Wind Effect on Snow Over Arctic Sea-ice: Evaluation of a Sea-ice / Snow / Blowing Snow Model

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Abstract: Blowing snow frequently occurs in the Arctic Ocean and Antarctica, transporting snow by saltation and suspension and yielding sublimation of snow particles. In this study, it is found that erosion due to blowing snow may account for snow depth overestimation in a multi-layer snow/sea ice coupled system. Atmospheric forcing measurements made during the Surface Heat Budget of the Arctic Ocean Experiment (SHEBA) were used to examine the effect of wind erosion on snow and ice evolution over the Arctic pack ice from October 1997 to October 1998. Total erosion due to blowing snow was found to be as large as 56 mm of snow water equivalent and was showed to strongly influence snowpack redistribution for the particular case under study. A sensitivity analysis of ice thickness has been also performed and revealed that ice depth depends on surface albedo, new snow density and thermal conductive fluxes at the ice/snow interface; results that are similar to those from a sensitivity analysis of snow depth. The snow/sea-ice coupled system was modified in order to account for wind erosion for low-level wind speed greater than 9 m/s. Results show that including blowing snow significantly improves the simulation of snow depth and of temperature at the snow/ice interface, but slightly degraded the simulated sea ice thickness. It also leads to other changes such as a decrease of snow temperature by an average of 0.87K and a decrease of snow depth by 4.93 cm on average. An overall effect is to shorten the duration of the snowpack and increase the underlying ice thickness.

KEYWORDS: PIEKTUK, SNTHERM, SHEBA, blowing snow, sea ice.

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1. INTRODUCTION

Strong low-level winds, which can occur as frequently as about once every four days in the Arctic Ocean and Antarctica (Xiao et al., 2000), is often responsible for transport of snow by saltation and suspension and was found to increase sublimation of snow particles (Déry and Taylor, 1996). Owing to the prevailing subfreezing conditions, long snow period and scarce vegetation (Déry, 1999b) in the Arctic, transport of snow and its concurrent sublimation have been recognized as important for the budgets of the Arctic environment, (Déry, and Yau2001a). Snow suspension and saltation above the surface (due to intense wind) can modify density gradients and sublimation of airborne snow, thus considerably affecting the near-surface atmospheric structure (Déry and Taylor, 1996). Meanwhile, snow sublimation acts as an abundant source of water vapor and sink of sensible heat in air, reducing particle sizes and their terminal velocity (Déry and Taylor, 1996). The snow redistribution by wind, followed by the production of highly variable snow depth and density, may account for variations in the surface energy during snow melt (Shook, 1995). For these reasons, the surface mass balance of the Arctic is subject to the wind redistribution and consequent snow sublimation (Déry and Yau, 2000) and relocation. The annual Arctic fluxes of water and energy, including fluxes of water vapor, sensible heat, snow and latent heat, can be altered by wind transport and sublimation of blowing snow.

The importance of blowing snow has been the subject of a considerable number of articles (e.g., Pomeroy, 1988; Uematsu et al., 1989; Mobbs and Dover, 1993; King et al., 1996; Pomeroy et al., 1997; Bintanja, 1998; Déry et al., 1998; Mann, 1998), including those discussing the development of models such as PIEKTUK-T (Déry et al., 1998), WINDBLAST (Mann, 1998) and SNOWSTORM (Bintanja, 2000a).

In these studies, the range of sublimation rate is large because this process critically depends on the particular modeling approaches adopted in each model (Déry and Yau, 2001b). This is demonstrated in the following: blowing snow can produce an erosion of a few mm of snow water equivalent (SWE) in Antarctica over a 6-month period (King et al., 1996), to 37 mm swe over a high-Arctic basin in winter (Pomeroy et al., 1997; Essery et al., 1999). Moreover, about 28% of winter snowfall has been reported to be sublimated in a small northern basin of the Arctic (Pomeroy et al., 1997) and 75% of the annual snowfall has been reported to sublimate due to snow transport in the Canadian prairies, with around half of this transported into the atmospheric boundary layer (Pomeroy and Gray, 1994). Pomeroy et al. (1993) reported that 70% of annual snowfall was removed up due to blowing snow. Benson et al. (1982) investigated the Arctic coast of Alaska, finding that 58% of snowfall remained accumulated on the tundra with 11% of annual snow relocated to other places and 32% of snowfall sublimated as blowing snow. These examples indicate that snow transport and sublimation of blowing snow can no longer be neglected in monitoring the Arctic snow evolution (King and Turner, 1997; Cullather et al., 1998).

