil temperature, and soil moisture were collected at 15 min increments from 18 November–29 December 2004.

Solar radiance

A Silicon Pyranometer Smart Sensor was installed 30 cm above the ground surface; measurement range is from 0 to 1280 W m\(^{-2}\) with an accuracy of ± 10 W m\(^{-2}\) and a resolution of 1.25 W m\(^{-2}\). Incoming radiation is detected using a silicon photodiode with a spectral range from 300 to 1100 nm.

Relative Humidity (RH)

HOBO (S-THA) RH sensors were deployed at 2 and 10 cm above the till surface. The operational range for these sensors is -40°C to 75°C. At 25°C instrument range is 0 to 100% with an accuracy of ± 4% in condensing environments. Sensitivity decreases when air temperatures are < 0°C (Onset Computer Corporation 2002), the result being that at subfreezing temperatures RH values are underestimated. RH values are calculated from the changes in electrical impedance and capacitance across an electrode.
Temperature sensors

HOBO (S-TMB) 12-bit temperature sensors were placed at 2 cm and 10 cm above the till surface (for a record of atmospheric temperature) and at 0 cm, -5 cm, -10 cm, -20 cm, -30 cm, -40 cm, and -50 cm depth (for a record of soil temperature); the deepest sensor rested directly on the buried-ice surface. To limit complications associated with direct solar heating, the atmospheric-temperature sensors were placed in vented radiation shields provided by Onset Computer Corporation. All temperature sensors have a measurement range of -40ºC to 75ºC ± 0.2ºC with a standard resolution of ± 0.03ºC.

Soil moisture

The potential for minor infiltration of snowmelt at the ground surface was monitored by installing a HOBO soil-moisture sensor at 2 cm below the till surface. Volumetric water content is calculated from the dielectric constant measured by an ECH2O Dielectric Aquameter probe. Sensors have a measurement range of 0 to 0.405 m³/m³ ± 0.031 m³/m³ and a resolution of ± 0.04%.

Existing environmental conditions in central Beacon Valley

Solar radiance

Incoming solar radiance during the study period ranged from 14.4 W m⁻² to 903.1 W m⁻² (Fig. 3). Values < 50 W m⁻² are likely due to the shielding effect of minor snowfall on the sensor head. Cloudless days, during which time the solar radiation was uninterrupted, show smooth sinusoidal radiation curves (Fig. 4), with the amplitude of the curve being a function of the continuously changing solar aspect. The influence of clouds on solar radiation is seen as a departure from the predicted sinusoidal radiation curve; partial cloud cover, occurring almost daily (and recorded in field notes), can cause short peaks of heightened solar radiance due to an increase of diffuse radiation (e.g. re-radiation from clouds back to the ground surface). If we consider a sky with 50% cloud cover, then the solar radiation sensor would receive a considerable fraction of diffuse radiation in addition to times of direct solar radiation; the two combine to produce short-lived, high-amplitude peaks in the record (the times of these high-amplitude peaks correspond well with our records for percent cloud cover) (Fig. 4; e.g. Monteith & Unsworth 1990).

Relative Humidity (RH)

RH at 2 cm above the till surface ranged from 6.75% to 90.75% over the study interval, with an average of 36.0% (Fig. 3). Trends were similar for sensors installed at 10 cm
above the till but showed a slightly lower average value of 35.2%. Although fog and snowfall occurred for a minimum of 10 days within the study period, RH sensors recorded a maximum of 90.75%, and not 100% as expected. The explanation is that at very low atmospheric temperatures (< 0°C), the HOBO sensors underestimate RH values (Onset Computer Corporation 2002). Our RH measurements presented here are minimum values for the 10 days experiencing fog and snowfall. One implication is that our derived sublimation rates are likely conservative, as ice loss via sublimation is inversely related to atmospheric RH.

Temperature

Atmospheric temperatures at 2 cm rarely rose above 0°C, varying from a high of 3.3°C to a low of -16.0°C (Fig. 3). Due to the high solar radiance and relatively low albedo of the till surface (albedo of dolerite rocks is ~0.07; Campbell et al. 1997), the ground-surface temperatures often exceeded atmospheric temperatures (as measured at 2 cm above the ground surface) by 5 to 10°C. Daily variations in atmospheric temperature were propagated through the sublimation till, but were attenuated abruptly at depth (Fig. 5); temperature inversions (warmer temperatures at depth) were common down to 30 cm. The maximum penetration of the 0°C isotherm in the sublimation till reached 14.6 cm (35.4 cm above the buried ice surface); this maximum penetration occurred ~6 hours after the ground surface showed a seasonal maximum of 12.2°C.

