



Morphodynamics of snow barchans at Concordia Station, Antarctica

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Abstract Barchans are crescent-shaped dunes that form and migrate under unimodal wind regimes in areas of low sediment availability. While sand barchan morphodynamics has been extensively studied, snow barchans remain poorly documented. Here, using hourly time-series images taken near Concordia Station, Antarctica, we measure the sizes (lengths 0.3 m to 13 m, widths 0.4 m to 7.5 m) and migration rates (0.13 m h^{-1} to 3.5 m h^{-1}) of 44 populations of snow barchans during 2017–2022. We compare this dataset with established height–velocity and length–width relationships for sand barchans in both air and water. Our results show that snow barchans follow the same scaling as sand barchans, allowing us to estimate a characteristic sintering (bonding of snow particles) time of about one day. This sintering process limits the size of snow barchans when active, reduces their aspect ratios, and, once wind falls below the transport threshold, explains their preservation over a few years. During wind events, migrating barchans are too small to maintain their shape and orientation, making them highly responsive to fluctuations in wind direction. Thus, studying snow barchans improves understanding of an elementary bedform encountered in multiple environments and also of the surface properties of snow on different timescales, offering insights into snow accumulation and wind-blown snow in ice cores.

Non-technical summary When wind blows constantly from one direction and sediment is limited, crescent-shaped dunes known as barchans can form on the Earth's surface. While these bedforms have been widely studied in sand deserts, snow barchans remain largely unexplored. In this study, we analyze time-lapse images taken near Concordia Station, in Antarctica, during 2017–2022 to measure the size and speed of different snow barchan populations. This unique dataset allows a comparison of the shape of snow and sand barchans and verifies relationships between their migration rate and height. Our study also shows how cohesion mechanisms limit dune size, and how snow barchans can be used to estimate a characteristic time for the consolidation of snow surfaces. Due to their small size (meter-scale), snow dunes respond more quickly to changes in wind direction than sand barchans (hectometer-scale). Three different barchan reorientation events are analyzed to provide new information on snow transport properties, including the threshold wind speed for beginning motion. It is concluded that snow dunes offer a new window into understanding dune behavior and the conditions in which dunes form, revealing more about the snow surface and the Antarctic atmosphere.

1 Introduction

Barchans are isolated crescent-shaped bedforms with two arms pointing downwind, which form on consolidated beds exposed to unimodal flow conditions and low sediment supply (Pye and Tsoar, 2010). Barchans are commonly found in terrestrial deserts (Finkel, 1959; Sauermann et al., 2000; Ould Ahmedou et al., 2007a; Engel et al., 2018; Yang et al., 2019, 2021), on Mars (Bourke et al., 2009; Bourke, 2010; Bridges et al., 2012; Hayward et al., 2014), in riverbeds, and on the ocean floor (Carling et al., 2000; Wynn et al., 2002; Todd, 2005; Daniell and Hughes, 2007; Ma et al., 2014). Conse-

quently, barchans have been the focus of numerous studies. Since the seminal work of Bagnold (1941), barchans have frequently been regarded as the fundamental objects for understanding and illustrating dune physics, along with the broader field of aeolian transport. Based on the quantitative relationships that can be derived from their size, orientation and dynamics (Hesp and Hastings, 1998; Hersen, 2004; Durán et al., 2010; Alvarez and Franklin, 2017; Alkalla et al., 2025a), barchans are widely used as environmental proxies for reconstructing past and present climatic conditions in both terrestrial and extraterrestrial settings (Gardin et al., 2012; Chen et al., 2022; Rubanenko et al., 2023). This approach has not yet been developed for snow dunes but

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could provide new quantitative constraints on meteorological conditions in cold environments and on the sintering processes that influence snow surface evolution.

Applying these concepts to snow requires accounting for its unique properties. Snow is a granular material that can precipitate from the sky and accumulate in layers to form snowpacks, which in exposed regions (tundra, sea ice, ice caps, and alpine regions) are reworked by wind. This re-mobilization by wind has multiple consequences for snow: 1) mass may be eroded and deposited in preferential locations in relation to terrain topography (Liston and Sturm, 1998), 2) particles when entrained break in smaller pieces (Comola et al., 2017), 3) sublimation of ice into the atmosphere is enhanced (Palm et al., 2017; Gadde and Van De Berg, 2024; Bordie et al., 2020), and 4) self-organized structures, snow bedforms, form at the snow surface (Filhol and Sturm, 2015; Mather, 1962). Unlike sand, snow is a warm material because it exists near its fusion temperature under the temperature conditions at the Earth's surface. Consequently, snow undergoes solid-phase metamorphism, therefore impacting its mechanical and thermodynamic properties. One effect relevant to snow bedforms is sintering. Sintering is the progressive formation of ice bonds between grains, gradually increasing cohesion, making snow harder the longer particles remain in contact and the smaller they are originally (pre-sintering) (Colbeck, 1997; Schweizer et al., 2003). Sintering occurs as the system seeks to minimize the free surface energy of the ice grains. The sintering process operates over different time scales, from seconds to hours, and is strongly influenced by environmental parameters, such as wind, humidity and surface temperature (Blackford, 2007; Herwijnen and Miller, 2013; Bernache-Assollant, 1993; Szabo and Schneebeli, 2007). The combination of wind reworking, topography, and layered history produces surfaces where snow patches of different age and history are exposed side by side (Picard et al., 2019). As a result, the snow exposed to the wind exhibit great variability in size, shape, and sintering state, both in time and space. So, unlike sand, snow is a highly dynamic material, whose properties can evolve even within a single transport event, including during dune migration. In this context, to demonstrate that snow barchans can be used to model the characterization of bedform and aeolian transport, especially in the presence of cohesion forces, a brief introductory section is devoted to the relevant properties of sand and snow barchans.

1.1 Snow barchans

It is unknown whether macroscopic dune-scale properties can be used to infer the underlying grain-scale physics in snow surface state. If so, snow bedforms could provide indirect constraints on processes that are otherwise difficult to measure in situ, such as sintering and the development of interparticle cohesion. Despite this potential, snow barchans, and snow bedforms more generally, have been largely overlooked even though they have been reported in a variety of cold environments. Snow barchans have been observed in

polar regions such as Antarctica (Birnbaum et al., 2010; Sommer et al., 2018; Kuznetsov, 1960), as well as in sub-polar and mid-latitude regions, including Alaska and Colorado (Filhol and Sturm, 2015; Kochanski et al., 2019; Cornish, 1902). In contrast to sand, snow particles are inherently cohesive, and their shape and size continuously evolve due to metamorphism, which is strongly influenced by temperature and other environmental factors, consequently changing their physical properties (Colbeck, 1997). These changes can influence the formation, migration, and longevity of snow barchans, yet few quantitative field studies have systematically analyzed these effects (Filhol and Sturm, 2015; Kochanski et al., 2019). Others, using a cellular automaton approach, have demonstrated that cohesion imposes a maximum size, ensuring the barchan turnover time (which refers to the time required for a dune to migrate one dune length) does not exceed the characteristic cohesion time (Sharma et al., 2018; Alkalla et al., 2025b). When combined with the minimum dune size, a crucial consequence is that snow barchans occur within a limited range of sizes that can be defined from environmental conditions according to the kinetics of the cohesion processes and transport rate.

The morphology of snow barchans is similar to that of sand barchans, but they are typically smaller and flatter, making them difficult to detect via satellite imagery and limiting large-scale studies. Furthermore, snow barchans only form during drifting snow events, complicating ground-based observations or high-resolution aerial photography as visibility of the snow surface is very low, and weather conditions may not be optimal for aerial vehicles. The few existing studies indicate that snow barchans range from 1 to 30 m in length, 2 to 15 m in width, and 0.01 to 0.5 m in height, with a height-to-length ratio of 1:70, much lower than the 1:15 ratio typical of sand barchans, with heights ranging from 0.7 m to several tens of meters (Filhol and Sturm, 2015). However, despite these differences in size, a linear relationship has been observed between various morphological parameters (i.e., height, length, width) in snow barchans, similar to what has been reported for aeolian and subaqueous sand barchans (Hersen, 2005; Endo et al., 2005; Andreotti et al., 2002).

Reports of snow barchan migration are scarce, even in Antarctica, while highly unidirectional winds and limited snow availability suggest that such dunes should be common (Kochanski et al., 2019; Filhol and Sturm, 2015). The few studies to date indicate that snow barchan migration rates range between 0.9 and 3.9 m h⁻¹. Smaller snow barchans have been reported to migrate faster than larger ones (Kuznetsov, 1960). Nevertheless, these data rely on a narrow range of wind speeds and do not allow the investigation of variables responsible for the overall migration: snow flux variability at the crest and the magnitude of the wind speed-up effect.

1.2 Morphodynamics of sand barchans

To address these challenges, we build on the existing theoretical framework developed for sedimentary

dunes and explore its applicability to snow barchans. Dune physics provides characteristic time and space scales for the formation and dynamics of sedimentary bedforms, as well as quantitative estimates of the associated sediment transport rates and flow properties, including for barchans. Based on the dune instability theory, which elucidates the size selection mechanisms behind the emergence of periodic dune patterns (Kennedy, 1963; Richards, 1980; Coleman and Melville, 1994; Elbelrhiti et al., 2005; Narteau et al., 2009; Gadal et al., 2019, 2020; Lü et al., 2021), it is generally accepted that aeolian and subaqueous barchans composed of sand exhibit a minimum length, λ_c , of about 10 m and 10^{-2} m, respectively, that scales with the saturation length,

$$L_{\text{sat}} \simeq 2.2 \frac{\rho_p}{\rho_f} d \quad (1)$$

where d is the grain diameter, and ρ_p/ρ_f the grain-to-fluid density ratio. This characteristic length is required for the saltation flux to reach saturation after a change in transport conditions, such as wind speed or bed properties (Sauermann et al., 2001; Andreotti et al., 2002; Parteli and Herrmann, 2007; Charru et al., 2013; Rambert et al., 2025). It is proportional to the drag length, $L_{\text{drag}} = (\rho_p/\rho_f)d$, which is defined as the inertia length required for a grain to be accelerated to the fluid velocity (Hersen et al., 2002). Therefore, when saltation is the predominant sand transport process, the minimum length of barchans can be determined as a function of the properties of grains and fluid, to be compared with one another regardless of the environment in which they develop (Endo et al., 2005; Claudin and Andreotti, 2006). As a first approximation, based on flow measurements over sand dune profiles, it is currently reasonable to consider that λ_c is equal to $4\pi L_{\text{sat}}$, where the prefactor accounts for the upwind phase shift between the wind speed and the bed topography (Claudin et al., 2013; Lü et al., 2021).

In addition, the crescent shape of a barchan is linked to its dynamics and the key role of sand fluxes perpendicular to the flow. On both sides of its central body the longitudinal sections of barchans decrease in height and aspect ratio until the slip face disappears. The barchan then releases sand at a constant rate ($\approx Q_{\text{flat}}$) from its arms. The morphology of the dune imposes lateral sand fluxes from the central body toward the arms, which, in turn, compensate for losses and ensure that all sections migrate at the same speed. This results in the distinctive crescent shape, with a curved crestline and arms pointing downwind. An isolated barchan can then be characterized by its longitudinal and transverse aspect ratios (i.e., slopes), which are then intrinsically related to its dynamics and the magnitude of the net sediment transport, both perpendicular and parallel to the crest (Hersen, 2004).

Sand barchans are rarely isolated in nature and form populations within which they constantly interact with each other via mass exchanges resulting from collisions or free fluxes emitted along the arms. These dune-dune interactions modulate all the relationships established for isolated barchans, and they can only be validated in the field through a statistical approach tak-

ing into account a large number of dunes. In most cases, sand barchans are large enough to accommodate to transient flow regimes, such as storm events in hot deserts (i.e., $\tau_{\text{theory}} \gg 1$ yr). Consequently, the way in which they reorganize and adapt to transient flow conditions (strength and orientation) has rarely been described (Gao et al., 2018; Lü et al., 2022).

1.3 Objectives

In this study, we examine the morphology and dynamics of successive populations of snow barchans near Concordia Station, near Dome C in Antarctica. To this end, we analyze barchan length, width, and migration speed using hourly time-series images taken by a fixed near infra-red (NIR) camera from August to May each year during 2017–2022. We compare the morphological parameters of the snow barchans observed at Concordia Station with those of aeolian and subaqueous barchans composed of sand, as well as with the available data of snow barchans from Alaska (Filhol and Sturm, 2015). We document the barchan reorientation time to determine how it relates to the threshold wind speed according to changes in wind speed and orientation. Combined with the maximum size of the barchans observed under stable wind conditions and their stabilization during periods of low wind strength, these data provide a basis for the quantification of the characteristic cohesion times in the extreme conditions of the interior of the Antarctic continent.

