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Brief communication: Rare ambient saturation during drifting snow occurrences in coastal East Antarctica

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Abstract. Sublimation of snow particles during transport has been recognized as the main ablation process on the Antarctic ice sheet. The resulting increase in moisture content and cooling of the ambient air are thermodynamic negative feedbacks that both contribute to increase the relative humidity of the air, inhibiting further sublimation when saturation is reached. This self-limiting effect and the associated development of saturated near-surface air layers in drifting snow conditions have been mainly described through modelling studies and few field observations. A set of meteorological data including drifting snow mass fluxes and vertical profiles of relative humidity collected at site D17 in coastal Adelie Land (East Antarctica) during year 2013 is used to study the relationship between saturation of the near-surface atmosphere and the occurrence of drifting snow in a katabatic wind region among the most prone to snow transport by wind. Atmospheric moistening by the sublimation of the windborne snow particles generally results in a strong increase in relative humidity with the magnitude of drifting snow and a decrease of its vertical gradient, suggesting that windborne-snow sublimation can be an important contributor to the local near-surface moisture budget. Despite a high incidence of drifting snow at the measurement location (61.3 % of the time), saturation, when attained, is however most often limited to a thin air layer below 2 meters above ground. The development of a near-surface saturated air layer up to the highest measurement level of 5.5 m is observed in only 9.6 % of the drifting snow occurrences or 5.9 % of the time and mainly occurs in strong wind speed and drift conditions. This relatively rare occurrence of ambient saturation is explained by the likely existence of moisture-removal mechanisms inherent to the katabatic nature of the boundary-layer flow that weaken the negative feedback of windborne-snow sublimation. Such mechanisms, potentially quite active in katabatic-generated windborne-snow layers all over Antarctica may be very important in understanding the surface mass and atmospheric moisture budgets of the ice sheet by enhancing windborne-snow sublimation.

1. Introduction

Drifting and blowing snow, respectively defined as an ensemble of snow particles raised from the ground at a height below and above 2 meters, occur frequently over windswept areas of the Antarctic continent. Erosion through divergence of drifting and blowing snow transport and concurrent sublimation of particles during transport currently represent the main ablation processes on the ice sheet (van Wessem et al., 2018). When the shear stress exerted by the wind on the snow surface exceeds the threshold value for erosion, particles become mobile and periodically bounce on the surface in a motion mechanism referred to as saltation. In even stronger winds, saltating particles are entrained from the top of the saltation layer by turbulent eddies and enter into suspension without contact with the surface.

The particles transported through saltation and suspension during drifting and blowing snow occurrences interact with the ambient air and influence the thermodynamic structure of the low-level atmosphere. Mass loss experienced by windborne snow particles through sublimation releases water vapour and removes heat from the surrounding air. Both processes contribute to an increase in relative humidity of the air in an inherently self-limiting fashion (Déry et al., 1998; Mann et al., 2000; Bintanja, 2000), eventually inhibiting further sublimation when saturation is reached. Since the mass concentration of windborne snow particles decreases rapidly with height above the snow surface, windborne-snow sublimation leads to the development of a downward sensible heat flux together with an upward latent heat flux that can balance each other in strong wind conditions (Bintanja, 2001a). Moisture exchange also occurs between the snow-covered surface and the atmosphere through surface sublimation but at much lower rates than windborne-snow sublimation because of the greater exposed surface area and the continuous ventilation of snow particles in the air (Schmidt, 1982).

The thermodynamic effects of windborne-snow sublimation are physical limitations to accurate determination of sublimation rates from automatic weather station data. The usual Monin-Obukhov similarity theory and classical bulk relationships cannot be considered valid in transport conditions since the atmospheric surface layer contains a moisture source and a heat sink (Bintanja, 2001b), implying that the requirement of vertical constancy in turbulent fluxes is not verified. In addition, the well-known profile method commonly employed to compute turbulent heat fluxes can become hardly applicable in drifting snow because vertical moisture and temperature gradients are weak due to windborne-snow sublimation and turbulent mixing, raising instrumental accuracy as a large source of uncertainty which strongly amplifies with wind speed (Barral et al., 2014).

