Annals of Glaciology

Letter

Cite this article: Warren SG (2023). Snow spikes (penitentes) in the dry Andes, but not on Europa: a defense of Lliboutry's classic paper. *Annals of Glaciology* 1–5. https://doi.org/10.1017/aog.2023.12

Received: 12 October 2022
Revised: 8 December 2022
Accepted: 14 February 2023

Key words:
Albedo; Europa; ice; penitentes; snow; sublimation; surface roughness

Author for correspondence:
Stephen G. Warren, E-mail: sgw@uw.edu

cambridge.org/aog

Snow spikes (penitentes) in the dry Andes, but not on Europa: a defense of Lliboutry's classic paper

Stephen G. Warren

Department of Atmospheric Sciences, University of Washington, Box 351640, Seattle WA 98195, USA

Abstract

Tall, spiky snow structures (*penitentes*) occur high in subtropical mountains, in the form of blades oriented east-west and tilted toward the noontime sun. By trapping sunlight, they cause a reduction of albedo by ~0.3 relative to flat snow. The formation of penitentes, explained by Lliboutry in 1954, requires weather conditions allowing the troughs to deepen rapidly by melting while the peaks remain dry and cold by sublimation, losing little mass, because of the 8.5-fold difference in latent heats. Lliboutry's explanation has been misrepresented in some recent publications. A concern has been raised that in the low latitudes of Jupiter's moon Europa, the ice surface may have developed penitentes, which would pose a hazard to a lander. They would require a different mechanism of formation, because Europa is too cold for melting to occur. If penitentes are present on Europa, they cannot be resolved by the coarse-resolution satellite images available now, but the high albedo of Europa (~0.7 at visible wavelengths) argues against the existence of such extreme roughness.

Formation of penitentes on earth

On Earth, penitentes reach their greatest heights of several meters in a restricted altitude zone on high subtropical mountains, in regions where summer is the dry season; they have been most intensively studied in the Andes of Chile and Argentina. Penitentes are exotic and beautiful (Fig. 1), but they can cause difficulty, for example by slowing the progress of mountaineers climbing Aconcagua. And Wentworth (1940) complained that snow spikes on Mauna Kea (Hawaii) made tobogganing impossible. More recently Hobley and others (2018) have identified what is perhaps a more severe hazard, namely a risk to the Europa Lander, which I will critique below.

Most of the tall penitentes found in the Andes (Fig. 1) consist of old snow, but they can also form in glacier ice. The explanation for their formation was given by Louis Lliboutry (1954) in his classic paper 'The origin of penitents', and reviewed in his book (Lliboutry, 1964). [Lliboutry argued for use of the term *penitent* in English-language literature, but the original Spanish spelling *penitente* (4 syllables) is now almost universally used.] Penitentes result from a selection process in which surfaces facing the Sun absorb more radiation and ablate more quickly, so the surviving surfaces are nearly-vertical wedges oriented east-west, parallel to the solar beam. This selection process is most active during the midday hours of maximum irradiance, so in the Southern Hemisphere the wedges become tilted toward the north, at approximately the noontime solar zenith angle, which varies seasonally. They were given the name 'penitentes' because a field of these inclined spikes had the appearance of white-robed monks on a religious pilgrimage. Their mechanism of formation was concisely stated in Lliboutry's abstract: 'The sublimation of the snow or ice allows the crests to maintain their temperature below 0°C, while in the spaces or passages between the penitents, where radiation is concentrated and removal of water vapour not so easy, melting takes place.' The latent heat of melting is 335 J g^{-1}, whereas the latent heat of sublimation is 2838 J g^{-1}, a factor of 8.5 larger. The extreme topography of penitentes results from this 8.5-fold difference: the peaks remain dry and cold by sublimation, losing little mass, but in the troughs the air becomes stagnant and humid, so that sublimation cannot occur; the absorbed solar energy is instead consumed by melting, resulting in rapid loss of mass. In an example documented by Lliboutry (1964, p. 375), on an afternoon at the end of November at 3500 m elevation, with air temperature above freezing but dew point below freezing, the sublimating spikes of 50-cm height were hard and dry with a temperature of −5°C, whereas in the troughs between them the snow was wet, containing 14% liquid water.