2 Study area and field data

The study site is located inland of Antarctica (-75.0977° N, 123.2982° E, at an elevation of 3233 m), approximately 800 m from the Concordia station (Figure 1a). The area under investigation is located upwind of the station to minimize disturbances from station activities, which are also restricted in this area. The site experiences a prevailing northerly wind (winds blowing towards South) with a mean wind speed of 2.8 m s^{-1} , an annual precipitation of $27 \text{ kg m}^{-2} \text{ yr}^{-1}$, a mean accumulation of 8 cm, a mean snow density of 320 kg m^{-3} , and a mean temperature of -55°C (Van Wessem et al., 2014). Despite these average values, which are associated with extremely low precipitation and wind speeds, the surface is sporadically reshaped by wind and snow transport events.

2.1 Monitoring of the surface with a near infra-red camera

A near infra-red (NIR) camera (Canon EOS 5D Mark II, $24 \times 36 \text{ mm}$ sensor) equipped with an Astronomik Planet IR Pro high-pass infrared filter (cutoff frequency of 807 nm, to improve contrast) and a 28 mm focal length lens, was installed on a tower at a height of approximately 20 m (Figure 1b). The effective surface area with sufficient resolution to clearly distinguish surface features monitored by the NIR camera is approximately 5200 m^2 .

To ensure operation under extreme conditions, the NIR camera is housed in a heated enclosure capable of

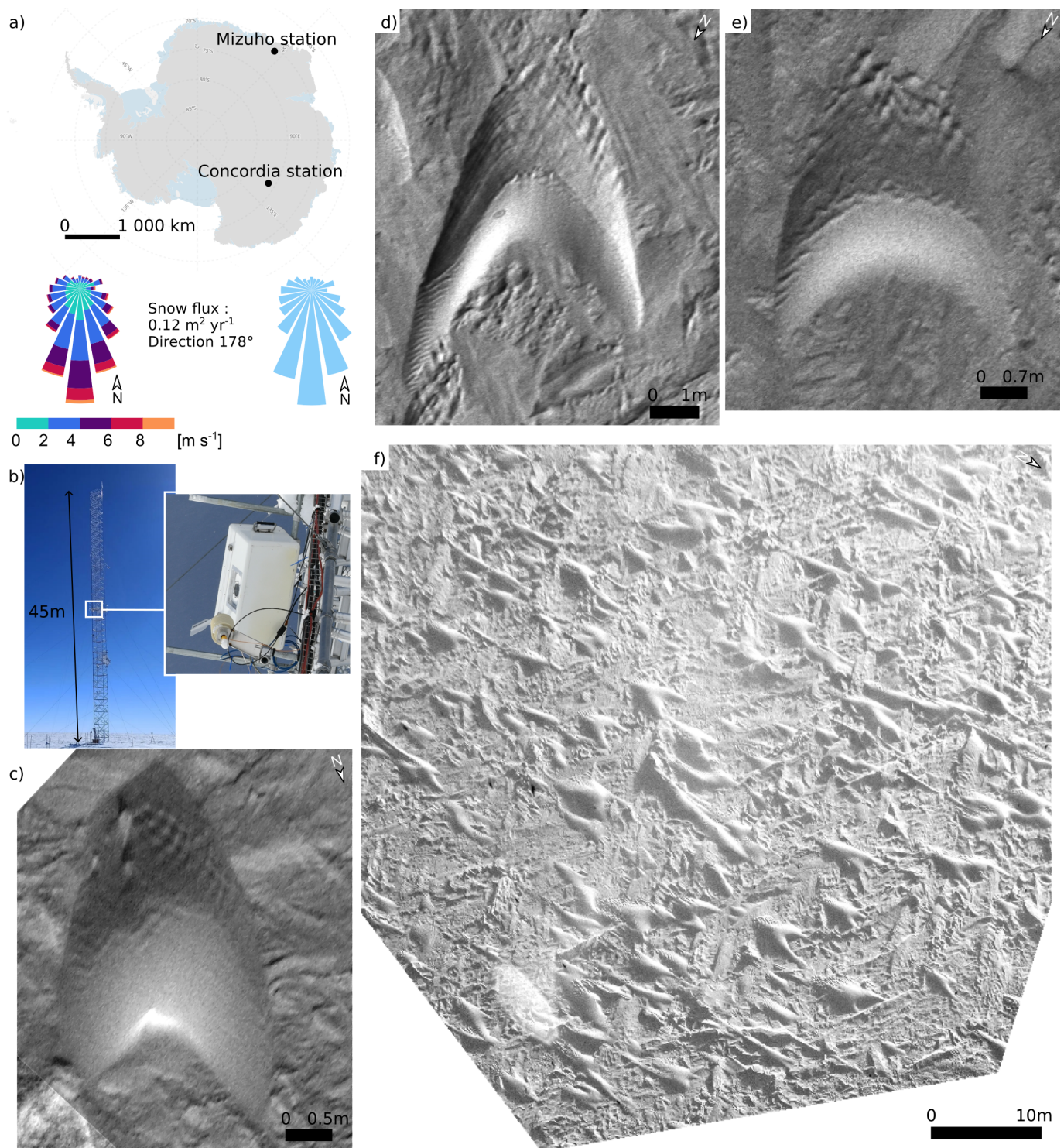


Figure 1 Study site and barchans observed at Concordia Station (-75.09766° N, 123.29836° E). (a) Location of the study site in Antarctica, along with the wind and flux roses at Concordia Station using Equations 5 and 6 with the data from the anemometer located at a height of approximately 1 m. Wind direction is the direction towards which the wind is blowing. 0° is Northern and 90° Eastern winds. Values are for the Drift Potential (DP) and the Resultant Drift Direction (RDD). (b) The tower on which the automated NIR camera shown in the inset is installed. Orthorectified images of (c-e) snow barchans, and (f) a field of snow barchans.

withstanding temperatures as low as -80°C (Figure 1b). The NIR camera captures one photograph every hour from August through May, starting in 2017, and remained operational at the time of writing. The time series is occasionally interrupted as a result of visibility limitations due to blowing snow or darkness. Routine maintenance of the tower and the NIR camera occasionally introduced slight shifts in the field of view.

2.2 Weather station

The wind regime (direction and speed) is monitored using three wind anemometers (Young A05103) installed at nominal heights ranging from 50 to 220 cm. Measurements are taken every 10 min. Wind speed below 100 m s^{-1} can be measured with an accuracy of 0.3 m s^{-1} , whereas its direction can be determined with an accuracy of 3° . The data series spans from 29 January

2015 to 12 January 2023. Depending on the ice burial of the lowest anemometer, two to three simultaneous wind speed and direction measurements at different heights are available. Anemometer heights are determined from occasional manual photographs or direct measurements, with linear interpolation between measurement points. To ensure reliable data collection, the lowest anemometer is manually raised as needed to compensate for burial.

3 Methods

An event of barchan formation and migration begins when snow drift leading to barchan formation is observed and ends when no barchan motion is visible. The morphology and dynamics of all identifiable barchans from which measurements can be taken during these events are examined.

3.1 Image orthorectification

The images are orthorectified using the open-source NASA Ames Stereo Pipeline (ASP) software for automated geodesy and stereogrammetry (Howat et al., 2019; Beyer et al., 2018). Because no calibration profile for the camera-lens system was established prior to installation, we retrieve a pinhole model (Tsai, 1987), which does not include geometric distortion correction, using ASP software. We orthorectify the images onto the Digital Elevation Model (DEM) from Reference Elevation Model of Antarctica (REMA) (Howat et al., 2019).

The pixel pitch is obtained from the manufacturer documentation (6.4 μm), and the focal length f is measured using an object of known dimensions (stakes) under the conditions of a far object, yielding $f = 32 \text{ mm} \pm 2 \text{ mm}$. The correspondence between Northing-Easting (EPSG:3031 - WGS 84, Antarctic Polar Stereographic) and pixel coordinates is established using the known positions of five stakes within the NIR camera's field of view.

With this camera model and ASP software, approximately 1 000 images in which barchans are visible have been orthorectified (Figure 1c-f). Orthorectification accuracy is assessed by comparing the retrieved and measured positions of 10 stakes within the NIR camera's field of view, including the five used for determining the NIR camera model. The position of the stakes are measured using a differential GPS, with a centimetric precision. The positional errors range from 0.5 to 2 m, and increase with the distance of the stakes from the NIR camera. Using these images, barchan geometry and migration rates are determined, with an estimated uncertainty of 10%.

3.2 Methods for the characterization of snow barchan morphodynamics

Barchan dimensions are measured from orthorectified images using a reference point at the base of the slip face where the curvature is maximum (Figure 2a). From this point, the segment to the upstream dune toe provides the length of the dune body, L_{body} , and its orientation, α , which is measured counterclockwise from

north. This orientation, also defined as the longitudinal alignment of the barchan, is used to measure the lengths of the horns, L_1 and L_2 , as the distances from the reference point to the tips of both horns. The overall length is defined as $L = (L_1 + L_2)/2 + L_{\text{body}}$. The overall dune width, W , is the distance between the two horn tips measured perpendicular to the orientation of the dune body.

The topography of the windward part of snow barchans is often rough, likely resulting from the kinetics of the cohesion process that occurs at the base of the dune during its migration. To quantify the longitudinal aspect-ratio of barchans and subsequently the magnitude of the speed-up effect, this part of the dune is excluded from consideration. Then, the dune length L_D measured on orthorectified images is defined as the distance over which the upstream face exhibits a smooth and homogeneous slope. According to these definitions of dune length, $L_D \leq L_{\text{body}} < L$, and $L_D = L_{\text{body}}$ for sand barchans in the absence of cohesion. The dune width at the crest, W_D , is measured perpendicular to the dune orientation. Due to the crescentic shape of barchans, $W_D < W$.

The dynamics of the barchans is quantified by measuring the displacement, Δd , of the reference point between two successive orthorectified images taken over a time interval Δt , which is usually one hour. The migration rate can be calculated as $c = \Delta d / \Delta t$, the direction of migration α_m as the orientation measured from the north of the line that connects the two successive reference points (Figure 2a,b). The barchan orientation and the migration direction are both determined with an accuracy of about 5°. In most cases, the wind direction remains constant, and these two field measurements are in perfect agreement (Figure 3a). Under unidirectional wind conditions, it can be assumed that they are equal, and the orientation of the flux at the crest (i.e., the direction of migration) can be considered perfectly perpendicular to the transverse alignment of the barchans.

As barchan morphology evolves, the choice of the reference point may affect the measurements of the migration rates. To evaluate the impact of this choice, the migration rates of the point of maximum curvature are compared with the migration rates of other reference points, including the upstream dune toe, and the horn tips. There is a general agreement between these measurements, in particular between the point of maximum curvature and the horn tips, which are equally affected by surface obstacles. A more substantial discrepancy is observed with the upstream dune toe (the root mean square error, RMSE, increases from 0.38 to 0.60 m h^{-1}), potentially caused by the delayed response of the upstream and downstream parts to surface changes. To standardize the measurements, the barchan migration rate is defined as the average of migration rates of the upstream toe, the point of maximum curvature and the horn tips (Figure 3b).