Although there appears to be a close link between wind intensity and winter snow depth, few studies have included blowing snow parameterizations in their snow modeling. Chung et al. (2008) discussed the error associated with the overestimation in model estimates in winter for the Arctic Ocean and found that erosion due to wind blowing snow may account for the snow depth differences between the model and observation in winter.

This work follows the modeling study of Chung et al. (2008) and examines the effect of blowing snow on the simulation of snow and sea-ice in the Arctic during the SHEBA experiment. In the following, the hypothesis that the inconsistency between the simulated and observed snow pack over the sea-ice were due to the effect of blowing snow is tested here. To accomplish this, a 1-D version of PIEKTUK has been incorporated within the coupled sea-ice and snow system described in Chung et al. (2008). We also intend in this study to investigate the seasonal contribution of many factors related to atmospheric forcing or snow and ice features on the new coupled system and possible impacts of wind erosion on snow and ice evolution. This coupled system is verified with the SHEBA dataset.

2. METHODS

2.1. Blowing snow model

A simple and efficient 1-D model, called PIEKTUK-B (PIEKTUK, also spelled “PIQTUQ”, an Inuktituk word for blowing snow), has been developed to estimate the temporal evolution of blowing snow mixing

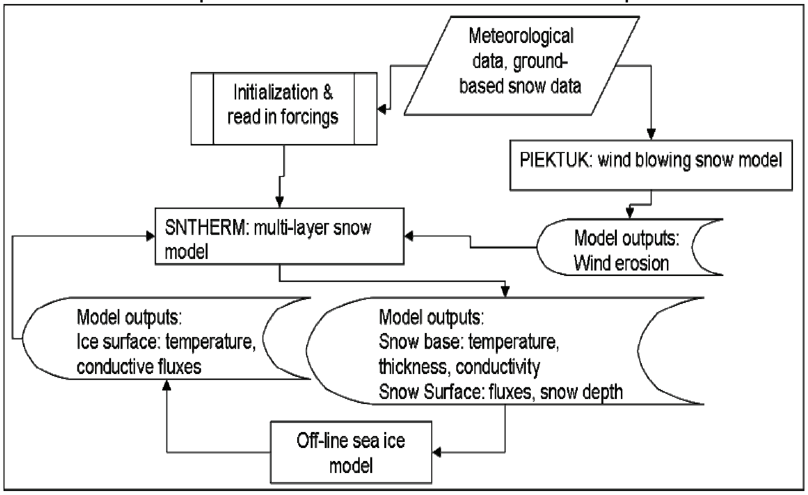

Fig. 1. Diagram of the coupled system, including the multi-layer snow model SNTHERM, the ice model, and the blowing snow model PIEKTUK.

ratio, moisture and temperature profiles for a column of air in the atmospheric boundary layer, by considering diffusion, settling and sublimation of blowing snow (Déry et al., 1998; Déry and Yau, 1999a). This model has been shown to accurately predict snow transport and sublimation rates (Xia et al., 2000). The amount of wind erosion can be computed in order to determine the loss from the surface snow.

2.2. Sea ice thermodynamic model

The sea-ice model has not yet been documented in the literature although some groups are using similar techniques in the sea ice component of their climate models. The ice model comes from a two-dimensional approach that has been modified for this study to a one-dimensional system, The model simulates the evolution of ice characteristics such as temperature and thickness. The model also allows an arbitrary fixed number of layers in the ice slabs, as introduced by Maykut and Untersteiner (1971) and Semtner (1976).

In the case of ice, the governing equation (11) can be written as (Maykut and Untersteiner, 1971):

$$\left(\rho c_p\right)_i \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial T}{\partial z}\right) - \frac{\partial}{\partial z} F^R \qquad (1)$$

$$F^R = I_0 (1-\alpha) F_{sw} e^{-\kappa z} \qquad (2)$$

where ρc_p represents the density and specific heat of ice; T is the temperature [K]; t is the time step [s]; z represents the depth positive downward from the ice surface [m]; K represents the thermal conductivity of sea ice [W/m-K]; F^R represents the penetrating solar radiation [Wm^{-2}]; I_0=0.17 is the fraction of shortwave radiation penetrating the ice surface; α is the albedo; F_{sw} represents the incident solar radiation [Wm^{-2}]; κ =1.5 is the extinction coefficient for shortwave radiation [m^{-1}].