The rate of windborne-snow sublimation both affects and depends on the mass concentration of windborne snow particles. It is also interdependent with the temperature and relative humidity gradients across the transport layer, since the water vapour removed from each particle must be compensated by a heat transfer to the particle. In the absence of direct turbulence measurements and despite the instrumental and calculation limitations mentioned above, this suggests that near-surface meteorological profiles can however provide information on the effect of snow transport on the moisture budget of the lowest atmospheric layers.

The development of near-surface saturated atmospheric layers through the negative feedback of windborne-snow sublimation has been mainly described from modelling approaches (Déry et al., 1998; Bintanja, 2001b) and few field measurements of individual blowing and drifting snow events (Mann et al., 2000; Bintanja, 2001a). The meteorological conditions and the relative frequency of such situations in a natural environment are however almost undocumented. This study investigates the relationship between low-level atmospheric saturation and the occurrence of drifting snow based on the analysis of detailed meteorological data collected during year 2013 in Adelie Land, a katabatic wind region of coastal East Antarctica among the most prone to snow transport by wind.

2. Field area and instrumentation

The detailed meteorological profiles and drifting snow measurements presented in this paper were acquired in the framework of an extensive drifting snow observation campaign that was run on the marginal slopes of Adelie Land in January 2010 (Trouvilliez et al., 2014). The campaign involved three unmanned weather stations (namely D3, D17 and D47) placed at different locations along a 100-km long transect to quantify spatial variations in the area. In this study, only the data collected at site D17 (66.7°S, 139.9°E; 450 m above sea level) is used because vertical profiles have been measured only at this location (see Amory (2019) for a detailed account of the measurements and local meteorological conditions).

D17 is situated in an accumulation zone 10 km inland from the coastline, near the downstream end of a sloping ice field. With frequent, strong and persistent katabatic flows originating almost exclusively from south-easterly directions owing to topographic channeling, D17 benefits from a long unobstructed snow-covered fetch of several hundreds of kilometers. This results in the regular occurrence of non-intermittent, well-developed drifting and blowing snow events (Amory, 2019) in which a local balance between upward turbulent diffusion, gravitational settling and sublimation of windborne snow particles is likely to be attained. Due to strong turbulent mixing induced by frequent katabatic flows, the near-surface atmosphere at D17 is mostly neutrally stratified throughout the year (Amory et al., 2017). The nearly-constant presence of an isothermal layer ensures that vertical changes in relative humidity during transport are governed by particle-air moisture exchanges along the profile.

Sensor	Type	Range	Accuracy
Wind speed	Vector A100LK*	0.2–60 m s^{-1}	0.1 m s^{-1}
Air temperature	Vaisala HMP45A	-39.2–60 °C	0.4 °C at -20 °C
Air relative humidity	Vaisala HMP45A	0–100 %	2 % (RH < 90 %) 3 % (RH > 90 %)
Snow height	SR50A*	0.5–10 m	0.01 m
Snow mass flux	second-generation FlowCapt™**	-	-

*Manufacturer Campbell Scientific
**Manufacturer IAV Engineering

Table 1. Characteristics of the sensors used at the profile station D17.

Wind speed, temperature, and relative humidity were measured at six levels logarithmically spaced (nominal heights 0.8, 1.3, 2, 2.8, 3.9 and 5.5 m above the surface), while changes in elevation due to accumulation and ablation were assessed with a sonic height ranger. The thermo-hygrometers were housed in naturally-ventilated radiation shields. Information on the occurrence and magnitude of drifting snow was retrieved from a second-generation acoustic FlowCapt™ device that was set up vertically and close to the ground to enable detection of the initiation of drifting snow events. The sensor consists of a 1 m long tube containing electroacoustic transducers that convert the acoustic vibration caused by the windborne snow particles colliding with the tube into a snow mass flux (vertically) integrated over the emerged length of the tube. Note that blowing snow may also occur in snow-transport occurrences necessarily identified as drifting snow since in this configuration detection of snow transport is limited to the first metre above ground. To ensure that significant events are detected and electronic or turbulence noise is removed, drifting snow has been considered to occur when the half-hourly mean of the snow mass flux η_1 exceeds a confidence threshold of 10^{-3} kg m^{-2} s^{-1} (Amory et al., 2017). The types and specificities of the instruments installed at D17 are summarised in Table 1. Sampling was done every 15 s and the 30-min statistics were stored on a Campbell CR3000 datalogger.