The lower limit to the altitude of penitente-formation was plotted as a function of latitude for North and South America by Troll (1942, Figure 14), from the Cascades at 50°N to the southern Andes at 40°S; this altitude-limit varied from 3000 m at 50°N to 5300 m at the Equator. Lliboutry (1954) identified three zones of altitude in the Andes above Santiago, Chile, at latitude 33°S:

(1) In the lowest zone, below 4000 m, the snow surface developed the familiar scalloped surface called 'suncups', 'ablation hollows' or 'honeycombed snow', seen in summer on mountain glaciers and snow-fields worldwide (Post and LaChapelle, 1971; Figure 2).

Fig. 1. A field of snow-penitentes in the Elqui Valley above La Serena, Chile, 21 December 2007.

Fig. 2. Suncups on Taku Glacier, southeast Alaska. [Figure 82 of Post and LaChapelle (1971).].

Suncups are melting at all parts of the surface (both hollows and ridges), but some topography does develop from initial small irregularities, by two mechanisms: (a) Different orientations of surfaces relative to the Sun are illuminated differently; also the hollow is illuminated not only directly but additionally by radiation reflected from the neighboring walls. (b) Evaporation of meltwater occurs more readily at the ridges, which are exposed to wind and can therefore dispose of much of their absorbed solar energy without further melting, in contrast to the hollows where the air is more stagnant and therefore more humid. The effect of debris on the snow can either enhance or suppress suncup formation, depending on the degree of illumination (Rhodes and others, 1987).

(2) In the highest zone of the Santiago Andes, above 5200 m, the snow was colder than 0°C everywhere, so melting could not occur; the dry snow surface remained nearly flat.

https://doi.org/10.1017/aog.2023.12 Published online by Cambridge University Press

(3) The intermediate zone, 4000–5200 m, where penitentes developed, was characterized by sublimation at the peaks and melting in the troughs. In the troughs the air became stagnant and humid, so that sublimation was impossible, so the snow heated up to the melting point and then consumed the absorbed solar energy by melting. Penitentes are spikier than suncups because on penitentes there is no melting at the peaks. In this intermediate zone the snow was nearly flat in winter because only sublimation could occur then; the penitentes began to develop in late spring when the weather became warm enough that melting could begin in the troughs.

Quoting Lliboutry (1954): '[We] have alternately troughs where the snow melts and penitents where it sublimes. In both cases the speed of the process depends on the thermal balance, so that melting goes further than sublimation… . Although sublimation is indispensible for penitent formation, in a field of penitents most of the ablation proceeds from melting'.

The mechanism identified by Lliboutry has been confirmed in subsequent studies, by Untersteiner (1957) in the Pakistani Karakoram at 36°N, by Kotlyakov and Lebedeva (1974) in the East Pamirs of Tajikistan at 38°N, and by Naruse and Leiva (1997) in the Argentinian Andes at 32°S. Quoting Untersteiner, 'Evaporation/sublimation plays a definite role in the *energy budget* [of penitents] … but a significant contribution to *ablation* is ruled out… . Growth of penitents by sublimation-ablation appears not to be possible, … so it must come about by means of melting.' Quoting Kotlyakov and Lebedeva, 'The facets were dry, but in the hollows the firn was soft and humid… . The melting on the surface perpendicular to midday solar rays can reach 20–30 mm day^{-1} in water equivalent… . The surface was smooth on the upper part of the glacier.' Quoting Naruse and Leiva, 'All the field data … support Lliboutry's hypothesis … enhanced melting at the bottoms due to absorbed shortwave radiation and ceased melting at the top due to cooling by sublimation … .'