3.2.1 Migration rate and fluxes

Snow barchans migration rates measurements are then compared to the theoretical framework built for sand

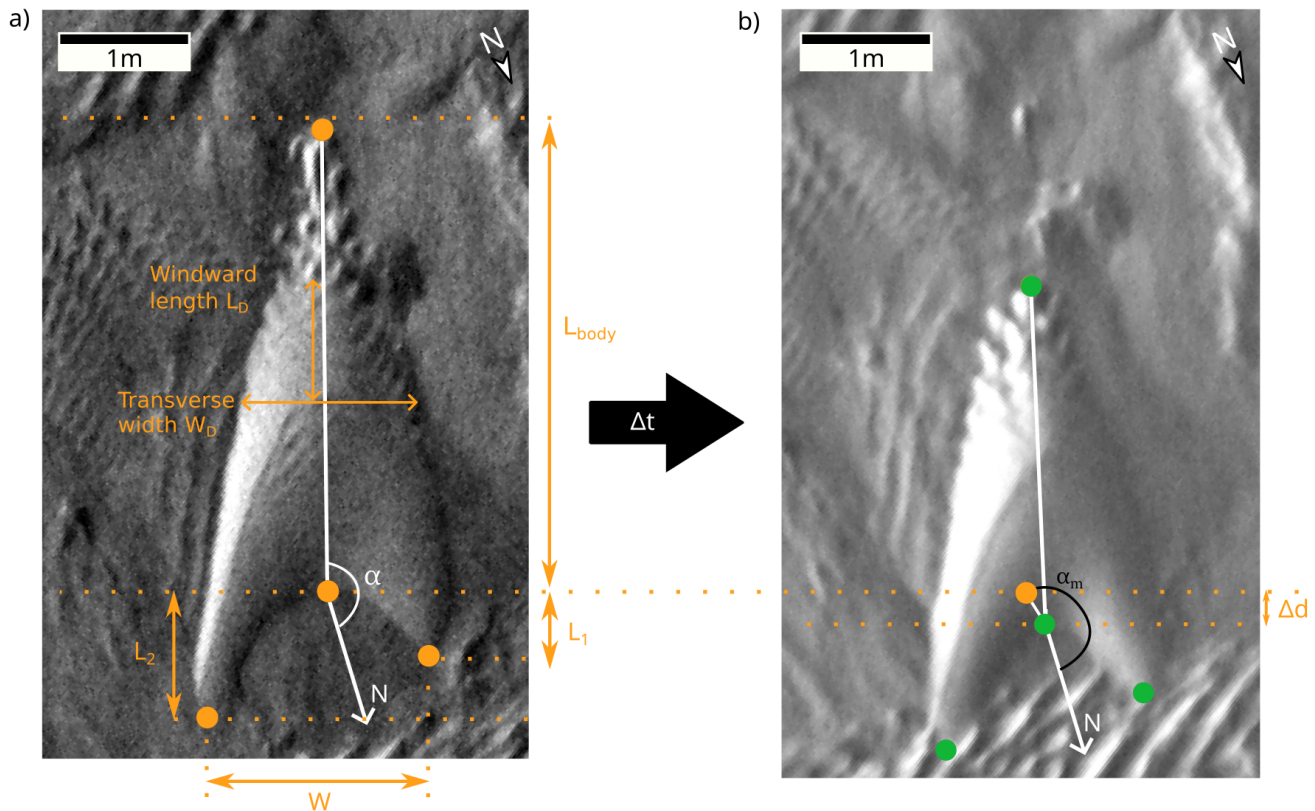


Figure 2 Reference points and measurements of barchan morphodynamics. (a-b) Four reference points are identified, at the bottom of the slip face where the curvature is maximum, at the upstream dune toe, and at the horn tips. They are used to measure the orientation, α , of snow barchans as well as their dimensions, including width W , horn lengths, L_1 and L_2 , and body length L_{body} (see text). Two successive images are used to estimate the migration rate, $c = \Delta d / \Delta t$, and the direction of migration, α_m .

dunes. In steady 2D flow conditions, an isolated dune can be conceptualized as a sediment trap due to the formation of a recirculation zone in the lee side of dunes and the subsequent development of a slip face. The material transported at the crest is deposited along the slip face by avalanches and is remobilized at a constant rate by the flow along the windward slope. Consequently, according to the principle of mass conservation, it is usually assumed that a steady-state barchan migrates at a constant speed,

$$c = \frac{Q_{\text{crest}}}{H} \quad (2)$$

with a constant turnover time,

$$\tau_{\text{theory}} = \frac{S}{Q_{\text{crest}}} \quad (3)$$

where Q_{crest} is the saturated sand flux at the crest, H the dune height, and S the area of its longitudinal cross-section. This saturated sand flux at the crest exceeds that observed on flat bed topography, Q_{flat} , because of the wind speed acceleration on the barchan windward slope. In practice, the linear theory of Jackson and Hunt (1975) of wind speed perturbation over a low hill can be expanded to describe the sand flux,

$$Q_{\text{crest}} = Q_{\text{flat}}(1 + \gamma) \quad (4)$$

In this expression, $\gamma = (Q_{\text{crest}} - Q_{\text{flat}})/Q_{\text{flat}}$ is the fractional flux-up ratio of sediment that directly derives from the fractional speed-up ratio of wind, i.e the wind

velocity increase at the top of the dune, $\delta = (u_{\text{crest}} - u_{\text{flat}})/u_{\text{flat}}$. At the first order of the dune aspect ratio, H/L_D , where L_D is the length of the dune windward slope, it can be expressed as $\delta = \beta H/L_D$, where β is a dimensionless coefficient that accounts for other physical components (e.g., roughness) affecting surface wind speed on dune slopes. Using Equations 2 and 4, it is therefore possible to derive the velocity of barchans as a function of their size whatever the transport law, as long as the sediment flux at the crest is known.

3.3 From wind speed to snow flux

Due to extreme conditions and the rare occurrence of transport events, direct measurements of snow flux are limited in Concordia, and more generally in Antarctica (Amory et al., 2020; Kobayashi, 1978; Mellor, 1986). There are not yet any direct measurements of snow transport at Concordia Station for comparison with local wind measurements. Instead, the local wind data are used to calculate the shear velocity

$$u_* = \frac{u\kappa}{\log(z/z_0)} \quad (5)$$

where $z_0 = 10^{-3}$ m is the aerodynamic roughness length, $\kappa = 0.4$ the Von Kàrmàn constant, and u the wind speed measured at the height z . Estimating snow mass flux is challenging due to the strong temporal variability of snow properties and the difficulty of direct in situ measurements Sturm and Stuefer (2013). Snow transport depends on wind speed and on evolving snow

properties such as cohesion, grain size, and metamorphic state but these parameters are difficult to constrain in situ. We therefore used the snow transport law developed by Schmidt (1982) (derived from Iversen, 1980; Iversen et al., 1975, 1976), which was evaluated against in situ snow flux measurements at Mizuho Station, Antarctica (Figure 1a). This formulation captures the primary dependence on atmospheric forcing and is widely used for estimating blowing snow fluxes. The flux is assumed to be in equilibrium with the local wind conditions and therefore to be at saturation, and actual fluxes may locally remain below these values where equilibrium conditions are not fully established.

$$Q_{\text{flat}} = \frac{\rho_{\text{air}}}{g} \frac{u_f}{u_*^{\text{th}}} u_*^2 (u_* - u_*^{\text{th}}) \quad (6)$$

In this transport law, $\rho_{\text{air}} = 0.95 \text{ kg m}^{-3}$ is the air density (for a pressure of 645 hPa, temperature of -35°C), $g = 9.81 \text{ ms}^{-2}$ the gravitational acceleration, $u_f = 0.75 \text{ ms}^{-1}$ the particle fall velocity which correspond to the standard value used, and $u_*^{\text{th}} = 0.26 \text{ ms}^{-1}$ the static threshold wind speed for snow transport (i.e., the wind speed needed to initiate transport $u_{\text{th}} = 6 \text{ ms}^{-1}$ at a height of 10 m (Schmidt, 1982)). Sensitivity to the threshold wind speed (Figure S1) and terminal fall velocity (Figure S2) were evaluated. In Antarctica, threshold wind speed was reported between 5 ms^{-1} to 12 ms^{-1} depending on snow cover conditions. Terminal fall velocity typically range between 0.5 ms^{-1} to 1.4 ms^{-1} depending on particle size, shape, density (Satoh and Takahashi, 2006; Zawadzki et al., 2010). The sensitivity tests indicate that the impact on the value of the snow flux of the uncertainty associated with the threshold wind speed is larger than that associated with the terminal fall velocity. This formulation exhibits a cubic dependence on the friction velocity, which results from the assumptions that the saltation length scales as the square of friction velocity and the near-surface particle velocity increases linearly with friction velocity Melo et al. (2024, 2022); Kok et al. (2012). Sensitivity to other transport laws were also evaluated (Table S1, Figure S3). The absolute differences of the flux between cubic, quadratic, and quartic dependencies remain generally below 50% (80th quantile) for the most frequently observed wind speeds. However, despite the limitations in estimating the flux, in part due to the transient nature of snow, estimates made here are of the same order of magnitude of snow flux values measured in Antarctica (Amory, 2020).

It is assumed that the wind data under consideration quantify wind speed and direction on a flat surface. Then, according to Courrech du Pont et al. (2024), the dune aspect ratio experimented by the wind determines the wind speed at the crest,

$$u_{\text{crest}} = u_{\text{flat}} \left(1 + \beta \frac{H}{L_D} \right) \quad (7)$$

In this study, $\beta = 6$ (Courrech du Pont et al., 2024), and $H/L_D = \tan(3^\circ)$ is the mean longitudinal aspect-ratio of the snow barchan measured in the field (see Section 4 and Figure 4d). As discussed in the Intro-

duction (Section 1), using those values we have a fractional speed-up ratio $\delta = \beta H/L_D \approx 0.3$. Flow deflection is neglected, so the snow flux at the crest of snow barchans is considered to be in the same direction as on the flat bed. The transport rate at the crest of a snow barchan is then determined by substituting the wind speed, u , measured in the field with the anemometers (Section 2.2) into Equation 7, and the estimated value of u_{crest} into Equations 5 and 6. All main equations and variables are referenced in Table 1.

Table 1 Key parameters and governing equations used.

Name	Parameter	Value
Wind speed	u	Measured
Grain diameter	d	$100 \mu\text{m}$
Grain density	ρ_p	917 kg m^{-3}
Air density	ρ_{air}	0.95 kg m^{-3}
Drag length	L_{drag}	$(\rho_p/\rho_f)d = 0.096 \text{ m}$
Particle fall velocity	u_f	0.75 ms^{-1}
Static threshold wind speed	u_*^{th}	0.26 ms^{-1}
Aerodynamic roughness	z_0	1 mm
Von Karman constant	κ	0.4
Friction velocity	u_*	$\frac{u\kappa}{\log(z/z_0)}$
Flux on flat bed	Q_{flat}	$\frac{\rho_{\text{air}}}{g} \frac{u_f}{u_*^{\text{th}}} u_*^2 (u_* - u_*^{\text{th}})$
Flux at crest	Q_{crest}	$Q_{\text{flat}}(1 + \gamma)$
Flux-up ratio	γ	$(Q_{\text{crest}} - Q_{\text{flat}})/Q_{\text{flat}}$
Dimensionless coefficient	β	6
Speed-up ratio	δ	$\beta H/L_D \approx 0.3$
Saturation length	L_{sat}	$2.2 L_{\text{drag}} \approx 0.2 \text{ m}$
Surface of barchan	S	$\frac{L_D H}{2}$
Turnover time	τ_{theory}	$\frac{S}{Q_{\text{crest}}}$
Left horn length	L_2	Measured
Right horn length	L_1	Measured
Length of horns	L_{horns}	$\frac{L_1 + L_2}{2}$
Width	W	Measured
Height	H	Measured
Length of body	L_{body}	Measured
Asymmetry	a	$\frac{L_1}{L_2}$
Length of dune windward slope	L_D	Measured
Migration rate	c	$\frac{Q_{\text{crest}}}{H}$ and measured

4 Snow barchan morphodynamics

4.1 Snow barchan morphology

Over the six years of the study (2017–2022), a total of 51 events of barchan formation were recorded by the NIR camera (Table 2). Seven populations of snow barchans could not be analyzed due to visibility issues. The duration of the remaining 44 events ranged from 4 hours to 3 days. During these events, 324 distinct active barchans were measured at different times on the orthorectified images, resulting in 969 individual morphology measurements.

Although the height of snow barchans can be occasionally ascertained through the analysis of their shadows, it is often impossible to accurately estimate this height from orthorectified images. Therefore, the analysis of NIR camera images is supplemented by field data estimating the height, H , of the dunes, as well as their length, L_D , and width, W_D . As shown in Figure 4a,b, these direct measurements were taken by placing a graduated metal plate into a barchan and extracting the profile. The linear relationships between height, length, and width, as determined by the measurements (Figure 4c,d), allow for the estimation of the

Table 2 Barchan events at Concordia Station during 2017–2022. No events occurred in 2019 or 2020. Hours are in UTC. Some events could not be analyzed due to the lack of light.