Soil moisture

Sensors at 2-cm depth recorded elevated soil moisture on six occasions (Fig. 6); field observations indicate that this meltwater was derived from the melting of recent snowfall. Given that temperatures at the ground-surface exceed 0°C almost daily, and that meltwater occurred only on six days during the study period, the development of moist, near-surface horizons is largely a function of snowfall availability, rather than surface temperature. Hence the potential for meltwater formation occurs almost daily, but given the current aridity of the region it is rare. Our measurements for the gravimetric water content (gwc) of the sublimation till at ≥ 15 cm depth average < 1% gwc, consistent with reported values for soils elsewhere in the western Dry Valleys region (Beyer et al. 1999).

Calculated vapour flux through sublimation till

The vapour flux within sublimation till is governed primarily by two mechanisms: molecular diffusion of water vapour in the pore space and advection of air through the till. Our model does not specifically track vapour pressures beyond saturation (as may occur with the formation of hoar frost), but results can be used to infer times when secondary ice would likely form in pore spaces within the sublimation till. Such secondary ice would decrease till porosity and increase tortuosity, both of which would tend to retard vapour diffusion (Fig. 2). Given the very dry soil conditions of this till (in comparison with seasonally wet and frozen tills with dynamic active layers in Arctic regions, e.g. Beyer et al. 1999, Bockheim & Hall 2002), phase changes associated with the development of minor pore ice would not significantly alter the thermal profile of the sublimation till.

Our parameters for porosity, tortuosity, and the diffusion coefficient are 0.41, 2, and 9.6 x 10^-4 m^2/min respectively, and are all within published values for Dry Valley soils (Hindmarsh et al. 1998, McKay et al. 1998, Pringle et al. 2003). We assume that the temperature of air in pores within the sublimation till is the same as that recorded for surrounding sediment; we also assume that RH is 100% just above the buried-ice surface and that it varies linearly within the till to measured RH values 2 cm above the ground surface. Our model stresses Fickian diffusion, which is the dominant vapour-transport process in sublimation tills (Schorghofer & Aharonson 2005) and ignores the very minor effects of Knudsen diffusion. Given the above, the molecular diffusion of water vapour in pores in sublimation till can in a general fashion be expressed using Fick’s First Law,

\[ q = D \left( \frac{\partial C}{\partial z} \right) \]

(1)

where \( q \) represents flux; \( D \), the diffusivity; \( C \), the concentration; and \( z \), the distance.

The concentration of water vapour is derived from the water vapour pressure \( (e) \), which is both a function of relative humidity and temperature and can be calculated via the Clausius-Clapeyron equation.
Fig. 7. a. Histogram showing the daily maximum in our calculated vapour flux through the sublimation till as a function of depth (measured in 10 cm increments). Bar colour represents the flux at given soil depths. Bars above the baseline represent daily maxima outward to the atmosphere, whereas bars below the base line show daily maxima inward to the buried ice. b. Temperature and RH measured at 2 cm above the ground surface from 18 November–29 December. Horizontal bars depict times when vapour moved from the atmosphere into the till (to a depth of at least 10 cm). c. Calculated model results for vapour flux in the sublimation till for a 13-hour period on 26 December 2004. Results are plotted as coloured contours (see scale bar for details). Blues indicate outward flux to the atmosphere; browns and yellows, inward flux to the ice surface. Ice accretion occurs between 12:30 and 19:00.
where \( e_0 = 0.611 \) kPa; \( T_s = 273 \) K; \( L/\Re \) is equal to the latent heat of deposition divided by the gas constant of water vapour 6139 K; \( T \) and RH are the measured temperature and the relative humidity, respectively. The density of water vapour \( \rho \) is a function of the vapour pressure and temperature and can be calculated using the ideal gas law.

\[
\rho = \frac{e}{\Re \cdot T}.
\]

We assume that \( \Delta C/\Delta z \) in Eq. (1) is equal to \( \Delta C/\Delta z \). We set \( \Delta C \) equal to the thickness of the till; \( \theta \) is porosity and \( b \) is tortuosity. Thus, Eq. (1) can be rewritten as

\[
q = -\left( \frac{\phi D}{b} \right) \frac{\rho_{\text{ice}} - \rho_{\text{atm}}}{z_{\text{till}}}. \tag{4}
\]

