THE ARCTIC OCEAN SNOW MASS BUDGET

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1. INTRODUCTION

At high latitudes, the world's oceans are covered by perennial or seasonal ice cover. Since subfreezing temperatures persist throughout most of the year, precipitation generally falls in the form of snow, covering the ice pack with a thin layer of highly reflective and insulating material. With its higher albedo, lower thermal conductivity and higher attenuation for shortwave radiation (when compared to sea ice), snow reflects a large amount of incoming solar radiation, insulates well the underlying ocean from the atmosphere during the cold season, and limits the amount of energy (and light) reaching the ice and mixed layer. Since all of these effects are directly or indirectly linked with the snow pack evolution, a good understanding of the snow mass budget of the Arctic Ocean is crucial.

The annual snow mass budget for Arctic sea ice may be expressed as:

$$S = P - E - M - X - D - Q_s - Q_l \qquad (1)$$

where S is the storage or accumulation of snow at the surface, P is precipitation, E denotes surface evaporation/sublimation, M is the divergence of water after melt, and X is the loss of snow through large-scale export of sea ice outside the domain of the Arctic Ocean. The three terms that remain in Equation 1 are all related to blowing snow: D denotes the divergence of airborne snow by wind transport out of the Arctic Ocean domain, Q_s is the sublimation of blowing snow, and Q_l represents the loss of mass into leads. All terms in Equation 1 are expressed in units of mm a^{-1} snow water equivalent (swe).

Some recent studies have provided crucial information on most processes contributing to the surface mass balance of Arctic sea ice (e.g., Yang 1999; Warren et al. 1999). However, given its high rate of occurrence, we must assess the role of blowing snow to fully close the snow mass budget of Arctic sea ice (Déry and Yau 1999, 2002). This study describes some numerical experiments with a blowing snow model adapted to the polar sea ice environment. Using these results, an estimate of all the terms contributing to the snow mass budget of Arctic sea ice is achieved.

2. BACKGROUND AND MODEL

Blowing and drifting snow occur when loose snow at the surface is entrained by wind into two substantive modes of transport: saltation and suspension. Saltation is the action by which particles of snow bounce or skip along the surface up to heights of a few centimeters. Through repeated surface collisions, the abrasion of saltating snow particles occurs rapidly such that they approach the density of ice. If turbulent motions in the atmospheric boundary layer (ABL) are sufficiently strong, some of the particles from the saltation layer may then be entrained into the suspension mode. In this situation, a balance between downward gravitational settling and upward turbulent diffusion leads to the suspension of blowing snow. In severe blizzards, snow particles transported by turbulent eddies can be found up to several hundred meters above the surface.

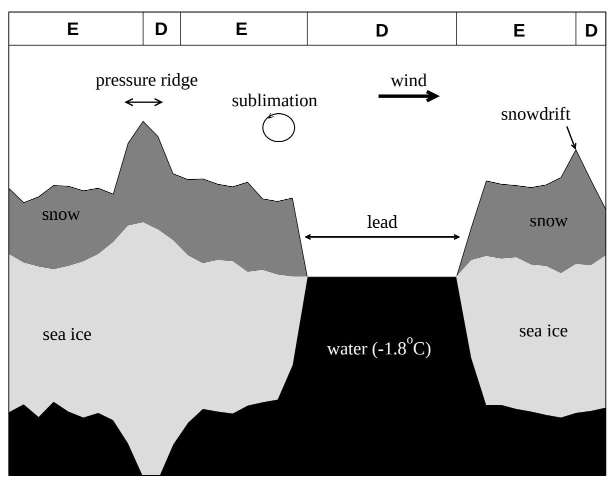

Figure 1: A schematic representation (not to scale) of the processes resolved by the PIEKTUK-TUVAQ model. In this situation, blowing snow carried by strong winds (here from left to right) is transported from erosion areas (E) and accumulates in deposition zones (D).

The model used to simulate these processes is the PIEKTUK-TUVAQ blowing snow model especially

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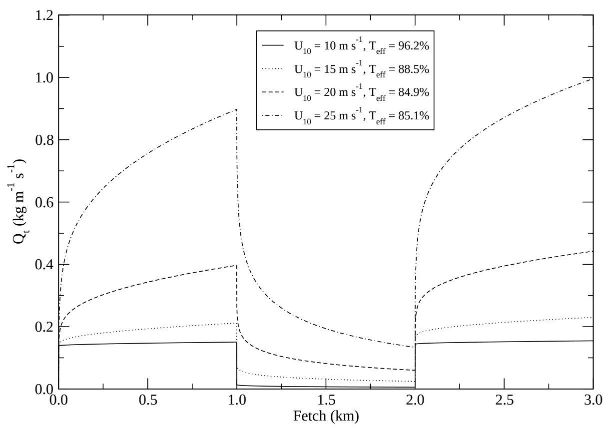

Figure 2: The spatial evolution of the transport rate of blowing snow (Q_t) for four values of the 10-m wind speed. At a fetch $x = 1$ km, the column of blowing snow traverses open waters over a distance of 1 km in length, before resuming its course over snow-covered sea ice. Values of the lead trap efficiencies (T_{eff}) are given for each wind speed.