2017-2018			2021-2022		
Event start time	Duration (h)	Analyzed	Event start time	Duration (h)	Analyzed
2017/01/27 22h	13	Yes	2021/01/03 02h	07	Yes
2017/01/31 05h	29	Yes	2021/01/18 03h	38	Yes
2017/02/21 05h	08	Yes	2021/01/24 23h	16	Yes
2017/02/22 22h	12	No	2021/02/13 00h	33	Yes
2017/04/06 01h	06	Yes	2021/02/19 00h	12	Yes
2017/09/26 02h	07	Yes	2021/03/24 06h	29	Yes
2017/11/02 17h	20	Yes	2021/03/27 22h	12	Yes
2017/11/03 18h	19	Yes	2021/04/03 00h	56	Yes
2017/11/05 01h	11	Yes	2021/09/21 00h	07	Yes
2018/01/11 01h	09	Yes	2021/09/22 00h	09	Yes
2018/01/13 15h	19	Yes	2021/10/03 02h	08	No
2018/01/28 07h	07	Yes	2021/10/06 07h	52	Yes
2018/02/05 04h	07	No	2021/11/15 15h	18	Yes
2018/02/08 00h	10	No	2021/11/18 05h	29	Yes
2018/02/19 21h	16	Yes	2022/01/01 23h	11	Yes
2018/03/08 03h	81	Yes	2022/09/03 00h	30	Yes
2018/03/14 01h	09	Yes	2022/10/02 00h	10	Yes
2018/03/17 02h	10	Yes	2022/10/06 05h	54	Yes
2018/04/26 00h	08	Yes	2022/11/23 20h	16	No
2018/05/04 01h	06	Yes	2022/11/26 01h	36	Yes
2018/05/08 02h	04	Yes	2022/12/10 21h	21	Yes
2018/05/11 01h	05	Yes			
2018/08/12 01h	72	Yes			
2018/09/02 00h	09	Yes			
2018/09/21 00h	11	Yes			
2018/10/17 15h	11	Yes			
2018/12/11 05h	06	No			
2018/12/15 03h	07	No			
2018/12/21 23h	35	Yes			
2018/12/24 00h	11	Yes			

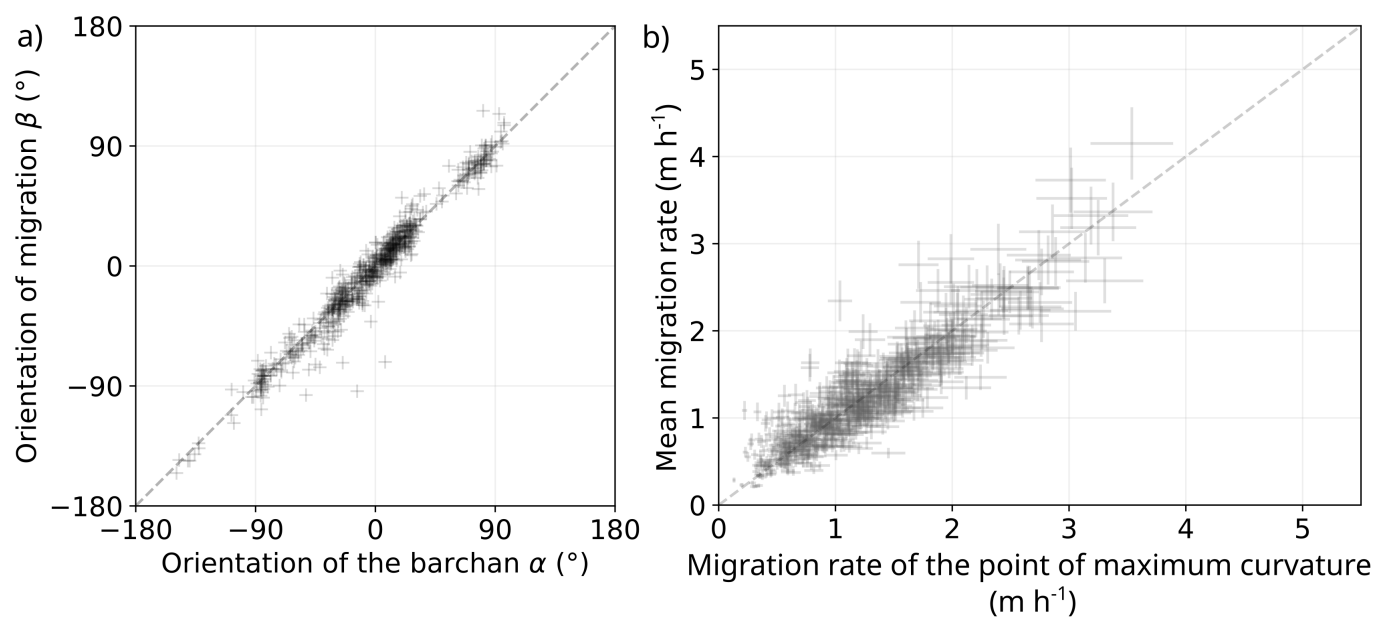


Figure 3 (a) Comparison between the orientation of barchans, α , and their migration direction, α_m . (b) Comparison between the migration rate estimated from the point of maximum curvature at the bottom of the slip face and the mean migration rate estimated from all the other reference points. Dashed black lines represent 1:1 relationships in (a) and (b).

transverse, $H/W_D = \tan(4^\circ)$, and the longitudinal, $H/L_D = \tan(3^\circ)$ aspect ratios of the snow barchans.

The transverse slopes for snow barchans (4°) are significantly lower than those estimated on sand barchans,

which is typically 11° . Their longitudinal slopes are also lower, than the 4° – 11° range observed for sand barchans (Hesp and Hastings, 1998).

In this paper, the height of snow barchans is estimated from their width measured on orthorectified images using $H = W_D \tan(4^\circ)$.

A full analysis of the data shows that the total length, L , of the barchans ranges from 0.3 to 13 m, with 80% (10th–90th percentile) falling within the range of 2.6 to 5.7 m (Figure 5a). Their width W varies from 0.45 to 7.5 m, with 80% ranging from 0.95 to 2.4 m. Despite the observed dispersion, there is a discernible linear relationship between the overall length L and width W of the snow barchans (Figure 5a). The best fit of a linear regression model gives $W \sim 0.39L$, $r^2 = 0.46$, with a RMSE of 0.7 m. This relationship is similar to the one found by Filhol and Sturm (2015) in Alaska, $W \sim 0.42L$, $r^2 = 0.52$ with a RMSE of 0.71 m, illustrating the consistency of snow barchan morphologies across different cold environments. However, when barchans are migrating over sea ice and not snow, such as in subarctic Unalakleet (Alaska) (Ritchie et al., 2023), the relationship differs, with $W \sim 1.2L$, $r^2 = 0.66$ with a RMSE of 1.0 m. As mentioned in the previous paragraph, these morphologies differ from those of sand barchans on Earth, for which $W \sim 1.7L$ (Andreotti et al., 2002), thereby emphasizing once again the more elongated shape of snow barchans. An important observation is that, irrespective of the environment, a minimum size of approximately $27 L_{\text{drag}}$ is consistently observed for barchans. Based on the measurements presented here, this corresponds to a minimum size of approximately 2.6 m for snow barchans at Concordia Station. Below this minimum size, the barchans disappear as they become longer and flatter.

In most cases, barchans are not perfectly symmetrical. The asymmetry is quantified by the ratio $a = L_1/L_2$ between the length of the two horns (defined in Figure 2, with L_1 the right horn and L_2 the left horn). This ratio has a median value of 0.75, with 80% (10th–90th percentile) of the measurements ranging between 0.2 and 2. The ratio, L_{horns}/W , between the mean horn length, $L_{\text{horns}} = (L_1 + L_2)/2$, and the width of the snow barchans ranges from 0.1 to 1.5 (Figure 5b). The ratio, L_{body}/W , between the body length and the width ranges from 0.2 to 5.3. It has a mean value of 2.2, which is considerably higher than the mean values observed for sand barchans in terrestrial and Martian dune fields, which are 0.72 and 0.92, respectively (Sherman et al., 2024). In both types of environment, sand barchans also have maximum L_{body}/W -values that rarely exceed 3, whereas this occurs in 24% of cases for snow barchans. Hence, according to the classification proposed by Bourke and Goudie (2009), snow barchans can be categorized as slim ($L_D/W \leq 0.375$), normal ($0.375 < L_D/W < 0.625$), pudgy ($0.625 < L_D/W \leq 0.875$) or fat ($L_D/W > 0.875$). Figure 1e displays an example of a slim barchan, where $L_D/W = 0.3$, $L_{\text{body}}/W = 0.6$, and $L_{\text{horns}}/W = 0.4$, and Figure 1c of a fat barchans, where $L_D/W = 0.9$, $L_{\text{body}}/W = 1.8$, and $L_{\text{horns}}/W = 0.5$. Such a wide range of morphologies highlights the diversity of conditions under which snow barchans form, de-

velop, and stop moving over time at the study site.

Insights into snow cohesion kinetics can be obtained by comparing the morphological parameters of snow barchans with meteorological data recorded at the time of the observations, when barchans are migrating. As an example, the maximum width of barchans is found to vary depending on temperature and wind speed (Figure 6). Large barchans (width over 3 m) were formed under median wind speed of 6 m s^{-1} (10th–90th percentiles of 5 m s^{-1} to 7.8 m s^{-1}), and median temperature of -31°C (10th–90th percentiles of -52°C to -23°C), while barchans with width under 3 m have median wind speed of 5.5 m s^{-1} (10th–90th percentiles of 4.2 m s^{-1} to 7.2 m s^{-1}), and median temperature of -48°C (10th–90th percentiles of -63°C to -28°C). This suggests that, at Concordia Station, snow barchans reach larger sizes at higher wind speed and in warmer conditions.

4.2 Migration rate of snow barchans

Over all the barchan events, we identified the migration of 242 dunes, resulting in 639 measurements of migration rate from successive orthorectified images (Figure 7d). Snow barchan mobility is associated with mean wind speed ranging between 3.8 and 8.8 m s^{-1} at 1 m height. The migration rate, c , of the barchans at Concordia Station ranges between 0.1 and 3.5 m h^{-1} , with 80% (10th–90th percentile) of the measurements ranging between 0.6 and 1.6 m h^{-1} . These migration rates are consistent with values previously observed in East Antarctica (Kuznetsov, 1960) but generally below those reported by Kochanski et al. (2019) in Colorado, where the snow barchan velocity can reach a mean velocity of 2.52 m h^{-1} , compared to the lower average over all the events at Concordia of 1.2 m h^{-1} . However, a comparison of these migration rates across different sites and at different periods of the year is not straightforward, because the rate depends simultaneously on the snow flux at the crest of the dune (i.e., wind speed and snow properties which vary both spatially and seasonally) and on dune size (Equation 2).

It is possible to compare two independent estimates of the snow flux at the crest, Q_{crest} , one derived from the dune properties measured in the field, cH , the other one, Q_{flat} , derived from the wind speed data. Given the limited barchan height measurements, we assumed a constant transverse slope value of 4° (Section 4), thereby allowing the estimation of dune height using $H = W_D \tan(4^\circ)$. Figure 7b shows the relationship between cH and Q_{flat} . A linear fit to the data gives

$$cH = 1.9 Q_{\text{flat}} \quad (8)$$

from which it is possible to conclude that $\gamma = 0.9$ using Equation 4. This value of the fractional flux-up ratio is consistent with the value of the fractional speed-up ratio under consideration, $\delta = 0.3$ (Section 3.3), and the low longitudinal dune aspect-ratio of snow barchans. Thus, based on Equations 2 and 4, the various populations of snow barchans observed at Concordia Station offer new quantitative insights into snow transport rates, not only at the crest of dunes, but also on surrounding areas taking into account the impact of snow bedforms on flow