On Earth, penitentes have not been observed to form under conditions of sublimation-only. Apparently, melting in the troughs is occurring wherever penitentes are forming on Earth. This claim by Lliboutry was substantiated by MacDonell and others (2013), who found no penitentes on a high-altitude Andean glacier where only sublimation was occurring.

Lliboutry did observe 'micropenitents' with heights of a few centimeters, in the spring before melting began, resulting from trapping of incident sunlight in incipient troughs. The lack of melting meant that only the trapping mechanism was active, limiting the microtopography to these tiny structures, two orders of magnitude smaller than typical penitentes (Figure 6 of Lliboutry, 1954). This process was also investigated in a laboratory experiment: with vertical illumination of a snow block, Bergeron and others (2006) were able to create conical micropenitents by sublimation alone, to a height of 1.3 cm and with a constant aspect ratio (height/spacing) of 2. With further illumination, melting began in the troughs, and both height and aspect ratio increased; the experiment was terminated when the height reached 3 cm.

It is not clear what limits the height of sublimation-only penitentes in nature to a few centimeters; it may be that the combination of adequate sunlight and subzero temperature just does not persist long enough on Earth's subtropics. Where lack of melting does persist for years, even millenia, is in the interior of Antarctica, but micropenitents are not observed there, probably because of the continuous light snowfall ('diamond dust'), as well as the low and nearly circular path of the Sun in the sky. Instead, a different kind of snow-surface roughness predominates, namely sastrugi, which are longitudinal erosion features aligned with the prevailing strong winds (Gow, 1965; Doumani, 1967; Armstrong and others, 1973; Filhol and Sturm, 2015), with typical height 0.2 m, width 1 m and length 5 m (Table 2 of Warren and others, 1998).

Are penitentes possible on Europa?

Europa is one of the four large moons of Jupiter. It is about the same size as Earth's moon. Europa possesses a deep ocean of liquid water beneath a several-kilometer-thick surface layer of ice. Europa is cold; the noontime equatorial surface temperature is 134 K.

Development of a lander mission to Europa is underway as a massive undertaking by NASA (Hand and 286 others, 2022). So it was alarming for the mission planners to read a prediction by Hobley and others (2018) that the low-latitude surface of Europa would exhibit 'metre-scale bladed roughness' in the form of penitentes.

Hobley's group made some peculiar statements about penitentes on Earth. They cited Lliboutry's classic paper to claim that 'On Earth, … formation of large and well-developed penitentes requires … a melt-free environment… . Sublimation in the absence of melting is particularly essential for penitente formation.' Hobley and his coauthors thus attributed to Lliboutry a statement which is the exact opposite of what he wrote. The Hobley paper included a picture of penitentes near the ALMA telescope site, at 5100 m elevation on the Chajnantor Plain of Chile, but neglected to mention that melting occurs at that location in summer, when the penitentes form. (I visited that location in winter, when melting was absent, and found no penitentes, nor even micropenitents.)

The Hobley paper was widely publicized, for example in *EOS* (Kornei, 2018) and in *Nature* (Anonymous, 2018); both articles included a photograph of penitentes in the Chilean Andes, as had the Hobley paper, with no mention of the importance of melt in forming penitentes on Earth. Indeed, they perpetuated Hobley's misrepresentation of Lliboutry's elegant explanation. For many readers of *Nature* and *EOS*, those news items will have been their first introduction to penitentes. It is therefore most unfortunate that the publicity about the Hobley paper reinforced its misconception that melting not only does not contribute to the formation of penitentes, but that melting would actually prevent their formation!