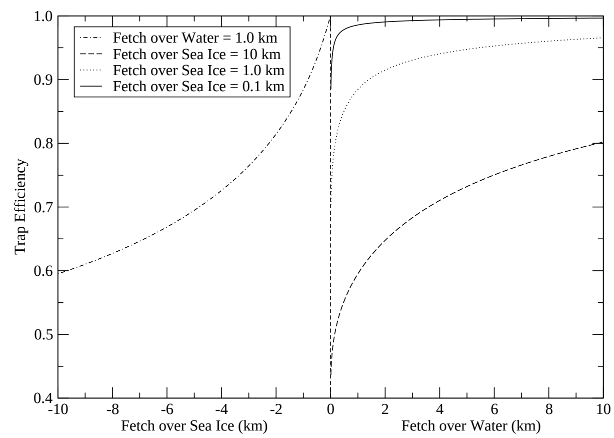

Figure 3: Values of the trap efficiency of a lead to capture blowing snow as a function of the fetch over snow-covered sea ice and the lead width. In all cases, we assume an unlimited supply of snow on the sea ice surface available for transport.

adapted to the sea ice environment (Déry and Tremblay 2003). PIEKTUK-TUVAQ depicts the evolution of a column of sublimating, blowing snow over sea ice. The model yields three important diagnostic quantities: the vertically-integrated sublimation and transport rates of blowing snow (Q_s and Q_t, respectively), as well as the amount of snow eroded over sea ice and transferred into leads (Q_l). Figure 1 depicts schematically the processes resolved by PIEKTUK-TUVAQ and provides information on erosion and deposition zones on Arctic sea ice.

3. RESULTS

In the first experiment, the transport of blowing snow into a 1-km wide lead along the direction of the flow and located at fetch $x = 1$ km, is investigated. Steady-state results are presented for 10-m wind speeds varying from 10 to 25 m s^{-1}. Figure 2 illustrates the abrupt decrease in Q_t where blowing snow encounters the open waters and the local source of blowing snow particles is shut off. The effect is particularly evident at low wind speeds when the upward turbulent transport is smaller and the suspended snow remains closer to the surface. As the column of blowing snow once again flows over sea ice, Q_t immediately jumps up to values near those achieved prior to the open waters. In these experiments, the trap efficiency (T_{eff}) of the lead, defined as the ratio of the mass captured by the open waters to the total mass transported in the column of blowing snow incident upon the lead edge, remains at or above 85% in all four cases.

Apart from variations in wind speed, the fetch for blowing snow over sea ice and over open waters determines to a large extent the trap efficiency of leads (Déry and Tremblay 2003). In Figure 3, we present additional results from PIEKTUK-TUVAQ integrated over various fetches with a constant 10-m wind speed of 15 m s^{-1}. This shows that as the upwind fetch for blowing snow over sea ice increases, T_{eff} diminishes. Conversely, as the lead width expands, T_{eff} gradually increases but begins to level off for large distances over open waters. In general, as the fetch for blowing snow over sea ice (open waters) increases, the upward transport by turbulent mixing (downward settling) of blowing snow particles increases and leads to the ever decreasing (increasing) values of T_{eff} with x. Typical values of T_{eff} range from 40 to 100% for upwind fetches spanning 0.1 to 10 km over sea ice. Additional sensitivity tests conducted with PIEKTUK-TUVAQ over a wide range of air temperatures, relative humidities and friction velocities provide values of $T_{eff} > 70\%$ in all cases (Déry and Tremblay 2003).

4. ARCTIC OCEAN SNOW MASS BUDGET

A complete snow mass budget for the Arctic Ocean is provided in Table 1. All source and sink terms presented in Equation 1 are included in this budget. A corrected climatology of precipitation data collected from Russian buoys shows that the Arctic Ocean is subject to 237 mm swe of snowfall each year (Yang 1999).

Table 1: Source and sink terms of the snow mass balance of Arctic sea ice. Each is expressed in units of mm a^{-1} swe, with positive (negative) quantities indicating source (sink) terms in the snow budget.

