troughs that are depressed ~1.0 m relative to elevated polygon centers (Fig. 6). The implication is that enhanced vapor diffusion through "porous" sand wedges may contribute to the development of high-centered polygons as noted in Marchant et al. (2002).

5.3. Modeling exercise 2: determining the role of facies thickness on ice sublimation

5.3.1. Strategy

In this series of tests, we determine the critical thickness, T_c, that effectively reduces annual ice loss via sublimation to near-zero levels (asymptotically approaching zero). To determine T_c, we modeled net ice loss beneath increasingly thick Mullins till. The uppermost 15 cm of Mullins till was composed of the weathered facies, with the fresh facies (only) occurring at greater depths. Meteorological input come from data collected halfway down Mullins Valley (site 4).

5.3.2. Results

Results show that as the till thickens from 10 to 50 cm there is a rapid decline in annual net ice loss. Ice loss approaches zero with a T_c of 145 cm (Fig. 8).

5.4. Modeling exercise 3: resolving spatial variations in ice sublimation along Mullins Glacier

5.4.1. Strategy

To determine the magnitude of spatial variation in ice sublimation along the debris-covered portions of Mullins Glacier, we calculated sublimation losses during a three-week summertime period at five localities along Mullins Glacier (3–24 December 2004; Tables 1a, 1b, and 1c); where longer term meteorological data were available, we also calculated net ice losses over a calendar year (2006) (Tables 1b and 1c). The sites examined cover an elevation range of ~350 m, and multiple facies of Mullins till are present at most locales. All sites are located along the glacier centerline. Modeled ice losses are reported in Table 3, with site-specific details provided below.

5.4.2. Results

Site 1 is located ~2500 m from the headwall of Mullins Valley (1550 m elevation). Mullins till is 10 cm thick and composed entirely of the weathered facies. The mean calculated vapor flux is 2.5×10^{-8} kg m^{-2} s^{-1} in the outward (upward to the atmosphere) direction. This yields a net ice loss of 4.5×10^{-2} mm during the 21-day summer interval (Table 3). In our calculations, a positive flux denotes outward flow toward the atmosphere, whereas a negative flux represents downward vapor movement toward the buried ice surface.

Site 2 site is located ~3000 m from the valley headwall (1524 m elevation). Mullins till is 18 cm thick and composed of the weathered facies to a 10-cm depth and the relict sand wedges facies thereafter. The calculated mean vapor flux is 9.9×10^{-9} kg m^{-2} s^{-1}, yielding a net ice loss of ~1.8×10^{-2} mm during the three-week summer interval (Table 3). Vapor consistently flowed outward toward the atmosphere. Long-term ice loss, as calculated during the 2006 calendar year, was 0.1220 mm (Table 3).

Site 3 is situated ~3800 m from the valley headwall (1442 m elevation). Mullins till is 22 cm thick and consists of the weathered facies to ~15 cm and the relict sand-wedge facies thereafter. The calculated mean vapor flux is 1.8×10^{-8} kg m^{-2} s^{-1} (Table 3). This yields a net ice loss of ~3.2×10^{-2} mm during the three-week summer interval; vapor consistently flowed outward toward the atmosphere.

Site 4 is located 4500 m from the valley headwall (1374 m elevation). The 25-cm thick section is composed of the weathered facies to a 14-cm depth and the fresh facies thereafter. The mean vapor flux is 1.2×10^{-8} kg m^{-2} s^{-1}, yielding a net ice loss of 2.1×10^{-2} mm for the three-week summer interval (0.1579 mm for the measured 2006 calendar year) (Table 3). Vapor exhibited bidirectional flow (moving inward and outward) during the 21-day study interval.

Site 5 is located 7800 m from the valley headwall in central Beacon Valley (1272 m elevation). The 50-cm thick till section consists of the weathered facies to a depth of 15 cm and the fresh facies thereafter. The mean vapor flux is 3.7×10^{-9} kg m^{-2} s^{-1}, yielding a net ice loss of 6.7×10^{-3} mm during the three-week summer interval (0.0656 mm for the measured 2006 calendar year) (Table 3). The vapor flowed both into and out of the till during the 21-day study interval.

Three conclusions arise from these model results. First, sublimation rates decrease with increasing distance downglacier. The decrease in net sublimation is due to progressive thickening of Mullins till, which more than offsets predicted gains in ice sublimation that are expected to occur from the greater concentration of porous sand-wedge deposits in the down-ice direction (see also Section 4.4; Fig. 9). Second, for exposures of Mullins till >~25 cm in thickness, complex thermal variations result in both outward and inward vapor fluxes; a similar conclusion for bidirectional vapor flow was reached by Kowalewski et al. (2006), who showed that downward vapor fluxes through granite drift in central Beacon Valley could produce thin layers of accretion ice at the buried surface of relict ice from Taylor Glacier. Third, although sublimation losses are greatest during summer months, the relative importance of December, January, and February (DJF) losses on net-annual ablation varies with till thickness. Apparently, DJF ice losses are greatest in regions with thin till (<~25 cm thick), where the impact of summertime warming at the buried ice surface is felt most quickly. At till thicknesses >~40 cm, delayed warming at the buried ice surface extends the season of maximum ice loss beyond DJF.

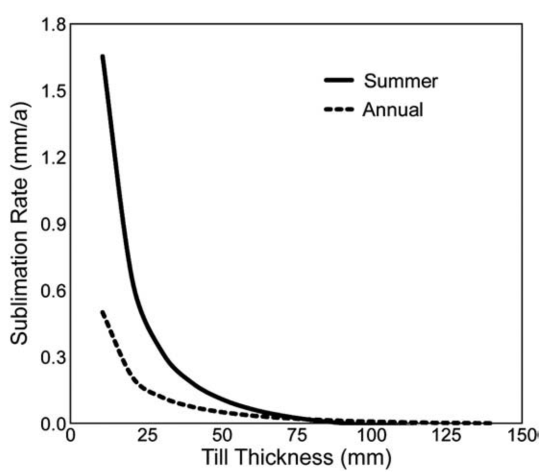

Fig. 8. Model results showing the variation in rates of buried ice sublimation as a function of increasing till thickness. Rates of annual sublimation asymptote to zero with increasing till thickness; the plot also emphasizes that, for sections of Mullins till <25 cm thick, sublimation rates are considerably higher during summer months (December, January February: DJF) than at other times of the year. As the till thickens, however, the relative importance of sublimation in DJF tends to diminish; the most likely explanation is that sublimation losses continue into the austral fall (e.g., March, April, and May) as a consequence of the longer duration penetration of the summertime thermal wave passing through thick exposures of Mullins till.

6. Discussion

6.1. Implications for long-term preservation of glacier ice

The potential for ancient buried glacier ice in the Dry Valleys has been debated for years (e.g., see Sugden et al., 1995; Hindmarsh et al., 1998; McKay et al., 1998; Schaefer et al., 2000; Stone et al., 2000; Marchant et al., 2002; Sletten et al., 2003; Ng et al., 2005; Hagedorn et al., 2007, 2010; McKay, 2009; Schorghofer, 2009; Morgan et al., 2010). Recent findings from the planetary-science community, which suggest that far older ice survives beneath thin debris on Mars, have