Modification of Eq. (4) allows us to treat thermal diffusivity, porosity, and tortuosity as both time and depth dependent variables. In Eq. (5), which is our model for Fickian diffusion in sublimation tills, we integrate Eq. (4) over 10 cm intervals (e.g., sensor spacing) in order to capture variable vapour flux as a function of depth \( z \) and time \( t \), whereby

\[
q_{z,t} = -\left( \frac{\phi_{z,t} D_{z,t}}{b_{z,t}} \right) \frac{\rho_{z-0.05,t} - \rho_{z+0.05,t}}{0.1}. \tag{5}
\]

Initial conditions of vapour density \( \rho \) at depth were derived from Eqs (2) and (3) using measured soil temperatures and calculated and measured relative humidity.

Figure 7 plots the time- and depth-integrated vapour flux in the sublimation till over the study period. The results show that vapour flux is both outward to the atmosphere and inward toward the buried-ice surface. This complex vapour-flow pattern differs from that discussed in Hindmarsh et al. (1998), whose model evaluated unidirectional vapour flow from the buried-ice surface to the atmosphere. It is one explanation for our relatively low rates of net sublimation of the buried glacier ice as compared to those derived by Hindmarsh et al. (1998) (see also below).

The maximum outward flux rate at the buried ice surface is \( 5.9 \times 10^{-7} \) kg m\(^{-2}\) min\(^{-1}\); the maximum inward flux rate at this same depth is \( -1.3 \times 10^{-7} \) kg m\(^{-2}\) min\(^{-1}\) (the negative value designates downward vapour flux). Because the rates for inward and outward fluxes are of the same order of magnitude, this finding highlights the importance of subtle changes in temperature and RH on buried-ice stability.

Figure 8 shows the net loss/gain of ice at the buried-glacier surface over the study interval. From this figure we calculate an average daily (summertime) sublimation rate of \( 3.9 \times 10^{-4} \) mm/day. A maximum rate of ice sublimation occurred on 21 December and was calculated as \( 7.9 \times 10^{-4} \) mm/day. Vapour flux moved downward into the till during about 10% of the study interval; this vapour reached the surface of the buried glacier during about 1% of the study interval. The implication is that the preservation of the buried ice represents a balance between outward ice loss via vapour diffusion to the atmosphere and inward vapour flux from the atmosphere to the buried-ice surface. During the study period, environmental conditions favoured sublimation (over ice accretion at depth) and a net ice loss of buried glacier ice of 0.017 mm.

### Ice sublimation under varying summertime environmental conditions

Given that current meteorological conditions favour a net loss of buried ice during summer months in central Beacon Valley, we now ask under what environmental conditions would summertime ice loss be reduced to zero? To answer this question we varied input parameters for atmospheric/soil temperatures, RH, and downward percolation of liquid water from snowmelt.

#### Temperature

To determine the stability of the buried-ice surface to thermal changes in the sublimation till, we adjusted incrementally the input for soil temperature. Adjustments were made in increments of 1°C and were applied evenly at all depths. The model results show that a net sublimation of zero is achieved given a 5.5°C decrease in average summertime soil temperature at all depths. Given the relatively dry conditions of the sublimation till (e.g. Beyer et al. 1999, Bockheim & Hall 2002), soil temperatures closely track atmospheric temperatures and a 5.5°C decrease in soil temperature is generally equivalent to a 5.5°C decrease in average air temperature. Our required

![Fig. 8. Calculated average daily sublimation rates for the buried glacier ice in central Beacon Valley.](image-url)
temperatures for long-term ice preservation are comparable with those of Schorghofer (2005), who found that a 5°C decrease in mean annual atmospheric temperature permits subsurface ice stability in Beacon Valley. In his model, Schorghofer (2005) calculated vapour flux using two fixed points, the mean annual saturation vapour pressure at the ice surface and the mean annual relative humidity at 3 m above the ground surface.

Relative humidity

The function of atmospheric RH on vapour diffusion and buried-ice stability was determined in a series of model experiments that retained existing soil and atmospheric temperatures but incrementally increased atmospheric vapour density. Results show that an increase in RH of 22% (from a summertime average of 36% to 58%) would result in a zero net loss/gain of buried glacier ice during the study period. By simultaneously adjusting both temperature and RH, we established a range of climate scenarios that would generate stable ice conditions at depth (Fig. 9).