2.3. Coupled ice, snow, blowing snow

Fig. 1 shows the diagram of the coupled model. The lost SWE due to wind erosion, estimated by PIEKTUK, is introduced as an additional loss term in mass transfer of snow. The snow density, required for transferring SWE into snow thickness, is determined from the snow model at current time step rather than using a constant value over the entire column. The parameterizations of the previous coupled model were described in Chung et al. (2008).

3. STUDY AREA

Data from the SHEBA field experiment are used in this study for the evaluation and forcing of the coupled system. Inputs for the model include hourly values of meteorological data, such as wind speed at two heights, relative humidity, air temperature and atmospheric pressure, along with surface roughness. For more detail on the data sets, see Chung et al. (2008).

4. RESULTS

4.1 Erosion and sublimation

Fig. 2 compares the erosion and sublimation caused by blowing snow. It is found that wind erosion is about 3 orders of magnitude greater than sublimation due to blowing snow, implying that a substantial amount of snow particles remained in the air. The total accumulated erosion was estimated as 56mm SWE over the SHEBA year (surface sublimation has been considered in the multi-layer snow model).

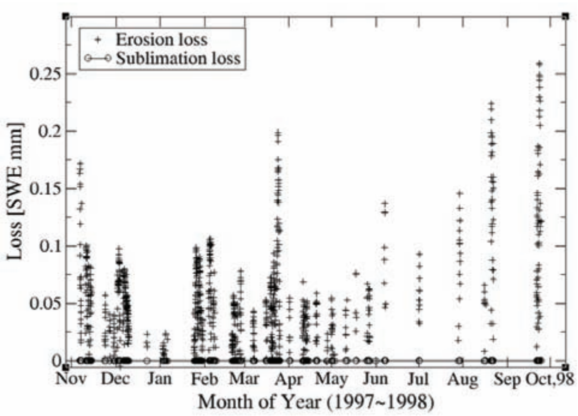

Fig. 2. Comparison of sublimation and erosion due to blowing snow (SWE mm).

4.2 Snow depth

Fig. 3a compares against measurements the measured and simulated snow depth before and after considering blowing snow.

It shows that blowing snow causes a significant decrease (4.93 cm in average) in snow depth through the entire annual cycle. The result in Fig. 3a are based on threshold wind speed of 9 m/s that better fits the data (analysis details in Section 5). The RMS error for snow depth (6.81) is lower than that (7.69) of a previous version of the model (Chung et al., 2008). The model performance is greatly improved in winter but was slightly degraded in abrupt winter-spring transition.

4.3 Ice thickness

*Fig. 3*b shows the measured and simulated ice thickness for the two model versions. Blowing snow is responsible for a slight increase of 1.43 cm in average in ice thickness in winter but the results of the two models are very similar in Spring. The RMS error of ice thickness is 11.08 cm with the new model, which is larger than the RMS error from the old model (9.57 cm, see Chung et al. (2008). Nevertheless, there is still a good agreement between the results and measurements, implying that the inclusion of wind erosion does not substantially degrade the model performance in ice thickness.

4.4 Thermal conductive flux and temperature at the snow/ice interface

Fig. 4a displays an annual variation of the simulated conductive heat fluxes at the snow/ice interface. The fluxes displayed a great variation during the winter and were progressively increasing toward summer. The negative values indicate that fluxes flow from the ice towards the snowpack. The differences between the two experiments are small (mean of 0.88 Wm^{-2}). Fig. 4b compares the measured and modeled temperature at the snow/ice interface. The RMS error of temperature was 1.96 K from the new model, lower than a RMS error of 2.22 K from the old model (Chung et al., 2008). On average, blowing snow is responsible for a temperature decrease of 0.87K, an improvement in Winter and Spring.

5. SENSITIVITY ANALYSIS

Fig. 5 shows a summary of the atmospheric forcing, model parameters and variables tested in the sensitivity experiments. More specifically, it compares ice thickness simulated from different experiments to shed light on the factors affecting the ice evolution. The most notable impacts are caused by surface albedo, conductive flux at the snow/ice interface and new snow density. The sensitivity of ice thickness to the fluxes is slightly different from what is shown in Table 1 and from what was reported in Chung et al. (2008) for snow depth.