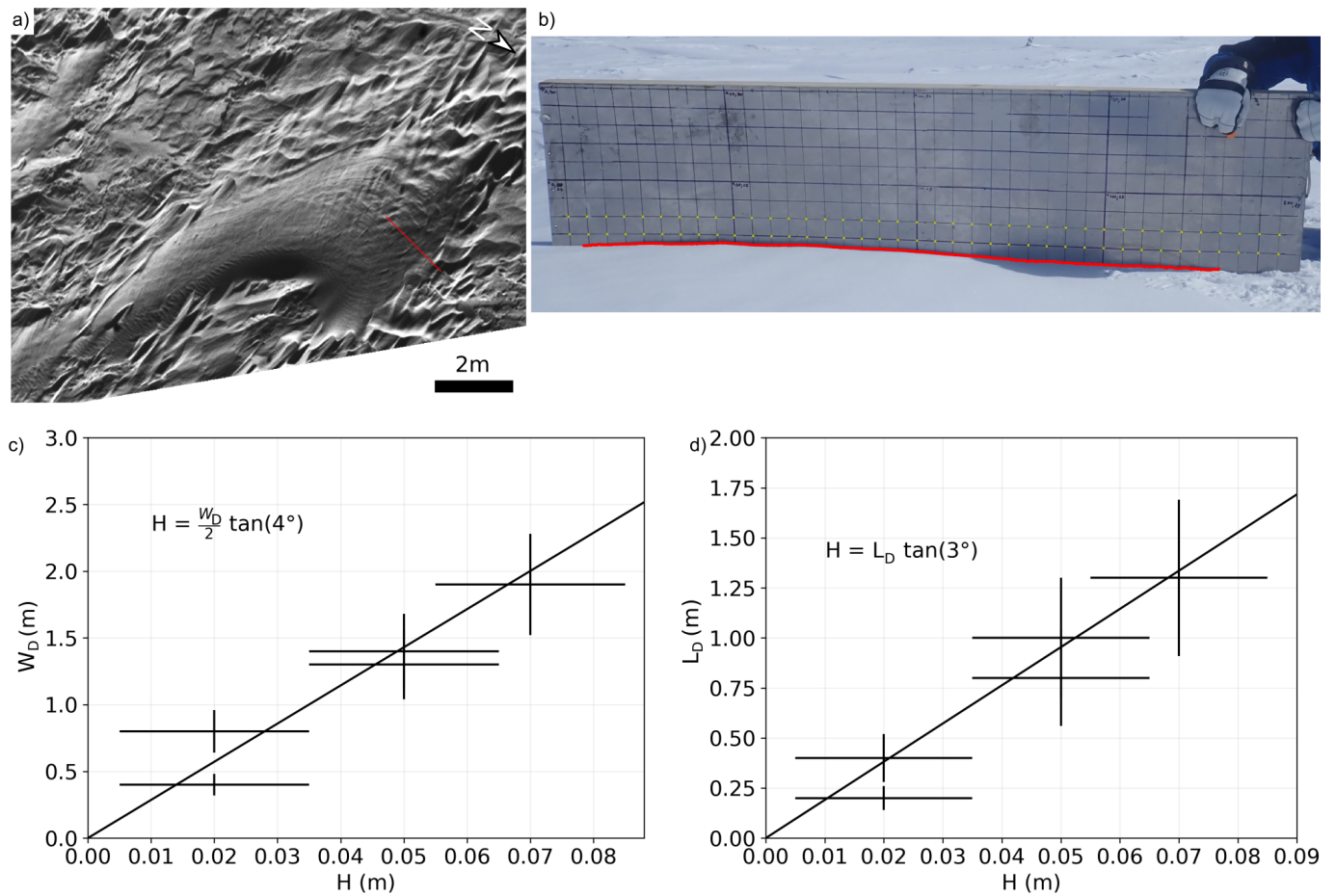


Figure 4 Relationships between snow barchan length, width, and height. (a) Orthorectified image of a barchan from which the measurements in (b) were taken. The red line shows the measurement transect. (b) *In situ* measurements of the barchan elevation profile along the red line. (c) Relationships between barchan height and transverse width. (d) Relationship between barchan height and windward length. Solid black lines in (c) and (d) represent corresponding fitted trends.

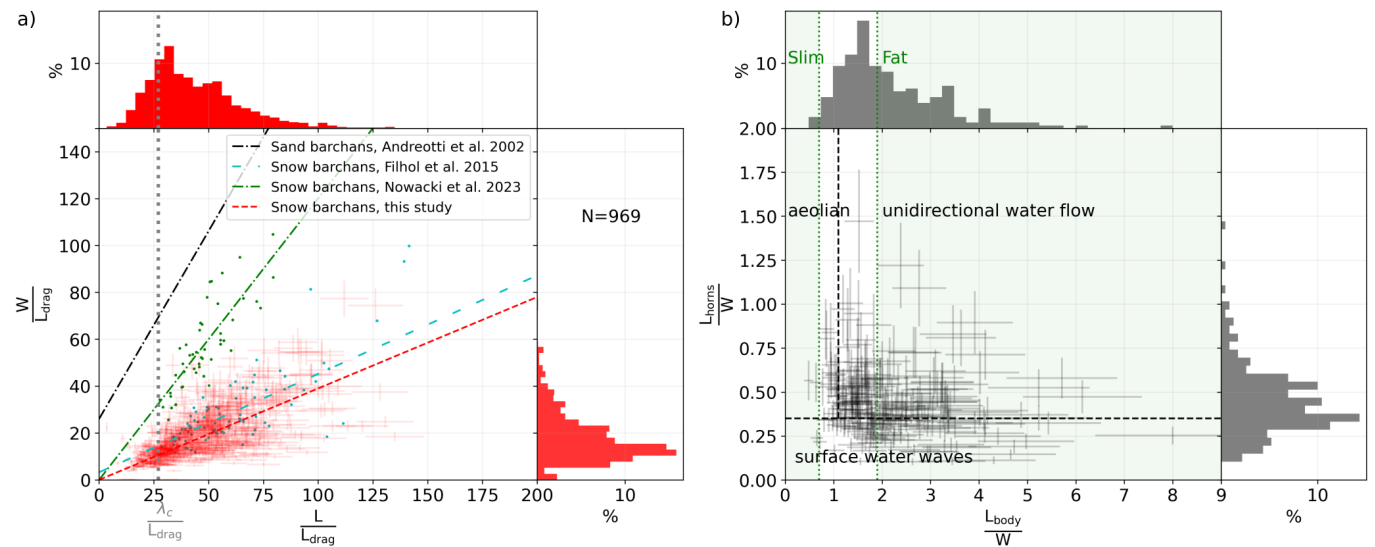


Figure 5 Comparative analysis between snow and sand barchan dimensions. (a) Relationship between the overall length and width of the snow barchans at Concordia Station. These dimensions are normalized by the drag length of snow ($L_{drag}^{snow} \approx 0.1$ m) to be compared with their counterpart for sand barchans ($L_{drag}^{sand} \approx 0.5$ m). Red, cyan and black lines show the best-fit of a linear regression model to the barchan data in Concordia Station, Alaska (Filhol and Sturm, 2015), and sand deserts (Andreotti et al., 2002), respectively. The gray dotted line indicates the minimum length derived from the dune instability, $\lambda_c \approx 27L_{drag}$. Cyan points are from Filhol and Sturm (2015). (b) Relationship between the body length and the mean horn length of the snow barchans at Concordia Station. These dimensions are normalized by the overall width to be compared with the classification proposed by Endo et al. (2005), which distinguishes aeolian barchans from subaqueous barchans under unidirectional water flow or surface water waves.

intensity. To evaluate the robustness of γ , we evaluated its sensitivity to the threshold wind speed by varying

it between 4 m s^{-1} to 8 m s^{-1} , which produced γ values ranging between -0.3 and 3.5 . Similarly, we also varied

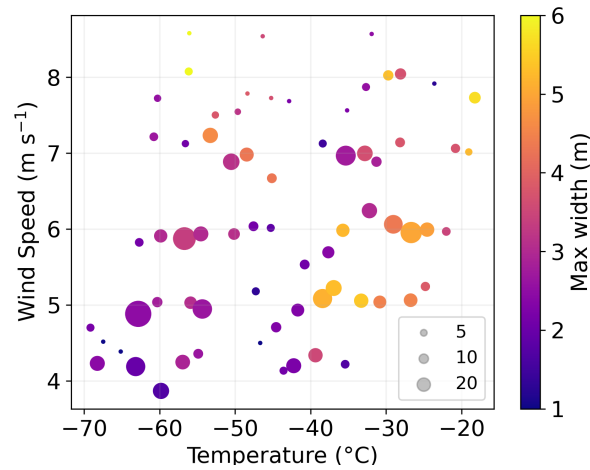


Figure 6 Maximum width of snow barchans with respect to air temperature at 1 m height and wind speed at 10 m. The size of the dot gives the number of data for this temperature and wind speed.

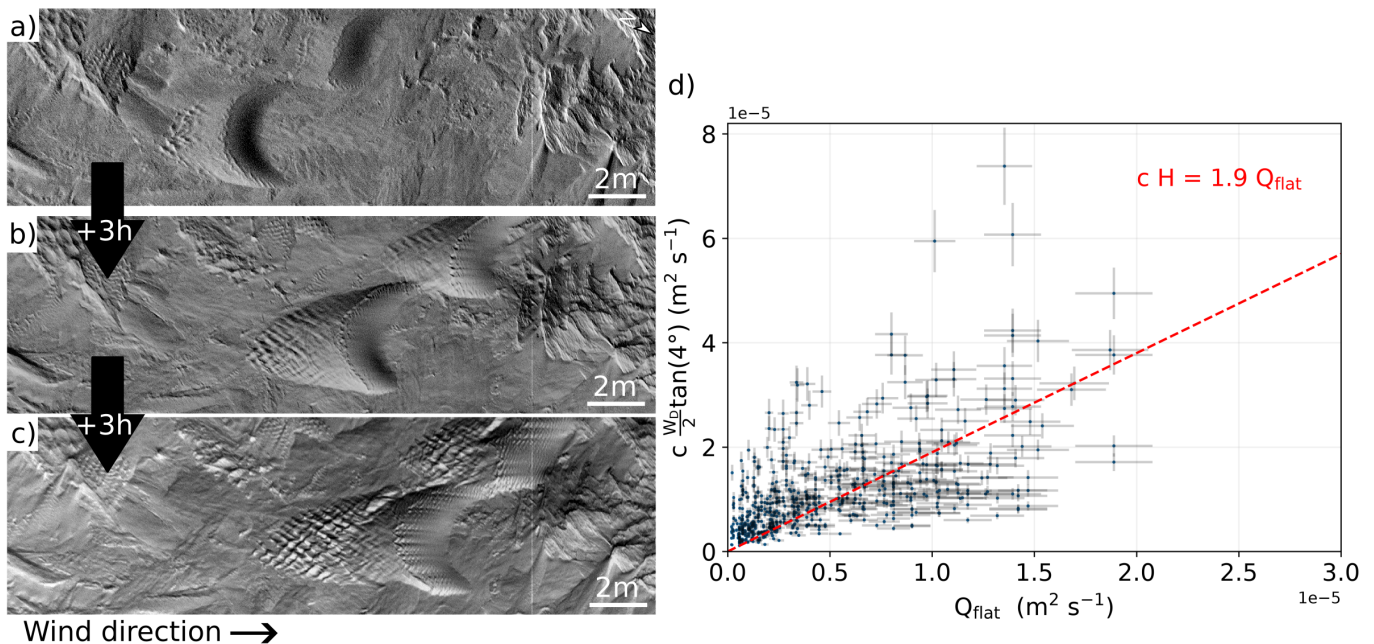


Figure 7 Migration rate of snow barchans. (a-c) Orthorectified images of the migration of an individual barchan on 18 January 2021 captured by the NIR camera at 7h, 10h, and 13h UTC. (d) Relationship between the snow flux predicted from field-measured data during migration, $cH = cW_D \tan(4^\circ)/2$, and derived from the wind data using the procedure described in Section 3.3. The dashed line is the best-fit of a linear regression model to the data. Using Equations 2 and 4, it can be deduced that $\gamma = 0.9$.

the particle terminal fall velocity between 0.5 m s^{-1} to 1.4 m s^{-1} , resulting in γ values between 0.26 and 2.54. As expected γ is sensitive to the flux parameterization, especially to threshold wind speed which is expected to vary between events.

4.3 Reorientation of snow barchans

Three barchan events in this study clearly exhibit changes in dune orientation and migration direction (Figures 8 and 9). These events last between 11 and 34 hours, with one event in March 2018 involving two successive reorientations (Figure 9c and 9d). Although certain populations of barchans are partially obscured by darkness, we estimate that the full reorientation of snow dunes lasts between 5 and 11 hours. For the most spectacular case, snow barchans adopted a new orienta-

tion within 7 hours, forming an angle of nearly 70° with the previous orientation (Figures 8 and 9a).

As shown in Figure 8, all the changes in barchan orientation and migration direction are associated with similar changes in wind direction, leading to complete reworking of the dune shape. Between phases of constant-direction migration, during which the dunes retain their crescent shape (Figure 7a-c), we observed transitional periods of crest reversal (Gao et al., 2021), during which the classic barchan shape is lost and then restored.