The meteorological profiles used in this study have been collected continuously from January 1st until December 30th 2013. Although data at D17 is available for a longer period of time (Amory 2019), this specific year was selected because the thermo-hygrometers remained functional at all levels throughout the year and almost all of the yearly accumulation as recovered by the height ranger occurred in February (Amory et al., 2017) guaranteeing that the measurement heights have undergone relatively little changes during the rest of the year.

This is important for consistent time statistics of relative humidity, since (i) the vapour pressure of the air increases with the proximity of the snow surface which acts as a moisture source (ii) the additional moisture loading through windborne-snow sublimation at a given elevation above the snow surface partly depends on the snow mass concentration which is a strongly decreasing function of height.

The thermo-hygrometers are factory calibrated to provide relative humidity with respect to liquid water rather than to ice for the whole range of measured temperatures. Goff and Gratch (1945) formulae were then used to convert the raw sensor value into relative humidity with respect to ice (RH) for below-freezing temperatures, using the sensor temperature reports in the conversion. Converted values in excess of 100 % were attributed to the limitations of both the instruments and the conversion method and were thus capped to 100 %. Although supersaturations have been reported in Antarctica for clean, cold atmosphere devoid of condensation nuclei (e.g., Genthon et al., 2013), they are not likely to be sustained at D17 because of the relatively high temperatures and windborne snow particles providing a large number of condensation nuclei (Barral et al., 2014).

3. Results

The evolution of the 2-m wind speed (U_2), snow mass flux integrated from 0 to 1 m above the surface (η_1) and relative humidity profiles with time during a drifting snow event recorded at D17 in May 2013 demonstrates that the near-surface air can readily become saturated in drift conditions (Fig. 1). Before the event begins, only a thin layer near the snow surface is saturated as a result of surface sublimation. Then, when U_2 rises above 10 m s^{-1} triggering erosion with drifting snow fluxes rapidly exceeding 2 10^{-1} kg m^{-2} s^{-1}, saturation (RH = 100 %) is observed up to the highest measurement level in less than 3 hours. When drifting snow begins to weaken on JJ 123.25, the saturated air layer progressively thins down to the lowest measurement level during the 12 hours that follow the cessation of the event. The match in timing between the rise in the drifting snow flux and in RH up to 100 % at all measurements levels strongly suggests that windborne-snow sublimation is responsible for the development of the saturated air layer. The absence of precipitation simulated by the regional climate model MAR (Agosta et al., 2019) for the fully continental grid point including D17 over this period provides additional support to this interpretation. In this specific example a timescale of less than 3 hours is necessary for a saturated air layer to grow up to 5.5 m but inspection at the database reveals that for some events ambient saturation can even occur simultaneously to the initiation of drifting snow. Mann et al. (2000) reported similar rapid time delays (1 hour) to reach saturation up to 11 m above the ground during blowing snow episodes at Halley station.

The structure illustrated in Fig. 1 is however repeated along only 9.6 % of overall drifting snow occurrences, indicating that saturation, when attained, is most often restricted to the first 2 meters above the surface (Fig. 2). On the other hand, a large majority (80 %) of the profiles showing saturation at each measurement level is associated with the occurrence of drifting snow, the rest of them being most likely linked to the prolonged presence of a saturated environment during calm conditions after the cessation of drifting snow events and/or to maritime air intrusions during cyclonic disturbances (e.g., Gallée, 1996; Kittel et al., 2018). Considering that surface sublimation is less effective at raising the moisture content of the near-surface air than windborne-snow sublimation because of enhanced particle ventilation in drift conditions, Fig. 2 also suggests that, due to the high incidence of drifting snow at D17 (61.3 % of the time), the occurrence of saturation is predominantly caused by windborne-snow sublimation.