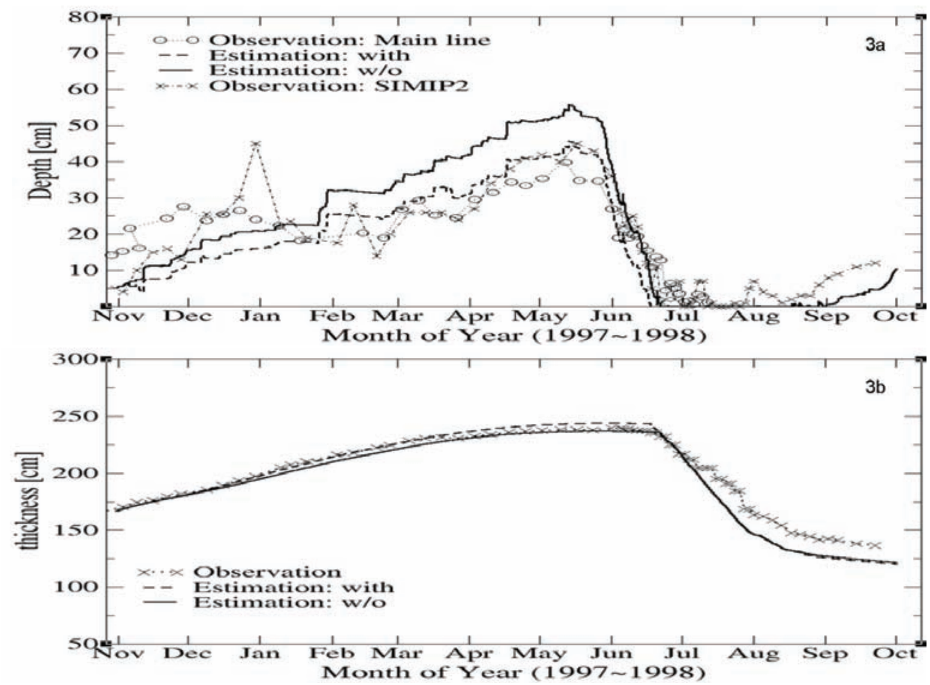

Fig. 3 Comparison of (a) snow depth and (b) ice thickness simulated with (dashed line) or without (solid line) wind erosion, with the measurements (circles, dotted line and crosses, dash-dot line).

Table 1 Summary of forcing, model parameters and variables tested in the sensitivity analysis of the coupled system with blowing snow.

Variables	$\left(d_{+10\%}/d_{con}\right)_{\max}$	$\left(d_{-10\%}/d_{con}\right)_{\max}$
Surface albedo	1.25	0.84
Conductive flux at snow/ice interface	0.96	1.06
New snow density	1.06	0.97
Wind speed	1.04	1.98
Initial bulk density of water	1.04	0.98

Fig. 6 demonstrates the sensitivity of simulated snow depth and ice thickness to wind speed threshold for blowing snow. Not surprisingly, it shows that snow depth decreases with increasing wind erosion, and this is followed by an increase in ice thickness. Table 2 and Fig. 6 show the RMS error of results based on wind speed threshold for wind erosion. To avoid an overestimation of snow depth, a threshold wind speed of 9 ms^{-1} was used. This led to smaller RMS error for snow depth, ice thickness, and temperature at snow/ice interface. This threshold wind speed is larger than the value of 5 m/s reported in Serreze et al. (1997) based on the analysis of the Comprehensive Ocean Atmosphere Data Set (COADS).

Table 2 Summary of statistic analysis on different threshold wind transport speeds.