The first effect of the new wind direction is to blow away the horns, the lowest parts of the dune. At the same time, a new crest line forms perpendicular to the flow on the highest part of the dune body. Then, the associated windward slope becomes increasingly gentler, and a slip face develops on the lee slope develops as the

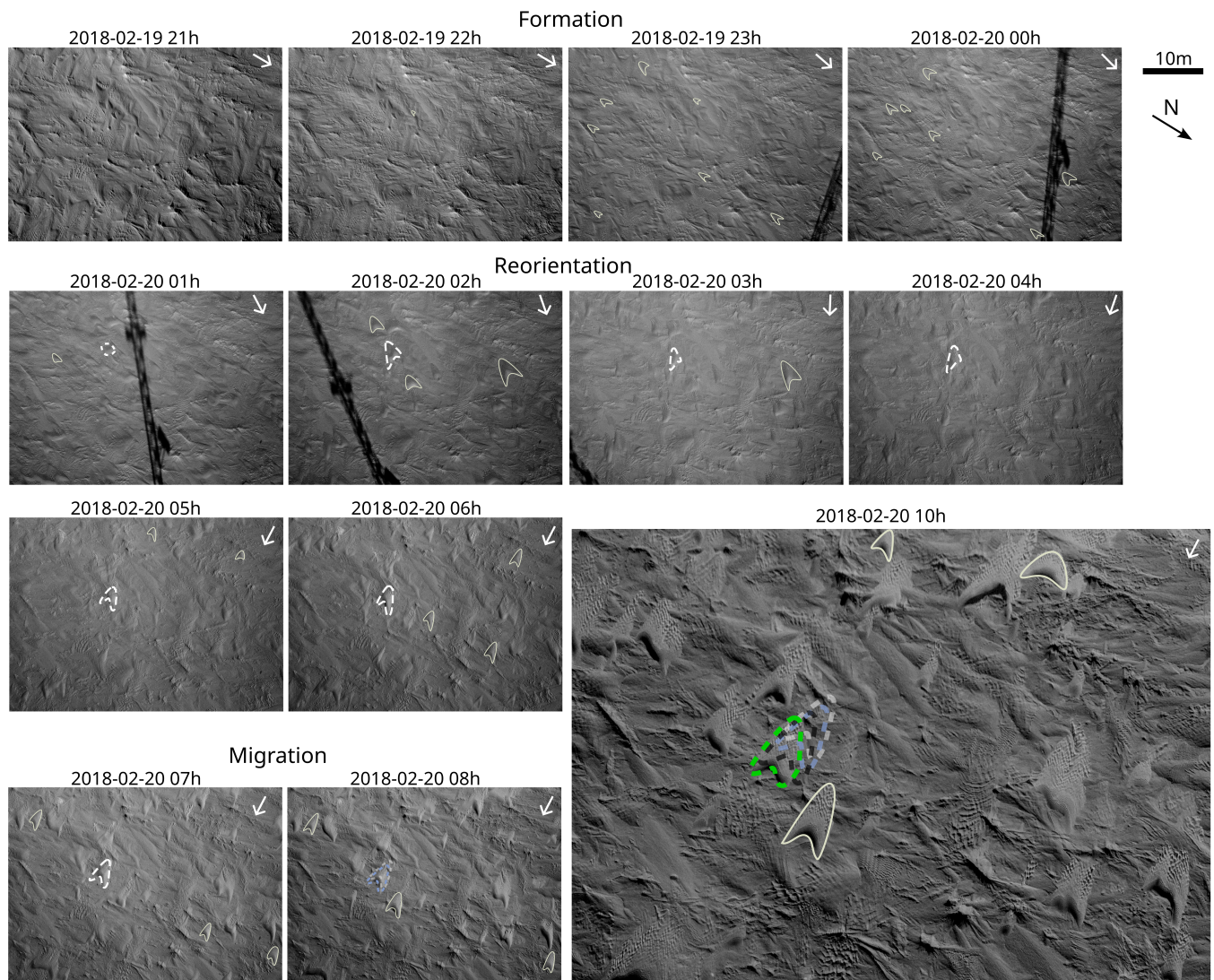


Figure 8 Orthorectified images during an event of snow barchan formation, migration and reorientation. The white arrow indicates the wind direction at the image time. To facilitate the visualization of the dynamics of snow barchans, some are delineated by solid lines, and the evolution of a single barchan can be tracked by dotted lines.

crest migrates downstream. According to Equation 2, this process is extremely rapid after wind reversals and slows down as the slip face grows in height (Gao et al., 2021). Thus, as a result of wind reversal, the barchans initially appear oblong with no horns (contours in Figure 8e). Subsequently, the horns aligned in the new direction of the wind reappear (contours in Figure 8f). However, the barchan clearly remains asymmetric until the reorientation process is complete, when the transverse snow fluxes allow all the longitudinal sections of the barchan to migrate at the same speed in the new wind direction.

4.3.1 Characteristic time of snow barchans

The snow dune populations observed at Concordia Station enable the estimation of the characteristic time for barchan reorientation, a time often inaccessible in the case of sand dunes, whose dynamics are on the order of years. In the absence of cohesion, sand barchans grow too large, resulting in excessively long response times to changes in transporting wind direction.

Qualitatively, the characteristic barchan reorienta-

tion time can be deduced solely from the morphology of barchans. As illustrated in Figure 8, dunes that have not had sufficient time to adapt to the new wind direction exhibit a transitional shape indicative of crest reversal. To obtain a quantitative estimate, we determined the characteristic time τ_{obs} of reorientation of snow barchans from both the wind data and the dune shape by examining, for each dune, the duration required for the integrated flux direction to align with the new barchan orientation. Using the snow transport vectors derived from Equation 6 at each time step of the wind data, here we compared the barchan orientation to the Resultant Drift Direction (RDD) (i.e., mean flux direction) integrated over different time intervals, ranging from 10 to 400 min. In practice, τ_{obs} is the time delay required for the integrated RDD to coincide with the current orientation of the snow barchan, with a margin of error of $\pm 6^\circ$. Because the wind data are sampled every 10 min, reorientation times shorter than this interval cannot be resolved; conversely, times on the order of a few tens of minutes are detectable as soon as the integrated RDD becomes consistent with the dune ori-

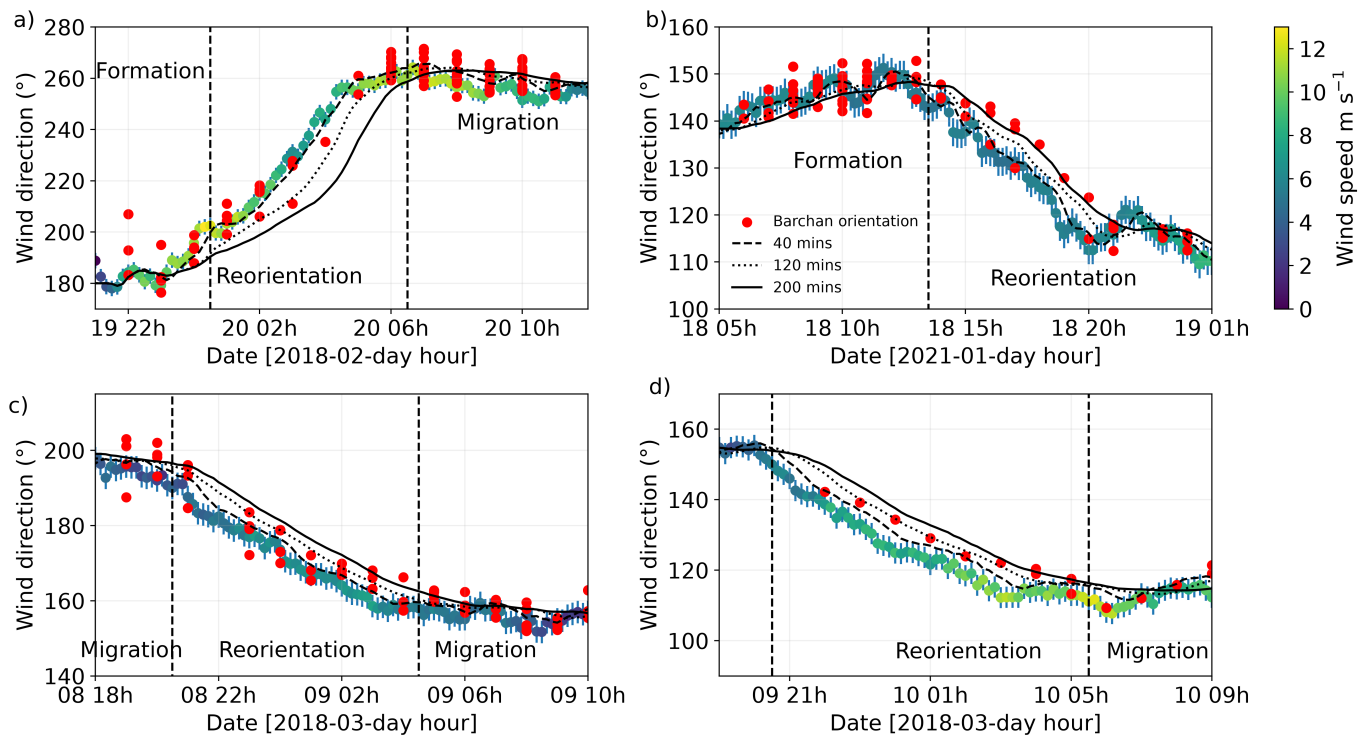


Figure 9 Snow barchan reorientation events at Concordia Station. Wind direction at 1 m height with respect to time during four reorientation events: (a) February 2018, (b) January 2021, (c) first and (d) second reorientation events in March 2018. The color of the markers indicates wind speed, and the red dots the orientation of the barchan. The solid, dashed, and dotted lines correspond to the Resultant Drift Direction (RDD) integrated over 40, 120, and 200 min, respectively. The different stages of barchan evolution are delineated by dashed vertical lines.

entation ($\pm 6^\circ$). As shown in Figure 9, this time delay can reach 350 min. In most cases, the time is much shorter, a few tens of minutes.

These reorientation times are commensurate with the volume of the dunes under consideration. However, the variability of these durations is more surprising when compared to the wind speeds under which the reorientations occur. Indeed, the snow barchans displayed in Figure 9b,c require a mean time of 10 min to adapt to new wind directions under a mean wind speed of approximately 6 m s^{-1} , while those displayed in Figure 9a,d require a longer mean time of 25 min under a higher mean wind speed of approximately 10 m s^{-1} . Because there is no significant difference in dune size among these various dune populations, this apparent paradox in the reorientation time may be attributed to a variation in the static threshold wind speed required for snow transport. This static threshold is known to vary widely both in space and time depending on the snow characteristics (e.g., grain size, He and Ohara, 2017) and environmental parameters (e.g., air temperature, Li, 1997) and is especially sensitive to cohesion (Selmani et al., 2024). However, without direct flux measurements, we cannot constrain the static threshold wind speed in the field where the environmental conditions change, and snow undergoes metamorphism. In our observations, wind speeds measured when snow transport is visible on the barchans range between 5 m s^{-1} to 12 m s^{-1} , indicating that the transport threshold must lie within these values (or be lower), but this threshold is probably variable across events. These values are consistent with previous studies in Antarctica, which report thresholds between 5 m s^{-1} to 12 m s^{-1} depending

on snow cover conditions (e.g., presence of fresh snow), 5.6 m s^{-1} for small particles and 7.2 m s^{-1} for coarser particles or 5 m s^{-1} at Mizuho station (Amory, 2020; Leonard et al., 2012; Nishimura and Nemoto, 2005). The value used here therefore lies on the lower end of the range reported in Antarctic studies, which is consistent with the relatively smaller particle sizes expected at Concordia. Therefore, we used a unique representative mean value over space and time, which might contribute this variability.

4.3.2 Threshold wind speed for snow transport

To estimate the static threshold wind speed and its impact on the observed reorientation time of the snow barchans in Concordia Station, the τ_{obs} value is compared to the dune turnover time, τ_{theory} (Equation 3). The time required for snow barchans to adjust to change in wind direction and align with the new transport direction is expected to scale with τ_{theory} , which can also be regarded as the upper limit of the reorientation time. The τ_{theory} value is here determined from the size of the dunes as measured on orthorectified images and the local wind data. The surface of the central longitudinal dune section is defined as $S = L_D H / 2 = L_D W_D \tan(4^\circ) / 2$. The snow flux at the crest, Q_{crest} , is derived from the local wind speed and the transport law (Equation 6), using the fractional speed-up ratio (Equation 7) to calculate the wind shear velocity at the crest (Equation 5). This snow flux is computed for all static threshold wind speeds of less than 9 m s^{-1} at a height of 10 m, i.e., threshold friction velocity of less than 0.39 m s^{-1} .