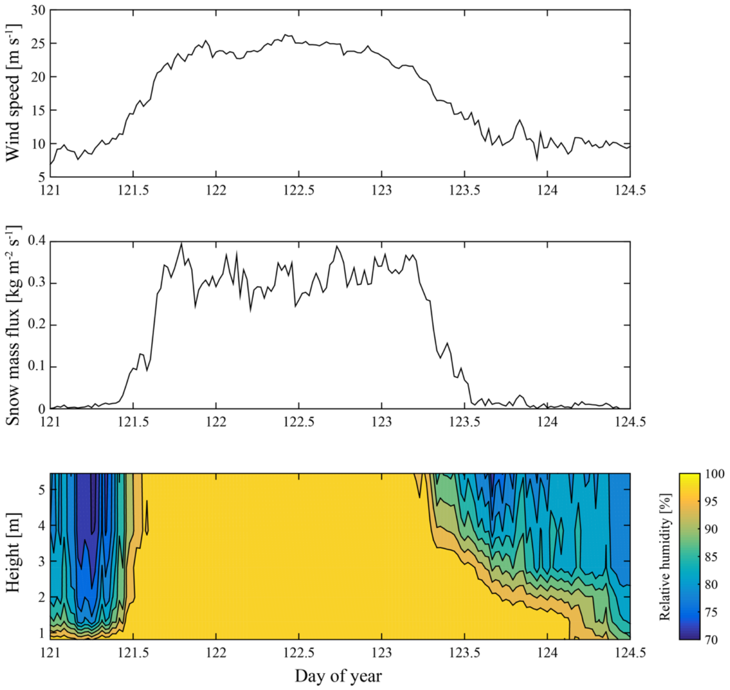

Figure 1. Timeseries of 2-m wind speed (upper panel), snow mass flux (middle panel) and contours of relative humidity with respect to saturation over ice (lower panel) showing the development of a saturated air layer during a drifting snow event in May 2013.

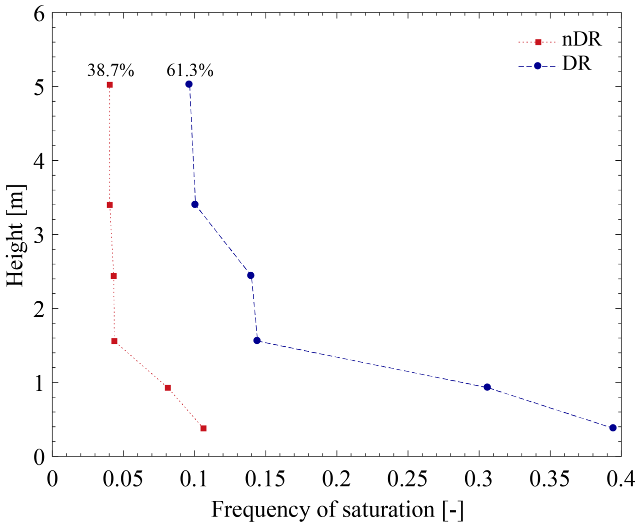

Figure 2. Frequency of saturation (RH = 100 %) at each measurement level showing that the saturated air layer that develops in drifting snow rarely exceeds 2 m in height. Profiles collected during non-drift (nDR: $\eta_1 < 10^{-3}$ kg m^{-2} s^{-1}) and drift (DR: $\eta_1 > 10^{-3}$ kg m^{-2} s^{-1}) conditions are treated separately, and their relative proportions are reported at the top of the corresponding curves. Note that saturation frequency values are expressed relative to the total number of profiles for non-drift or drift conditions. Yearly average instrument heights are used.