Threshold wind speed [m/s]	0	8	9	12
RMS for temperature at snow/ice interface	1.90	1.91	1.96	2.17
RMS for snow depth	7.92	7.47	6.81	6.94
RMS for ice thickness	10.69	10.87	11.08	10.43

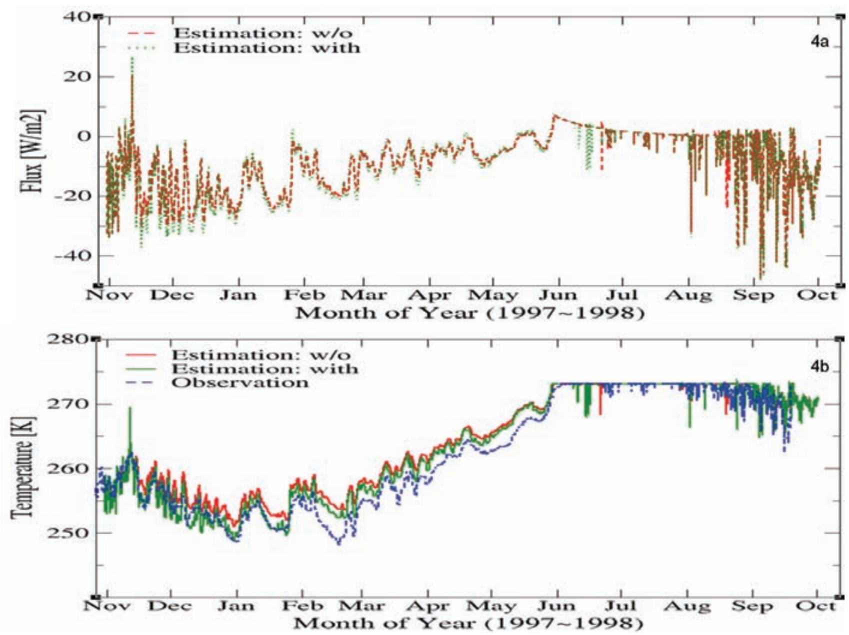

Fig. 4. Comparison of the conductive heat fluxes and (b) the temperature simulated with (red line) or without wind erosion (green line), along with measurements (blue dashed line) at snow/ice interface.

6. CONCLUSIONS

This study was performed using the same data and coupled system as those reported in Chung et al. (2008), but with special emphasis on the erosion due to blowing snow. Intercomparison of simulations performed with and without this effect, along with several sensitivity analyses have demonstrated the following:

1) The total accumulated erosion of 56 mm SWE was sufficiently large to affect the distribution in winter snowpack.
2) Blowing snow caused a snow depth decrease of 4.93 cm on average. The model performance in estimating snow depth was greatly improved in winter but was slightly degraded during the abrupt winter-spring transition.
3) The snow depth decreased, followed by an increasing ice thickness of 1.43 cm in average. The results of the two models are very similar during Spring.
4) Blowing snow also caused a temperature decrease of about 0.9K and improved the estimates in later winter and spring.
5) Besides the surface albedo and new snow density, the ice thickness is also sensitive to conductive heat fluxes at the snow/ice interface.
6) The threshold wind speed of 9 ms^{-1} led to smaller RMS error for snow depth. This wind speed is larger than the threshold of 5 ms^{-1} reported in Serreze et al. (1997) based on the analysis of the Comprehensive Ocean Atmosphere Data Set (COADS) because the SHEBA snow surface was hard and old (Xiao, 2000), frequently with a formation of wind slab.

Although the simple coupled system described in this study performs relatively well for snow and ice evolution, it may become computationally restrictive for two-dimensional snow-ice studies. Future studies need to explore the possibilities of using this approach for 2-D modeling of snow and sea ice.