The ratio $\tau_{\text{obs}} / \tau_{\text{theory}}$ as a function of the wind thresh-

old speed for transport u_{th} for the different reorientation events is shown in Figure 10. For values of τ_{obs}/τ_{theory} between 0.2 and 0.8, the different reorientation events correspond to narrow ranges of static threshold wind speed. Two events exhibit the same range, from 3.8 to 6.7 m s^{-1} in February 2018, and from 3.2 to 6.4 m s^{-1} on 8 March, 2018. Two others exhibit lower and higher threshold wind speeds, respectively, from 1.4 to 3.9 m s^{-1} in January 2021, and from 3.9 to 8.3 m s^{-1} on 9 March, 2018. Due to the extreme conditions and the rarity of snow transport events, no direct measurements of the threshold wind speed are available for comparison at Concordia Station; thus, our threshold estimate cannot be validated with direct *in situ* observations. Nevertheless, reported static threshold values over the warmer coast of Adélie Coast reveal similar variations, from 5 to 12 m s^{-1} for wind speed measured at an height of 2 m (Amory et al., 2020). The lower values inferred here may indicate the colder conditions at Concordia, with a minimum value of 1.4 m s^{-1} , i.e. a friction threshold velocity of 0.06 m s^{-1} . Interestingly, this value agrees with the classical friction threshold values used in the absence of cohesion for sand grains, $u_*^{th} = \sqrt{\theta_t \Delta \rho g d} = 0.13 \text{ m s}^{-1}$, where d is the grain size (set to 100 μm), $\Delta \rho = (\rho_p - \rho_f)/\rho_f$, and θ_t the critical value of the Shields number (set to $\sqrt{\theta_t} = 0.082$) (Courrech du Pont et al., 2024). Therefore, the formulation of snow flux remains associated with uncertainties, because it is not solely controlled by wind shear; formulation of snow flux also depends on the properties of snow grains at the surface and subsurface, and those properties evolve during snow transport and are therefore intrinsically variable (Sturm and Stuefer, 2013). Consequently, the flux values derived here should be interpreted as approximations of instantaneous transport conditions, constrained by the best available observations and by formulations tailored for snow, but still limited by the transient nature of the material. Therefore, while the formulation of snow flux remains associated with uncertainties, more accurate flux estimates could help refine the constraints on threshold wind speeds inferred from barchan migration. Barchan dynamics can provide an independent constraint on the range of plausible threshold wind speeds and be used as an integrative indicator of snow transport conditions.

4.4 Immobilization of barchans and evolution of the snow surface

For all dune events under investigation, once snow barchans ceased migrating, no further remobilization is observed, even when snow transport resumes shortly after they became immobile. For example, Figure 11 illustrates the conditions recorded during a dune event in November 2022. During the migration phase, barchans move at rates between 1.3 and 2.5 m h^{-1} (Figure 11b,c). However, migration stops on 27 November 2022 at 12:00 UTC, at a measured wind speed of 4.8 m s^{-1} at a height of 1 m. Twenty-seven hours later, on 29 November 2022 at 00:50 UTC, wind speed once again reaches and exceeds 4.8 m s^{-1} , yet the dune remains immobile with

no evidence of snow transport. By 29 November 2022 at 04:00 UTC, when wind speed increases to 6.8 m s^{-1} , snow transport was readily apparent from the formation and migration of new snow patches (highlighted by the white dashed rectangles in Figure 11d). This visible impact of snow transport on surface topography persists until 29 November 2022 at 12:00 UTC, when the wind speed drops under 5.5 m s^{-1} , and no further migration of newly formed snow patches is observed. Thus, the interval between the end of barchan migration and the onset of the next visible transport event is approximately 40 hours. However, despite the snow transport and clearly visible snow deposition, there has been no change in the original barchans (Figure 11c,e).

Similar timescales are observed in other events, such as on 27 January 2017 (Figure S4b), when barchans formed and ceased migrating by 28 January 2017 at 11:00 UTC, under wind speeds ranging from 4.2 to 6.6 m s^{-1} at a height of 65 cm. Snow transport resumed on 31 January 2017 at 05:00 UTC, 78 hours after migration had ceased. The aged barchans remain immobile, while new barchans began to form under mean wind speeds of 5.3 m s^{-1} , with gusts reaching 6.8 m s^{-1} (Figure S4a). Here, as in all the other cases, there was no remobilization of the aged barchans. Instead, new bedforms emerge, grow and migrate according to the duration of the wind event.

As wind events generate new bedforms, immobile barchans remain visible in the landscape for an extended period, gradually disappearing as the snow surface is reworked. The evolution of the surface following a barchan formation event is shown in Figure S4. Following a 13-hour wind event on 27 January 2017, several newly formed snow barchans became immobilized, as described in the previous section (Figure S4b). Nearly two years later, on 31 December 2018, some barchans remained recognizable in the field despite clear change in surface properties (dotted black rectangle in Figure S4c). However, by the following month (Figure S4d), this barchan had become barely discernible, with only the upper part of its main body remaining visible. Three years after its formation, it completely disappeared (Figure S4e). This suggests that barchans can persist in the landscape for multiple years before eventually fading from view, which is consistent with previous estimate of surface snow age at this location (Picard et al., 2019). Such multi-year surface preservation is remarkable and, to our knowledge, unique to the Antarctic Plateau where the combination of extremely low precipitation and low wind speeds prevents snow features from being rapidly buried or eroded. In contrast, at sites such as Summit in Greenland, higher precipitation rates (approximately four times higher than at Concordia Station) quickly bury surface snow features within a few weeks (Zuhr et al., 2021).

5 Discussion

A comprehensive analysis of 969 barchan measurements collected at Concordia Station reveals a wide spectrum of snow barchan shapes and dynamics. Using these active landforms composed of snow as analogs of

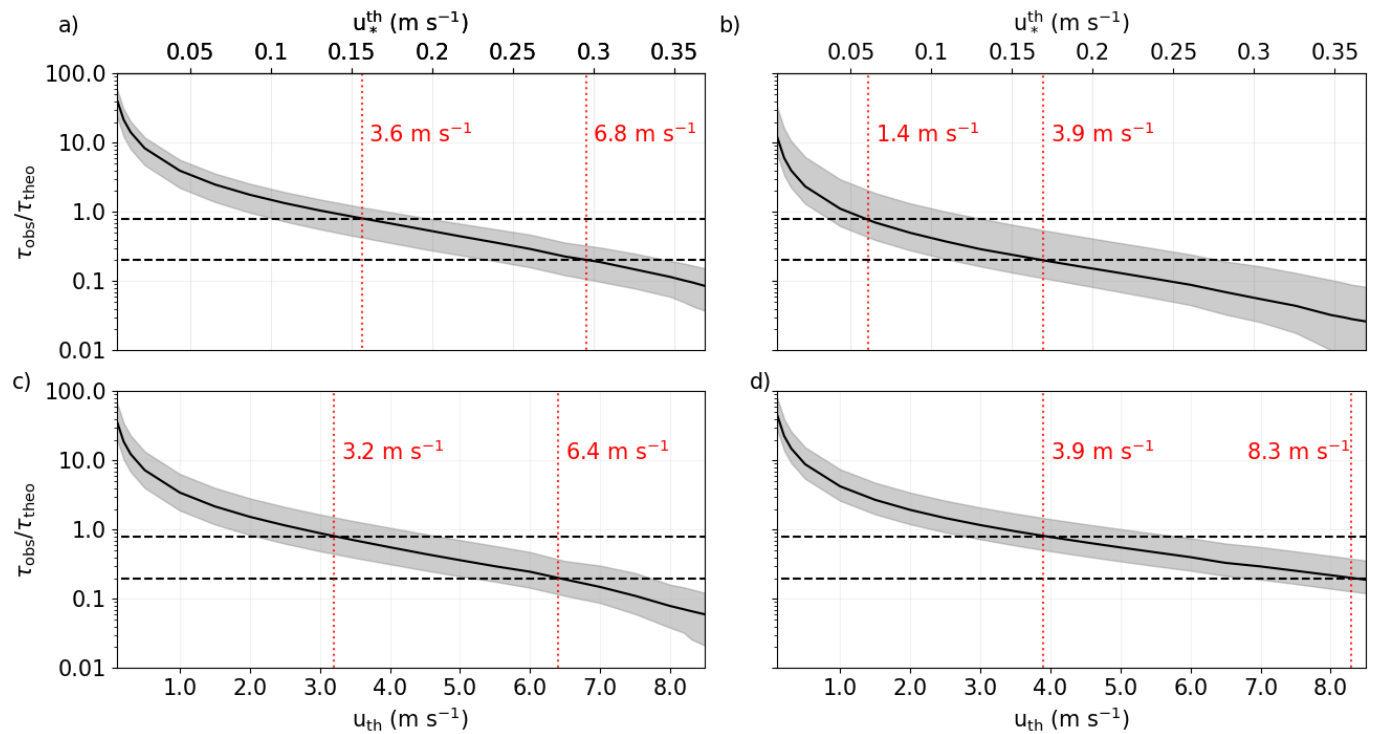


Figure 10 Threshold wind speed for a constant ratio between the reorientation and turnover times of snow barchans. As in Figure 9, four reorientation events are shown: (a) February 2018, (b) January 2021, (c) first and (d) second reorientation events in March 2018. The black line is the median ratio between the reorientation times, τ_{obs} , measured in the field (Figure 9), and the dune turnover time, τ_{theory} , derived from the wind data. The gray shaded region shows the interquartile range. The vertical red lines indicate the range of wind speed threshold values corresponding to the region between the horizontal black lines, which represent $0.2 \leq \tau_{\text{obs}}/\tau_{\text{theory}} \leq 0.8$.

sand barchans in the presence of cohesion, this dataset provides information on the morphodynamical properties of barchans, as well as on the current environmental variables in Antarctica.

5.1 Snow and sand barchans, what can they learn from each other?

The diversity in barchan shapes observed at Concordia Station has also been documented in other environments, including hot deserts on Earth, on Mars, and underwater (Bourke and Goudie, 2009; Sherman et al., 2024; Endo et al., 2005). As with sand barchans, we documented a linear relationship between total length L and width W for the snow barchans under consideration. The width to length ratio for sand is found to be equivalent to that estimated in Alaska over snow, though the atmospheric forcing (precipitation, air temperature) and therefore the properties of snow differ from those in Antarctica. However, under similar atmospheric forcing, changing the underlying medium (e.g., from snow to bare ice) over which snow is transported changes the relationship observed between width and length of snow barchans. This indicates that while snow barchans have unique morphologies shaped by cohesion and substrate, they also provide a benchmark that can be used for understanding how environmental properties influence barchan dimensions.

The morphological classification proposed by Endo et al. (2005), which links barchan shape to different types of flow, does not seem to be relevant for snow barchans. In fact, the observed barchan shapes can be associated with all flow categories (Figure 5b). In

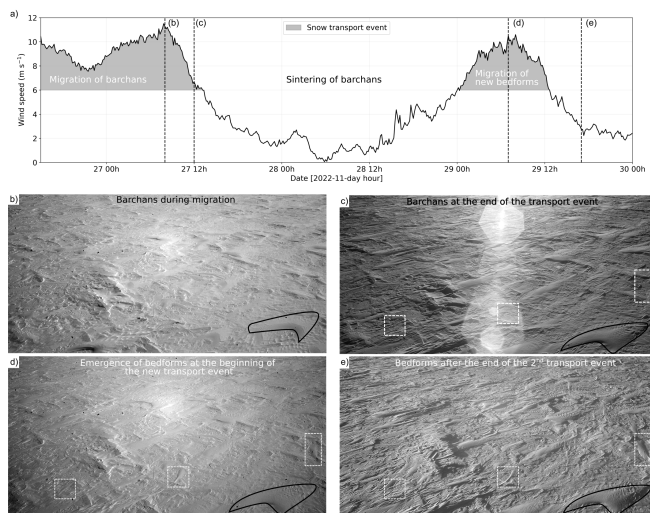


Figure 11 Evidence for cohesion of snow barchans between two transport events. (a) Time series of the wind speed at 10 m height. Raw images taken on (b) 27 November 2021 8h UTC, during an event with barchan migration, (c) 27 November 2021 12h UTC, at the end of an event of barchan migration, and (d) 29 November 2021 7h UTC, during the following snow transport event. A migrating snow barchan during the first snow transport event and stabilized during the second is outlined in black. New mobile snow patches occurring during the second transport event are visible within the white dashed rectangles. (e) Raw image taken on 2021-11-27 17h UTC, after the second snow transport event.

addition, the shape ratio of snow barchans, L_{body}/W , varies from $0.2 \pm 15\%$ to $5.3 \pm 15\%$, exhibiting a wider range than that of sand barchans in hot desert, 0.3 to 1.5, or underwater, 0.6 to 2.9 (Endo et al., 2004). The observed variability in the shape ratio of snow barchans is indicative of the variability in the cohesion and the associated transport threshold, arising from the environmental conditions under which they develop. The more elongated shape of barchans is likely to be influenced by the ratio of the wind velocity to the transport threshold velocity wind for transport. In the limit of small u/u_{th} -values, corresponding to either a low wind speed or a high threshold, the barchan elongates due to the discontinuity in transport that may occur between the immobile upstream base and the crest (Howard et al., 1978; Zhang et al., 2010). Because cohesion increases the transport threshold, it is not surprising that snow barchans are flatter and take a more elongated shape. Similarly, over sea ice in Unalakleet (Alaska), the length-width relationship deviates from that found over snow surfaces, tending instead toward the relationship for sand. Snow transport is strongly influenced by surface properties. On ice, snow can be more easily eroded and redistributed in the absence of frost or hoar. For example, it was observed that barchanoid dunes (which are barchan dunes connected with each other) move faster on glazed snow (Doumani, 1967). Although the available snow supply may be limited, its cohesion to the substrate is weaker, making mobilization more efficient. This reduced threshold for transport likely explains the elongated shapes of barchans observed on sea ice (Liston et al., 2000; Bintanja et al., 2001). However, this behaviour is likely not universal across all sea-ice conditions, because surface conditions of sea ice can vary substantially. The presence of frost, hoar, or other roughness elements may instead inhibit transport and modify dune dynamics.