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Even though the development of a saturated air layer extending up to the uppermost measurement level is relatively rare, the occurrence of drifting snow and high relative humidity values are intimately related (Fig. 3). Binned average profiles of RH are shown for three classes of drift conditions of increasing magnitude, each class being sorted according to three classes of increasing wind speed. When drifting snow does not occur, a general decrease of RH with increasing wind speed is observed at all levels. This results from turbulent mixing and adiabatic warming of near-surface air with the increase in pressure as katabatic flows reach the coast (Gosink, 1989). The saturation vapour pressure of air (with respect to ice) increases strongly with temperature. As the air warms, its saturation vapour pressure increases without substantial changes in moisture content due to the absence of windborne-snow sublimation, and hence its relative humidity decreases. Only surface sublimation in that case contributes to the vertical moisture gradient and leads RH to increase when approaching the surface. Contrastingly, in drift conditions a reversal is observed; windborne snow particles sublimate and lead to an increase in RH with wind speed all along the average profile, offsetting the katabatic drying effect. This increase is greatest when drifting snow is most pronounced, and the vertical gradient reduces as U_2 becomes stronger and induces more efficient ventilation and turbulent mixing. The residual gradient is then due to surface sublimation and/or vertical gradients of snow mass concentration and thus of windborne-snow sublimation. For the strongest winds speeds (U_2 > 20 m s^{-1}) associated with strong drift conditions (η_1 > 2 10^{-1} kg m^{-2} s^{-1}), the profiles display saturation up to the highest measurement level. This demonstrates that windborne-snow sublimation can be a significant contributor to the near-surface moisture budget at D17, whose importance increases with wind speed. However, as saturation inhibiting further moisture release (i.e., the negative feedback) is systematically reached in the most extreme wind and transport conditions, the greatest contribution of windborne-snow sublimation to the total moisture flux might occur at moderate wind speeds (U_2 < 20 m s^{-1}) when the negative feedback mechanism does not lead to the development of a low-level saturated air layer.

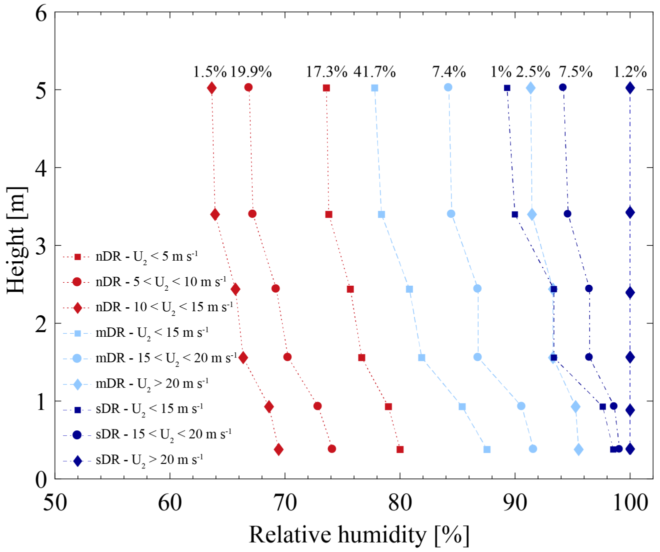

Figure 3. 30-min mean profiles of observed relative humidity (with respect to saturation over ice) averaged into bins of increasing 2-m wind speed (U_2) and discriminated using the snow mass flux (η_1) according to non-drift (nDR: η_1 < 10^{-3} kg m^{-2} s^{-1}), moderate drift (mDR: 10^{-3} kg m^{-2} s^{-1} < η_1 < 2 10^{-1} kg m^{-2} s^{-1}) and strong drift (sDR: η_1 > 2 10^{-1} kg m^{-2} s^{-1}) conditions. The numbers at the top of the average profiles indicate the proportion of observations used to produce each average profile. Yearly average instrument heights are used.