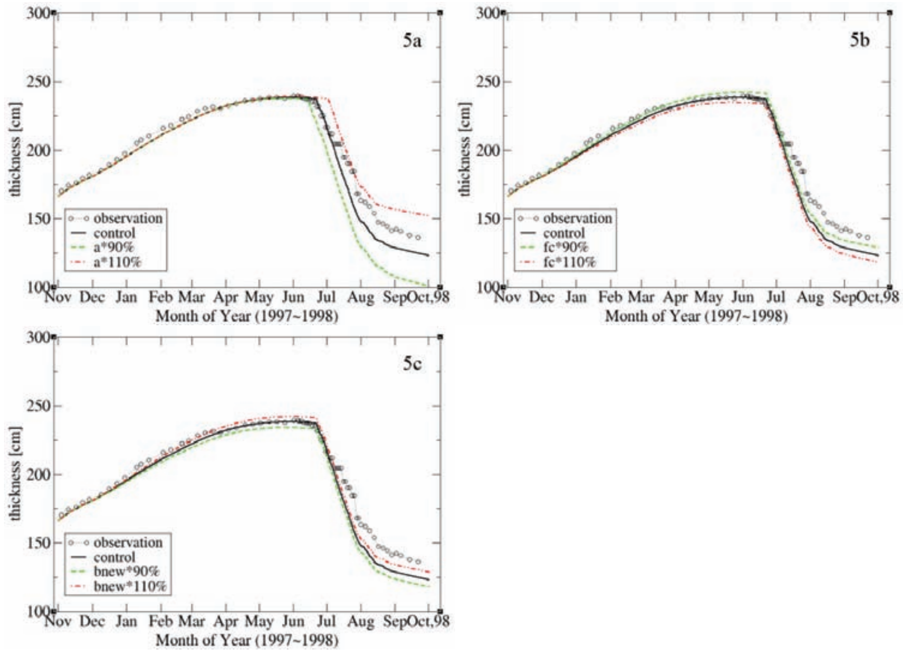

Fig. 5. Sensitivity analysis of simulated ice thickness produced by the coupled system including blowing snow on (a) albedo, (b) conductive heat flux at snow/ice interface and (c) new snow density. The red dash-dot line represents the ice thickness for the experiment with a perturbation of +10%; the green dashed line represents the ice thickness for the experiment with a perturbation of -10%; and the black line represents results of the control experiment.

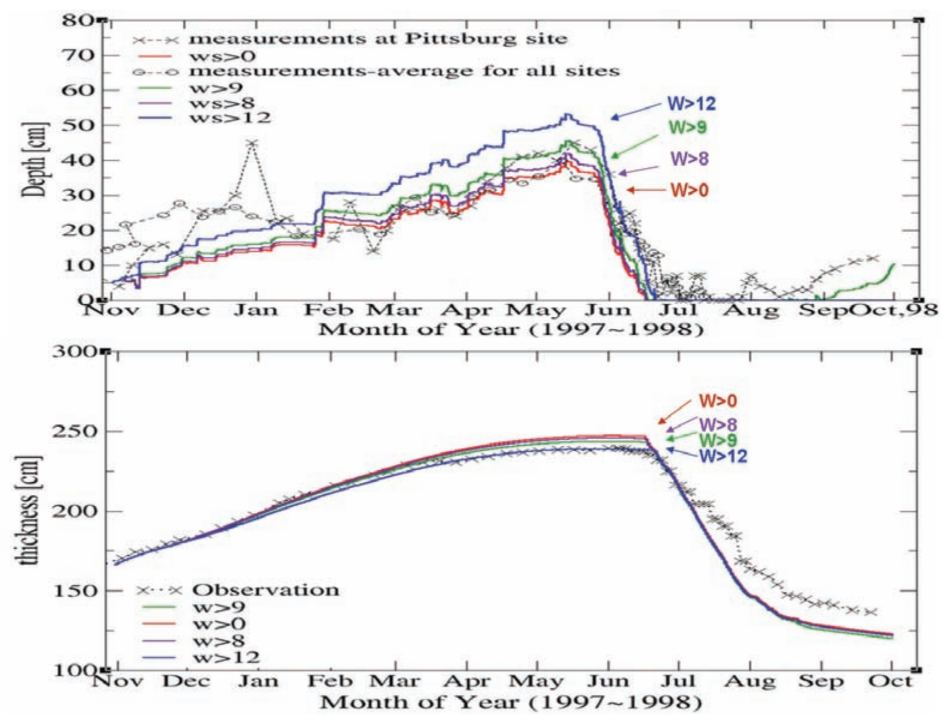

Fig. 6. Sensitivity analysis of simulated (a) snow depth and (b) ice thickness on different wind speed threshold for blowing snow. The red line represents the experiment with wind erosion occurring all the time; the purple line represents the experiment with wind erosion occurring when wind speed is greater than 8ms^{-1}; the green line represents the experiment with wind erosion occurring when wind speed is

greater than 9ms^{-1}; and the blue line represents the experiment with wind erosion occurring when wind speed is greater than 12ms^{-1}.

7. REFERENCES

Benson, C.S., 1982. Reassessment of winter precipitation on Alaska's Arctic slope and measurement on the flux of wind-blown snow. Geophysical Institute Report UAG R-288. Geophysical Institute, University of Alaska, Fairbanks. 26.

Bintanja, R., 2000a. Snowdrift suspension and atmospheric turbulence. Part I: theoretical background and model description. Boundary-Layer Meteorol. 95, 343–368.