With a maximum daytime surface temperature of 134 K on the equator of Europa, and a near-vacuum atmosphere, melting cannot occur, thus ruling out the terrestrial mechanism for formation of penitentes on that planetary body. But we must still consider the possibility of a different mechanism on Europa using sublimation only, because of the long time available. Penitentes on Earth have only about 4 months to grow before they melt away in late summer. But Hobley and coauthors estimated that the time available for penitente formation on Europa would be eight orders of magnitude longer, because the average age of the Europan ice surface before resurfacing is ∼50 million years.

Inspired by the laboratory experiments of Bergeron and others (2006), in which micropenitents were grown, Hobley and his coworkers estimated the height that penitentes could attain on Europa. They did not model the evolution of surface roughness. Instead they just assumed an aspect ratio (height-to-spacing ratio) of 2, and equated the energy of sublimation to the radiation energy budget, concluding that, at equator, 15 m of ice could sublimate in 50 million years. If most of this sublimation occurred from troughs (and if erosion of the spikes by sputtering and impact-gardening were slow), the penitentes could be 15 m tall. By contrast, modeling by Hand and others (2020), in a comment on the Hobley paper, has indicated that penitentes cannot grow on Europa, because of the absence of an atmosphere to impede

https://doi.org/10.1017/aog.2023.12 Published online by Cambridge University Press

the diffusion of water vapor. And a subsequent laboratory experiment by Hand's group (Berisford and others, 2021) showed that, in their words, 'Pre-formed penitentes undergo sublimation erosion, evolving toward a flat morphology, during simulated solar irradiance.'

As evidence for penitentes on Europa, the Hobley group cited radar measurements of Europa at wavelength 12.6 cm, in particular the latitudinal variation of reflectivity and an anomalous polarization ratio, which might be explained by penitentes. But those observations could alternatively be explained by subsurface irregularities (Ostro and others, 1992), since the absorption-length in ice for 12.6-cm radar is 100 m.

A more-definitive test of the Hobley hypothesis can be made using visible wavelengths, by considering how penitentes would alter the reflection of sunlight. Penitentes trap solar radiation, resulting in reduced albedo of a field of penitentes relative to a flat horizontal surface, in the same way that crevasses reduce the albedo of glaciers (Pfeffer and Bretherton, 1987). Solar photons reflected by a horizontal surface will escape to space, but many of the photons reflected by a spike-wall will be intercepted by the neighboring wall, getting another chance for absorption.

The triangular-shaped penitentes of Glaciar Tapado in Chile, with heights 2 m and spacing 1.4 m, caused a reduction of broadband albedo from its flat-surface value of 0.64, down to 0.32, as estimated by Lhermitte and others (2014, Figure 2D and Table 4D). A similar albedo-reduction, from 0.60 to 0.33, was obtained for idealized penitentes in a radiative-transfer model by Cathles and others (2014). If the flat-surface albedo of Europan ice at a particular wavelength is ~0.7, for example, penitentes would thus be expected to reduce the area-averaged albedo to ~0.4. But the area-averaged albedo of the leading hemisphere of Europa is actually quite high, averaging 0.72 at mid-visible wavelengths 550–750 nm (Figure 13c of Carlson and others, 2009), suggesting that penitentes, if present, are not prominent. The angular dependence of visible reflectance also argues against meter-scale surface roughness (Belgasem and others, 2020).

In conclusion, the low latitudes of Europa are likely to have smooth surfaces, suitable for a lander.

Penitentes on Pluto?

The surface of Pluto consists mainly of nitrogen ice and methane ice, at temperatures ~40 K. In 2015 the New Horizons spacecraft obtained images of Pluto at a resolution (pixel size) of 320 m, which showed some large areas of long parallel ridges, consisting mostly of methane ice, on high plateaus at low latitude. These areas have been called 'bladed terrain' (Moore and others, 2018), 'penitentes' (Moores and others, 2017) or 'megadunes' (Traversa and others, 2023). With their heights of 300 m and spacing 3–7 km, they might better be called 'rolling hills' or 'undulating terrain'. Their aspect ratio of 0.1 is 1–2 orders of magnitude smaller than that of Andean penitentes, and two orders of magnitude larger than that of Antarctic megadunes, which are only 2–4 m tall but spaced 2–5 km apart (Frezzotti and others, 2002).