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4. Discussion

Examination of the RH profiles revealed that the air is saturated with respect to ice over the entire measurement range only 5.9 % of the time, indicating that the negative feedback effect of windborne-snow sublimation does not dominate the local moisture budget of the atmospheric boundary layer. This however does not mean that the negative feedback is not at work. Rather it is more likely the result of mechanisms inherent to the katabatic nature of the local flow that effectively remove moisture from the transport layer and prevent the formation of a near-surface saturated environment, thereby weakening the negative feedback (Bintanja et al., 2001b). Examples of such mechanisms are turbulent mixing within the transport layer, downward entrainment of dry air from above the katabatic layer through wind speed and directional shear and both horizontal and vertical advection of dry air through adiabatic warming of the descending katabatic flow. Note that windborne snow particles may also contribute to an increase in temperature, and then to a decrease in saturation vapour pressure in the transport layer through additional absorption of longwave radiation (Yang et al., 2014). These moisture-removal mechanisms have been considered as the physical explanation for the persistence of undersaturated air in the upper portion of deep Antarctic blowing snow layers (> 100 m) revealed from dropsonde measurements (Palm et al., 2018). The influence of such mechanisms down to lower levels of the transport layer would also explain why the near-surface RH profiles are also so infrequently saturated (only in the strongest wind and drift conditions) despite large snow mass fluxes and the attenuating effect due to the increase in RH caused by windborne-snow sublimation. Such mechanisms, potentially quite active in the coastal area of Adelie Land, and more generally in katabatic-generated blowing snow layers all over Antarctica (Bintanja, 2001a; Palm et al., 2018) may be very important in understanding the surface mass and atmospheric moisture budgets of the ice sheet by enhancing windborne-snow sublimation. In contrast, RH profiles collected at Halley over a flat ice shelf, therefore in the absence of a katabatic flow, suggest that the negative feedback of sublimation might locally govern the surface-atmosphere moisture flux (Mann et al., 2000), depending on the dynamical origin of the boundary-layer flow.

5. Conclusion

Meteorological profiles and drifting snow mass fluxes collected continuously during year 2013 at site D17 in coastal Adelie Land have been analysed conjointly to characterize the moistening of the near-surface atmosphere during drifting snow occurrences. In snow transport conditions occurring 61.3 % of the time, relative humidity increases and its vertical gradient diminishes with the magnitude of drifting snow, as a result of a major source of moisture from windborne-snow sublimation in the near-surface atmospheric layer. Although saturation is preferably confined below 2 metres, low-level atmospheric moistening by the sublimation of the windborne snow particles can lead to the rapid development of a saturated environment along the whole measurement range that can even coincide with the initiation of drifting snow. However, this is shown to be relatively rare (only 9.6 % of drifting snow occurrences or 5.9% of the time) at the measurement location and mainly occurs in strong drift conditions (> 0.2 kg m^{-2} s^{-1}) associated with high wind speeds (U_2 > 20 m s^{-1}). The low frequency of ambient saturation despite the high incidence of drifting snow is explained by the likely existence of moisture-removal mechanisms that can counterbalance the negative feedback of sublimation by preventing the near-surface air from reaching saturation, raising windborne-snow sublimation as an important contributor to the local surface mass and atmospheric moisture budgets.

The dataset also demonstrates that the occurrence of snow transport does not necessarily involve saturation of the near-surface atmosphere, and conversely the occurrence of a saturated near-surface air layer is not systematically associated with snow transport. But during those events for which the occurrence of drifting snow (i.e., < 2 m) and a saturated air layer of several metres is concurrently reported, the height reached by the suspended snow particles, or the depth of the transport layer, likely extends beyond the uppermost measurement level (i.e., > 5.5 m). Remote sensing techniques have shown that blowing snow can frequently reach heights of 100 m or more (Palm et al., 2011). Since satellite detection only captures blowing snow layers 30 m or greater in thickness during clear-sky or optically thin-cloud conditions and is limited by the satellite revisit frequency, a comparative study between satellite products and near-surface measurements would help to assess the proportion of missed events when surveying snow transport from space and study the conditions that lead drifting and shallow (< 30 m) blowing snow events to evolve into deep blowing snow layers.

Data availability. All data presented and described in this study are freely available by contacting the authors.

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Competing interests. The author declares that he has no conflict of interest.

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