Component	Value	Source[1]
Snowfall	237	1
Surface Sublimation	-99	2
Blowing Snow Sublimation	-23	2
Wind Divergence	-0.1	2
Snowmelt	-97	3
Export with Sea Ice	-7	4
Transport into Leads	-7	4
Accumulation/Residual	4	4

[1]Sources: 1, Yang (1999); 2, Déry and Yau (2002); 3, Warren et al. (1999); 4, This study.

According to Déry and Yau (2002), the combination of surface and blowing snow sublimation ($E + Q_s$) removes 122 mm a^{-1} swe (99 and 23 mm swe a^{-1} swe, respectively) or more than half of the annual precipitation falling over the Arctic Ocean. The large-scale divergence of blowing snow out of the Arctic Ocean domain, on the other hand, remains negligible (-0.1 mm a^{-1} swe). In an observational study of snow thickness on Arctic sea ice, Warren et al. (1999) report that, for the period 1954-1991, 97 mm a^{-1} swe of snow melts on Arctic sea ice during summer. The snow transported out of the Arctic Ocean via sea ice export can be estimated using satellite area fluxes through Fram Strait derived from the Radarsat Geophysical Processor System (RGPS). Assuming a yearly mean area flux of 9.2 $\times$ 10^5 km^2 (Kwok and Rothrock 1999) and a yearly mean snow depth of 20 cm (at a density of 300 kg m^{-3}; Warren et al. 1999) on the migrating sea ice, a loss of 7 mm a^{-1} swe through sea ice export is calculated.

The remaining term in our budget is the snow mass transported into leads (Q_l). This quantity is obtained from (Déry and Tremblay 2003):

$$Q_l = \frac{f Q_t T_{eff}}{\rho_w \overline{x_l}} \tag{2}$$

where ρ_w (kg m^{-3}) is the density of water, f is the large-scale fractional coverage of open waters, and $\overline{x_l}$ (m) is the mean lead width along the wind direction. We take here a mean annual blowing snow mass flux over the Arctic Ocean of 4.5 $\times$ 10^{-3} kg m^{-1} s^{-1} (Déry and Yau 2002) and a 1% lead fraction (Lindsay and Rothrock 1995). As seen from Figure 3, the trap efficiency strongly depends on $\overline{x_l}$ (m) and the upstream fetch over sea ice. Assuming the distribution of lead orientations to be isotropic and a given lead fraction f, however, the mean fetch over sea ice is fixed at $\overline{x_l}/f$. The mean lead width can be evaluated assuming a lead width x_l (m) distribution following a power law of the form (Wadhams 2000):

$$P(x_l) = K x_l^{-n} \tag{3}$$

where

$$n = \begin{cases} 1.5 & 0 < x_l < 0.1\,\text{km} \\ 2.5 & x_l \geq 0.1\,\text{km} \end{cases} \tag{4}$$

and where K is a scaling factor such that the total probability P to find a lead between 5 m and several kilometers is equal to 1. This distribution was derived from submarine draft measurements made in the Eurasian Basin of the Arctic Ocean (Wadhams 2000). The mean lead width can then be expressed in terms of the probability function as:

$$\overline{x_l} = \frac{\int_{x_0}^{\infty} P(x_l) x_l \mathrm{d}x_l}{\int_{5\,\text{m}}^{\infty} P(x_l) \mathrm{d}x_l} = 150\,\text{m}\,. \tag{5}$$

where x_0 is the lower bound over which the average is performed. Clearly, the mean lead width will be strongly dependent on the choice of x_0; however, as x_0 increases, the mean lead width increases, but so does the trap efficiency. Consequently, Q_l remains insensitive to the choice of x_0. For the calculations of Q_l, we therefore use $\overline{x_l} = 150$ m. In addition, we set $T_{eff} = 74\%$ based on average 10-m wind speeds of 10 m s^{-1} during Arctic blowing snow events (Déry and Yau 1999) and on results from section 3. With these values, we then find from Equation 2 that the transport of snow mass into leads removes 7 mm a^{-1} swe on average for the Arctic Ocean (Table 1). A residual of 2% of the total precipitation input remains in the snow mass budget calculations.

5. SUMMARY

A snow mass budget for the Arctic Ocean has been presented. According to this budget, the combined effects of blowing snow sublimation and redistribution into leads remove 13% of the total annual snowfall over Arctic sea ice. After surface sublimation and snowmelt, blowing snow represents the most significant sink term in the snow mass balance of the Arctic Ocean.

6. ACKNOWLEDGMENTS

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