Snow megadunes are found on large areas of the East Antarctic Plateau, as long low ridges of length 10–100 km, aligned perpendicular to the katabatic wind direction. They can be seen in satellite images, but because of their low profile they are difficult to discern from the surface. Field expeditions inspired by the satellite images have found that they are formed by sublimation from the leeward side of a dune and deposition on the windward side of the next dune down-wind, causing the entire dune field to migrate slowly upwind (Frezzotti and others, 2002; Dadic and others, 2013).

Pluto, unlike Europa, does possess a thin atmosphere, with a surface pressure of about 10 μbar or 1 Pa (Stern and others, 2015), so a wind-driven mechanism for formation of Pluto's ridges may be possible, analogous to that which forms the Antarctic snow-megadunes. Some of the published images of Pluto (Moore and others, 2017; Moores and others, 2017) do resemble satellite images of Antarctic megadune fields (Fahnestock and others, 2000; Frezzotti and others, 2002). In any case, since the aspect ratio and mechanism of formation of Pluto's ridges are so different from those of Andean penitentes, it seems inappropriate to label them 'penitentes'. A news article in *Nature* about the images from Pluto (Hall, 2020) included the same photograph of Andean penitentes that had been used in *Nature*'s earlier news story about Europa cited above, unfortunately again neglecting to mention the crucial role of melting in the Andes, so it was similarly misinforming the readers about Earth's penitentes.

Recommendations for future work

Several groups have designed computational models to explain the growth of penitentes by sublimation alone (Betterton, 2001; Tiedje and others, 2006; Cathles and others, 2014; Claudin and others, 2015). Those models accounted for such factors as the diurnal cycle of the direction of incident sunlight and its dependence on latitude, the 'trapping' of solar energy in topographic depressions, and resultant temperature gradients and sublimation rates. Those models could still be improved, even when considering only sublimation. For example, a recent highly-cited model (Claudin and others, 2015) completely ignores emission and absorption of thermal infrared radiation, and its lack of spectral resolution for the near-infrared solar radiation (and its attribution of visible-wavelength attenuation to absorption instead of scattering) lead to an absorption-depth that is at least an order of magnitude too large (Brandt and Warren, 1993).

Those published models have limited themselves to what can be achieved by sublimation alone. Modelers are of course wise to start out simple, and modeling the onset of penitente growth by consideration of sublimation alone was a good first step. But to make the models relevant to the tall penitentes that have reliably amazed travelers in the Andes, it will be necessary to include melting. This will require modeling of air turbulence within a trough to compute the humidity-gradients that are central to Lliboutry's explanation. Models should be structured to compute vertical profiles of humidity and temperature within the trough, thus allowing them to diagnose the vertical profiles of sublimation rates and melting rates as penitentes grow through the spring and summer, and then finally decay in late summer as the melting/sublimation boundary migrates upward.

Some fieldwork would be desirable to support the modeling. Several papers describing penitentes in the Andes (e.g. Nicholson and others, 2016) have commented on the saturated humidity in the troughs, which is essential for preventing sublimation and leading to warmth and melting, but measurement of vertical profiles of humidity within the troughs has not been reported.

Acknowledgments. I thank the leader of the IGS seminar series, Tavi Murray, for sponsoring the talk I gave in November 2020 together with Kevin Hand, who presented the work he had published in Hand and others (2020). I thank the editor, Doug MacAyeal, for suggesting that penitentes would be an appropriate topic for this special volume of *Annals of Glaciology*. I thank Lindsey Nicholson and Shelley MacDonell for discussions during field trips in Chile, and Kevin Hand and Dale Winebrenner for discussions during preparation of this paper. The section on Pluto was added at the request of an anonymous reviewer.