Snowmelt

Field observations show that on six occasions minor snowmelt infiltrated the upper 1–2 cm of till at the study site. To model the influence of increased snowmelt on vapour flux, we raised incrementally our values for vapour density in the upper few cm of the till. The model predicts that evaporation of the liquid water creates a lens of high vapour pressure just below the surface of the till. Model results show that the buried ice surface would show zero net ice loss/gain with meltwater infiltration at a rate of ~0.002 mm day⁻¹.

Implications for long-term survival of buried glacier ice

Assuming our modelled summertime sublimation rate can be extrapolated over an entire year (a scenario which likely overestimates annual ice loss), then our calculated annual ice loss is ~1.4 x 10⁻⁴ m a⁻¹ (over 8.1 Ma, this results in a vertical ice loss of ~1150 m). This rate is an order of magnitude less than that calculated by Hindmarsh et al. (1998). However, given that summertime sublimation exceeds wintertime sublimation (Hindmarsh et al. 1998), a more realistic assessment for annual ice loss might be 1.05 x 10⁻⁴ m a⁻¹ (calculated using a reduced wintertime sublimation rate equal to 50% of the summertime sublimation rate). Applying this lower rate over 8.1 Ma yields a total vertical ice loss of ~850 m.

Potter et al. (2003) showed that the level of remnant Taylor Glacier ice in central Beacon Valley has lowered by ~400 m. Their estimate is based on the elevation difference between the mapped upper limit of sublimation till in central Beacon Valley (granite drift) and the current elevation of remnant ice. Such an ice loss would require an average sublimation rate of 4.9 x 10⁻⁵ over 8.1 Ma. Using our model for vapour diffusion, this sublimation rate could be achieved given the following changes in average climate conditions: a decrease in atmospheric temperature of ~3°C; or an increase in RH of ~15%; or a snowmelt infiltration equal to ~0.001 mm day⁻¹ (Fig. 9). To help assess whether such conditions are feasible, we examined past climate records derived from ice cores in central Antarctica and from nearby Taylor Dome, the latter being only 30 km west of Beacon Valley. The magnitude of temperature variation at both sites is similar. The record at Vostok shows that during the last five glacial-interglacial cycles, near-surface atmospheric temperatures varied by 12°C (Petit et al. 1999, Indermühle et al. 2000) and the average surface temperature was ~3°C below today’s value (Petit et al. 1999). Although the ice core records do not allow for speculation of mid Miocene climate in the Dry Valleys, they do suggest that today’s climate is on average warmer than the last 500 ka.

Lastly we note that a simple increase in summertime cloud cover over Beacon Valley might be sufficient to greatly retard ice sublimation. An increase in cloud cover would result in cooler soil temperatures (Fig. 4) and, if associated with increased precipitation as one might expect, higher RH and increased potential for snowmelt, all of which favours preservation of underlying ice.

Conclusions

Our results suggest that buried ice in central Beacon Valley could survive for millions of years given very minor
changes in local climate conditions.

A stable, buried ice surface (no net gain or loss of ice during summer months), is achieved with any one of the following summertime changes: atmospheric temperature drops ~5.5°C (from -7°C to -12°C); RH rises 22% (from 36% to 58%); snowmelt equals ~0.002 mm day⁻¹.

Assuming that there is no significant departure in seasonality and that rates for summertime sublimation can be applied year-round (an overestimate for annual ice sublimation), a 400 m ice loss over the past 8.1 Ma (e.g. Potter et al. 2003) could be achieved with any one of the following changes: atmospheric temperature drops ~3°C; RH rises 15%; snowmelt equals ~0.001 mm day⁻¹. Such changes are reasonable, given that Antarctic ice-core records show that air temperatures over the last 5 glacial-interglacial cycles were on average ~3°C colder than today (Petit et al. 1999). An increase in cloud cover alone might yield the requisite conditions for long-term ice preservation; this would likely lead to an overall decrease in air temperature, an increase in RH, and if accompanied by precipitation as would be expected, a potential increase in the magnitude of snowmelt.

The results presented here are conservative in that our model does not consider the reduction in vapour diffusion (ice loss) that would accompany

1) the progressive increase in tortuosity that might arise from the development of salt and/or ice crystals in pore spaces (Bao et al. 2002),

2) the burial of ice and sublimation till beneath long-lived perennial snow banks and/or ice (Marchant et al. 2002), and

3) the influence of surface roughness on atmosphere-till-boundary layer conditions that could result in elevated RH across the till surface (e.g. Fig. 2).

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