Chung, Y.-C., S. Bélair and J. Mailhot, 2008. Simulation of snow-covered sea ice in the Arctic Ocean using a coupled snow/ice model. Journal of Hydrometeorology, in preparation.

Cullather, R.I., D.H. Bromwich, and M.L. Van Woert, 1998. Spatial and temporal variability of Antarctic precipitation from atmospheric methods. J. Climate 11, 334-367.

Déry, S.J. and P.A. Taylor, 1996. Some aspects of the interaction of blowing snow with the atmospheric boundary layer. Hydrol. Proc. 10, 1345-1358.

Déry, S.J., P.A. Taylor, and J. Xiao, 1998. On the thermodynamic effects of sublimating blowing snow in the atmospheric boundary layer. Boundary-Layer Meteorology. 89, 251-283.

Déry, S.J. and M.K. Yau, 1999a. A bulk blowing snow model. Boundary-Layer Meteorol., 93(2), 237-251.

Déry S. J., and M.K. Yau, 1999b. A climatology of adverse winter-type weather events. J. Geophys. Res. 104, 16657–16672.

Déry S.J. and M.K. Yau, 2001a. Simulation of blowing snow in the Canadian arctic using a double-moment model. Boundary-Layer Meteorol. 99, 297–316

Déry S.J. and M. K. Yau, 2001b. Simulation of an Arctic ground blizzard using a coupled blowing snow-atmosphere model. Journal of Hydrometeorology. 2, 579-598.

Essery, R., L. Li, and J.W. Pomeroy, 1999. A distributed model of blowing snow over complex terrain. Hydrol. Proc. 13, 2423–2438.

Mann, G.W., 1998. Surface heat and water vapour budgets over Antarctica. Ph.D. Thesis, The Environment Center, The University of Leeds, U.K., 279.

Maykut, G.A., and N. Untersteiner, 1971. Some results from a time dependent thermodynamic model of sea ice. J. Geophys. Res. 76, 1550–1575.

Mobbs, S.D. and S.E. Dover, 1993. Numerical modeling of blowing snow. Antarctic Special Topic, British Antarctic Survey, Cambridge. 55–63.

King, J.C., P.S. Anderson, M.C. Smith, and S.D. Mobbs, 1996. The surface energy and mass balance at Halley, Antarctica during winter. J. Geophys. Res. 101, 19119–19128.

King, J.C. and J. Turner, 1997. Antarctic meteorology and climatology. Cambridge University Press, Cambridge. 409.

Pomeroy, J.W., 1988. Wind transport of snow. PhD Thesis, Division of Hydrology, University of Saskatchewan, Saskatoon, Saskatchewan. 226.

Pomeroy, J.W. and D.M. Gray, 1994. Sensitivity of snow relocation and sublimation to climate and surface vegetation. in H. G. Jones, T. D. Davies, A. Ohmura, and E. M. Morris (eds.). Snow and Ice Covers: Interactions with the Atmosphere and Ecosystems. IAHS Publ. Wallingford, 223, 213-225.

Pomeroy, J.W., P. March, and D.M. Gray, 1997. Application of distributed blowing snow model to the Arctic. Hydrological Processes. 11, 1450-1465.

Semtner, A.J., 1976. A model for the thermodynamic growth of sea ice in numerical investigations of climate. J. Phys. Oceanogr. 6, 379–389.

Serreze, M.C., J.A. Maslanik, and J.R. Key, 1997. Atmospheric and sea ice characteristics of the Arctic Ocean and the SHEBA field region in the Beaufort Sea. Nat. Snow and Ice Data Cent., Coop. Inst. for Res. in Environ. Sci., Boulder, Colo. 4, 217.

Shook, K., 1995. Simulation of the ablation of prairie snowcovers. Doctoral Thesis, Division of Hydrology, University of Saskatchewan, Saskatoon. 142.

Uematsu, T., Y. Kaneda, K. Takeuchi, T. Nakata, and M. Yukumi, 1989. Numerical simulation of snowdrift development. Ann. Glaciol. 13, 265-268.

Xiao, J., R. Bintanja, S.J. Déry, G.W. Mann, and P.A. Taylor, 2000. An Intercomparison among Four Models of Blowing Snow. Boundary-Layer Meteorol. 97, 109–135.