Depositional landforms such as barchans offer the unique opportunity to analyze, at a macroscopic scale, the influence of cohesion processes on sand and snow transport. In sand, cohesion is largely governed by external factors such as vegetation, electrostatic forces, and/or the presence of fine material that establish solid bridges between grains during dehydration of the particle surface (Rubin and Hesp, 2009; Méndez Harper et al., 2017; Seiphoori et al., 2020; Alkalla et al., 2025a). In contrast, under conditions of extreme hot aridity, the impact of cohesion is often negligible. In snow, cohesion always plays a dominant role. Cohesion arises from different processes, such as van der Waals interactions for small grains, liquid water films and capillary forces, or sintering, the growth of bonds between grains. Because temperatures are generally low ($< -20^\circ\text{C}$) and the air is dry in Antarctica, cohesion relies almost exclusively on sintering. Sintering depends on temperature (snow surface, snow gradient), air humidity, wind, and grain shape and is likely to operate at different rates (Maeno and Ebinuma, 1983) within bedforms compared to cohesion processes in sand that are much more homogeneous spatially. These properties can be analyzed in greater detail by examining dune shape and orientation of snow dunes. In particular, sastrugi, which

are erosional snow bedforms, whose geometry may be indicative of sintering contrast and the snow volume eroded, and also the secondary features (e.g., superimposed bedforms, apparent residual roughness upstream as they migrate), which have not been sufficiently described (Colbeck, 1998; Courrech du Pont et al., 2014; Gao, 2015; Poizat et al., 2024; Moss, 1938).

Snow barchan mobility shows the same dependence on dune height and flux at the crest as sand barchans (Andreotti et al., 2002; Ould Ahmedou et al., 2007b; Ren et al., 2024), with smaller barchans migrating faster, as illustrated in Figure 7. As in sand systems, snow barchans also collide (Hersen and Douady, 2005), and their migration is influenced by other nearby bedforms of similar size, such as sastrugi, which can partially explain the variability we observed because they can stop barchans migration (Kochanski et al., 2019). These interactions, however, remain poorly characterized in snow, and further studies would be needed to quantify the effects of collisions and neighboring bedforms on snow barchan dynamics. However, we observed that snow barchans remain immobile as soon as they stop migrating when the wind speed falls below the dynamic threshold speed for transport, which is the wind speed needed to maintain transport, even when strong wind conditions return a few days later (Figure 11). This non-reactivation of barchan mobility contrasts with the usual dynamics of sand barchans, unless cohesion is involved. This provides an upper limit on the order of days for the snow cohesion processes within barchans which help understand the dominant mechanism governing sintering and constraining its kinematics, because the characteristic timescales of sintering processes span from microseconds to multiple days depending on the specific mechanism.

5.2 Characteristic length scales for snow barchans

According to the theory developed for sand barchans, snow barchans would be expected to exhibit a minimum size of approximately $27L_{\text{drag}} \approx 2.6 \text{ m}$ for a grain diameter of $100 \mu\text{m}$ and grain-to-fluid density ratio $\rho_p/\rho_f = 965$, which is consistent with observations and once again reveals that they rely on the same growth mechanisms as sand dunes (Claudin and Andreotti, 2006; Narteau et al., 2009; Zhang et al., 2014). In addition, the observed dunes have horizontal dimensions of less than 15 m and are significantly smaller than sand barchans. Although it is challenging to establish a direct correlation between these size measurements and environmental variables such as wind speed, the collective analysis of the data indicates the presence of a maximum dune size at Concordia Station that is potentially influenced by the kinematics of cohesion processes. Filhol and Sturm (2015) suggested that sintering is acting against the growth of dunes because snow grains need to be remobilized before being sintered in order for the dune to grow. Therefore, they suggested that sintering is limiting dune growth and age. Sharma et al. (2019) have demonstrated such a dependence between the kinematics of cohesion processes and the barchan

size numerically using a cellular automaton dune model with cohesion. Based on a similar approach, Alkalla et al. (2025b) have refined this result showing that the characteristic time for sintering, τ_s , sets the maximum dune turnover time, thereby imposing an upper limit on dune size that scales with $\sqrt{Q_{\text{crest}} \tau_s}$. From Equation 3 and the windward slope measured in the field (Figure 4c), it is therefore possible to solve for the characteristic time for sintering, $\tau_s = (L^2 \tan(3^\circ)/2)/Q_{\text{crest}}$. For a typical estimated value of the transport rate at the crest of dunes, $Q_{\text{crest}} = 10^{-5} \text{ m}^2 \text{ s}^{-1}$ (Figure 7), and for snow barchans with maximum lengths of 5 and 10 m (Figure 5a) the resulting characteristic times for sintering are approximately 18 hours and 3 days, respectively. Given the uncertainty in flux estimation, including threshold wind speed and parametrization, these values should be interpreted as order of magnitude estimates. Despite these uncertainties, the estimates are broadly consistent with the sintering time scales inferred from observations of barchan mobility, thereby suggesting that snow bedforms may be used as proxies for the quantification of snow processes in environments where such features form.

Finally, the identification of a minimum length scale and a maximum length scale provides a restricted range within which snow dunes are likely to exist. Together with the snow processes, this range of length scales will allow us to explore dune dynamics on short time scales and may be used for focusing on aspects of dune morphodynamics that are often inaccessible on sand dunes.

5.3 Snow barchans as proxies for environmental variables

The challenges in understanding snow sintering arise from the complexity of modeling the interdependent processes occurring in natural snow, which are influenced by environmental factors such as temperature, wind, and air humidity, each of which is interrelated and highly variable over time (Maeno and Ebinuma, 1983; Blackford, 2007). Temperature and grain size are the primary factors driving the formation and enlargement of the ice bridge that develops at contact point between adjacent snow grains, i.e. snow grain neck growth, and sintering rates, with smaller grains and higher temperatures promoting faster sintering. Additionally, repeated particle rebounds during blowing snow events further enhance cohesion (Comola et al., 2019).

At Concordia Station, temperatures generally remain below -20°C in the summer, which is generally associated with low cohesion, low sintering rates (Herwijnen and Miller, 2013), and a low shear velocity for the transport threshold, $u_*^{\text{th}} \approx 0.2 \text{ m s}^{-1}$ (i.e. approximately 3.5 m s^{-1} at 1 m height for 1 mm roughness length) (Hosler et al., 1957; He and Ohara, 2017; Clifton et al., 2006). However, despite these conditions, we did not observe remobilization of barchans, suggesting that sintering for the barchans' snow occurs rapidly within a few days. This could indicate enhanced cohesion due to the wind transport process itself (Sommer et al., 2018, 2017; Szabo and Schneebeli, 2007). However, a key con-

tribution could also result from the presence of small water ice particles, due to sublimation or fragmentation during transport (Nishimura et al., 2014; Nishimura and Nemoto, 2005; Comola et al., 2017). While temperature is generally considered the primary driver of the sintering rate, grain size also plays a crucial role and exhibits an even stronger dependence on sintering rate than temperature (Herwijnen and Miller, 2013).

This dependence could also explain the counter intuitive observation of wider barchans when temperature increase from -70°C to -20°C , because snow would sinter faster at low temperature, leading to smaller barchans. Nevertheless, at such low temperature, temperature can not be used as an effective proxy for sintering. The observed trend for the barchan's size may also be linked to an increase in the available snow rather than a change in cohesion, as higher temperatures are associated with increased precipitation (Schlosser et al., 2017). These questions remain unresolved, underscoring the necessity for further research on the sintering process. The output of this research could lead to a better understanding of snow bedforms and a better characterization of snow surface properties, in the current environment and the geological record. As barchans sinter and remain visible for several months, their presence induces spatial variability in snow accumulation (Pétré et al., 1986). This spatial variability is likely contributing to the variability observed on surface mass balance measurements using stakes, and is even more crucial because mean dune height can be higher than the mean accumulation height. This impacts the surface mass balance and the interpretation of ice cores, particularly by introducing variability in the isotopic composition, which is sensitive to post-depositional processes (Ekaykin et al., 2016).

Cross-hatched and scalloped tails are observed in both Concordia and Alaska (Figures 1, 2, 4, 7, 8 in this work and Figure 11 in Filhol and Sturm, 2015). These features may indicate redistribution of snow and its erosion and possible sintering processes during barchan migration, although their origins and precise roles remain unclear. Although these features are frequently present at Concordia, we did not observe them systematically. They have no known equivalent in sand barchans and therefore, they warrant further investigation.

To better constrain the relationships among barchan morphology, wind speed, and snow flux, additional data from different locations with varying snow properties would need to be compared. Given the broad dispersion observed in our data (Figure 5), such comparative studies would also be critical for establishing the dependence of snow transport on various environmental parameters, and clarifying the previously documented variability of shapes in barchan fields (Filhol and Sturm, 2015). Snow transport is complex and influenced by time-dependent changes in snow properties, such as sintering, fragmentation, and sublimation, which can evolve over the course of a single transport event. Sintering, in particular, can rapidly modify inter-particle cohesion, thereby affecting both sediment availability and the effective transport threshold. In addition, spa-

tial variability in snow supply and interactions with surrounding bedforms (e.g., sastrugi) can locally enhance or inhibit transport. These combined effects likely account for a significant part of the observed dispersion. This approach based on the dynamics of depositional and erosional aeolian landforms could facilitate the characterization of the snow surface.

6 Conclusion

We document the morphology and migration of snow barchans near Concordia Station, Antarctica, over a period of six years. Our observations reveal that barchans are frequently encountered at the site, with 51 events recorded during the summer and likely even more during the winter months. In addition to unidirectional migration, we observe 3 different cases of snow barchan reorientation in response to changes in wind direction. Such reorientations highlight the rapid adaptation of barchans to changes in transporting wind direction, as well as the importance of snow flux and barchan morphology on the duration of these reorientations. Eventually, these barchans' snow undergo sintering processes, allowing them to remain visible on the surface for several months, and in some cases, for more than a year. In agreement with the observations of snow barchan mobility, a characteristic sintering time scale on the order of one day is deduced from dune dimensions and the snow fluxes derived from wind data.

Similar relationships between morphological parameters and dynamics are observed across sand, underwater, and snow barchans. The dispersion in the data is likely driven by sintering processes, which emerge as a critical factor in advancing our understanding of snow barchan morphodynamics. A deeper exploration of these processes would be needed to improve our knowledge of snow surface properties, and advance studies on snow barchans and cohesive bedforms. Such investigations will contribute to broader research on snow surface properties, with significant implications for climate studies and the description of snow accumulation processes.

Author Contribution Statements

M. Poizat, J. Alkalla, C. Narteau, L. Arnaud, G. Picard conceptualized the research. M. Poizat, J. Alkalla, C. Narteau developed the methodology. M. Poizat, J. Alkalla conducted data analysis. S. Filhol validated the study. Formal analysis was carried out by M. Poizat and J. Alkalla. Investigation was conducted by M. Poizat, G. Picard, E. Lefebvre, L. Arnaud, and D. Nowacki. Resources were provided by M. Poizat, E. Lefebvre, L. Arnaud, G. Picard, C. Narteau, and D. Nowacki. M. Poizat prepared the original draft. J. Alkalla, E. Lefebvre, L. Arnaud, G. Picard, S. Filhol, C. Narteau, and D. Nowacki contributed to review and editing. Visualization was performed by M. Poizat. Supervision was provided by G. Picard, L. Arnaud, and C. Narteau, who also oversaw project administration. Funding was acquired by G. Picard, L. Arnaud and M. Poizat.

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Land Recognition

After consulting relevant resources and checking with the relevant local communities, the authors have confirmed that the lands containing their institutions and all work sites associated with this study do not have cultural or historical significance to a particular Indigenous group.

Data and Codes Availability

Wind data and orthorectified images from Concordia Station are available from Poizat et al. (2026).

Alaska data from Filhol (2020).

Unalakleet (Alaska) data from Ritchie et al. (2023).

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Conflict of Interest Disclosure

The authors have no competing interests.

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Declaration on Artificial Intelligence Use

During manuscript preparation, generative AI tools Grammarly Editor (web application, continuously updated; version current as of 01 November 2025) were used to improve grammar, clarity, and coherence of the text. All AI-generated suggestions were reviewed, revised as needed, and approved by the authors to ensure accuracy and maintain the integrity of the scientific content.

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