References

Anonymous (2018) Ice spikes span a Jovian moon. *Nature* **562**, 311.

Armstrong T, Roberts B and Swithinbank C (1973) *Illustrated Glossary of Snow and Ice*. Cambridge, UK: Scott Polar Research Institute, 60 pp + 79 plates.

Belgasem I, Schmidt F and Jonniaux G (2020) Regional study of Europa's photometry. *Icarus* **338**, 113525.

Bergeron V, Berger C and Betterton MD (2006) Controlled irradiative formation of penitentes. *Physical Review Letters* **96**, 098502.

Berisford DF and 9 others (2021) Erosion of penitentes under experimental conditions relevant to ice-covered airless worlds. *Journal of Geophysical Research: Planets* **126**, e2021JE006955. https://doi.org/10.1029/2021JE006955.

Betterton MD (2001) Theory of structure formation in snowfields motivated by penitentes, suncups, and dirt cones. *Physical Review E* **63**, 056129.

Brandt RE and Warren SG (1993) Solar heating rates and temperature profiles in Antarctic snow and ice. *Journal of Glaciology* **39**, 99–110.

Carlson RW and 7 others (2009) Europa's surface composition. In Pappalardo RT, McKinnon WB and Khurana KK (eds), *Europa*. Tucson: University of Arizona Press, pp. 283–327.

Cathles LM, Abbot DS and MacAyeal DR (2014) Intra-surface radiative transfer limits the geographic extent of snow penitents on horizontal snowfields. *Journal of Glaciology* **60**, 147–154.

Claudin P, Jarry H, Vignoles G, Plapp M and Andreotti B (2015) Physical processes causing the formation of penitentes. *The Physical Review* **E92**, 033015.

Dadic R, Mott R, Horgan HJ and Lehning M (2013) Observations, theory, and modeling of the differential accumulation of Antarctic megadunes. *Journal of Geophysical Research: Earth Surface* **118**, 2343–2353. doi: 10.1002/2013JF002844

Doumani GA (1967) Surface Structures in Snow. In Oura S (ed.), *Physics of Snow and Ice*. Sapporo, Japan: Bunyeido, pp. 1119–1136.

Fahnestock MA and 5 others (2000) Snow megadune fields on the East Antarctic Plateau: extreme atmosphere-ice interaction. *Geophysical Research Letters* **27**, 3719–3722.

Filhol S and Sturm M (2015) Snow bedforms: a review, new data, and a formation model. *Journal of Geophysical Research: Earth Surface* **120**, 1645–1669. doi: 10.1002/2015JF003529

Frezzotti M, Gandolfi S and Urbini S (2002) Snow megadunes in Antarctica: sedimentary structure and genesis. *Journal of Geophysical Research* **107** (D18), 4344. doi: 10.1029/2001JD000673

Gow AJ (1965) Accumulation and seasonal stratification of snow at the South Pole. *Journal of Glaciology* **5**, 467–477.

Hall S (2020) The dark side of Pluto. *Nature* **583**, 674–678.

Hand KP and 5 others (2020) Penitente formation is unlikely on Europa. *Nature Geoscience* **13**, 17–19. doi: 10.1038/s41561–019-0496-2

Hand KP and 286 others (2022) Science goals and mission architecture of the Europa lander mission concept. *Planetary Science Journal* **3**(22), 1–31. https://doi.org/10.3847/PSJ/ac4493.

Hobley DEJ, Moore JM, Howard AD and Umurhan OM (2018) Formation of metre-scale bladed roughness on Europa's surface by ablation of ice. *Nature Geoscience* **11**, 901–904.

Kornei K (2018) Huge blades of ice may partially cover Jupiter's moon Europa. *EOS Earth & Space Science News*, December 2018, 5.

Kotlyakov VM and Lebedeva IM (1974) Nieve and ice penitentes, their way of formation and indicative significance. *Zeitschrift für Gletscherkunde und Glazialgeologie* **10**, 111–127.

Lhermitte S, Abermann J and Kinnard C (2014) Albedo over rough snow and ice surfaces. *The Cryosphere* **8**, 1069–1086.

Lliboutry L (1954) The origin of penitents. *Journal of Glaciology* **2**, 331–338.

Lliboutry L (1964) *Traité de Glaciologie*, vol. **1**. Paris: Masson, pp. 372–376.

MacDonell S, Kinnard C, Moelg T, Nicholson L and Abermann J (2013) Meteorological drivers of ablation processes on a cold glacier in the semi-arid Andes of Chile. *The Cryosphere* **7**, 1513–1526.

Moore JM, Howard AD, Umurhan OM and White OL and others (2017) Sublimation as a landform-shaping process on Pluto. *Icarus* **287**, 320–333. doi: 10.1016/j.icarus.2016.08.025

Moore JM, Howard AD, Umurhan OM and White OL and others (2018) Bladed terrain on Pluto: possible origins and evolution. *Icarus* **300**, 129–144. doi: 10.1016/j.icarus.2017.08.031

Moores JE, Smith CL, Toigo AD and Guzewich SD (2017) Penitentes as the origin of the bladed terrain of Tartarus Dorsa on Pluto. *Nature* **541**, 188–190.

Naruse R and Leiva JC (1997) Preliminary study on the shape of snow penitents at Piloto Glacier, the central Andes. *Bulletin of Glacier Research* **15**, 99–104.

Nicholson LI, Petlicki M, Partan B and MacDonell S (2016) 3-D Surface properties of glacier penitentes over an ablation season, measured using a Microsoft Xbox Kinect. *The Cryosphere* **10**, 1897–1913.

Ostro SJ and 11 others (1992) Europa, Ganymede, and Callisto: new radar results from Arecibo and Goldstone. *Journal of Geophysical Research* **97**, 18227–18244.

Pfeffer WT and Bretherton CS (1987) The effect of crevasses on the solar heating of a glacier surface. *The Physical Basis of Icesheet Modelling* (*Proceedings of the Vancouver Symposium*), IAHS Publication **170**, 191–205.

Post A and LaChapelle ER (1971) Glacier ice. University of Washington Press [Revised edition published 2000 by International Glaciological Society].

Rhodes JJ, Armstrong RL and Warren SG (1987) Mode of formation of 'ablation hollows' controlled by dirt content of snow. *Journal of Glaciology* **33**, 135–139.

Stern SA and 150 others (2015) The Pluto system: initial results from its exploration by New Horizons. *Science* **350**, 292. doi:10.1126/science.aad1815

Tiedje T, Mitchell KA, Lau B, Ballestad A and Nodwell E (2006) Radiation transport model for ablation hollows on snowfields. *Journal of Geophysical Research* **111**, F02015. doi: 10.1029/2005JF000395

Traversa G, Fugazza D and Frezzotti M (2023) Megadunes in Antarctica: migration and characterization from remote and in situ observations. *The Cryosphere* **17**, 427–444. doi: 10.5194/tc-17-427-2023.

Troll C (1942) Büsserschnee in den Hochgebirgen der Erde. *Petermanns Geographische Mitteilung*, Ergänzungsheft Nr. 240. Justus Perthes, Gotha, 125 pp.

Untersteiner N (1957) Glazial-meteorologische Untersuchungen im Karakorum, II. Wärmehaushalt. *Archiv für Meteorologie, Geophysik und Bioklimatologie* **8**, 137–171.

Warren SG, Brandt RE and O'Rawe-Hinton P (1998) Effect of surface roughness on bidirectional reflectance of Antarctic snow. *Journal of Geophysical Research: Planets* **103**, 25789–25807.

Wentworth CK (1940) Ablation of snow under the vertical Sun in Hawaii. *American Journal of Science* **238**, 112–116.