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## Simulations of blowing Snow over Antarctica

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**ABSTRACT:** The regional climate model MAR has been used to simulate transport of snow by the wind in Adélie Land, Antarctica, over a small domain (500 x 500 km<sup>2</sup>) and with a fine horizontal resolution (5 km). Simulation of wind and temperature in the Surface Boundary Layer (SBL) for January 2011 agrees with the observation, but the horizontal flux of blowing snow is underestimated. The set-up of the model over the whole antarctic ice sheet with an horizontal resolution of 40 km exhibits a contribution of the transport to the surface mass balance which that may be much larger than previously estimated.

**KEYWORDS:** Climate Modeling, Antarctica, Snow Transport by the Wind, Snow pack.

### 1 INTRODUCTION

Erosion of snow by the wind and its subsequent sublimation and eventual export over the ocean is probably a significant component of the antarctic ice-sheet surface mass balance.

Previous estimates made by regional climate models (RCM) for the present climate indicate that its contribution amounts to roughly 10% (e.g., Lenaerts et al., 2012). The estimations may be obtained offline or performed by a blowing-snow model coupled to the RCM. Snow properties and in particular snow density play an important role in snow erosion by the wind and consequently the coupling.

The Regional Climate Model MAR is coupled to detailed snow and blowing snow models in order to provide such an estimate. The interest is in the coupling procedure which describes eventual delays between snow precipitation and snow erosion by the wind, allowing to take into account the possibility to erode fresh erodible snow and the subsequent densification of the snow pack during the erosion-deposition process.

The aim of the present paper is (i) to provide a preliminary comparison between the model and the results of a long term observation campaign in Adélie Land, made with instruments adapted to this harsh environment, and (ii) to re-assess the simulated antarctic surface mass balance, taking into account the performances of the model.

In the rest of the paper the experimental set-up and the model are shortly described in section 2 and 3 respectively. Comparisons between observation and simulation are made in section 4. The re-assessment of the antarctic surface mass balance is given in section 5 and conclusions are provided in section 6.

### 2 EXPERIMENTAL SET-UP

Observations of blowing snow were made at D17 and D47 in Adélie Land, Antarctica (see figure 1).

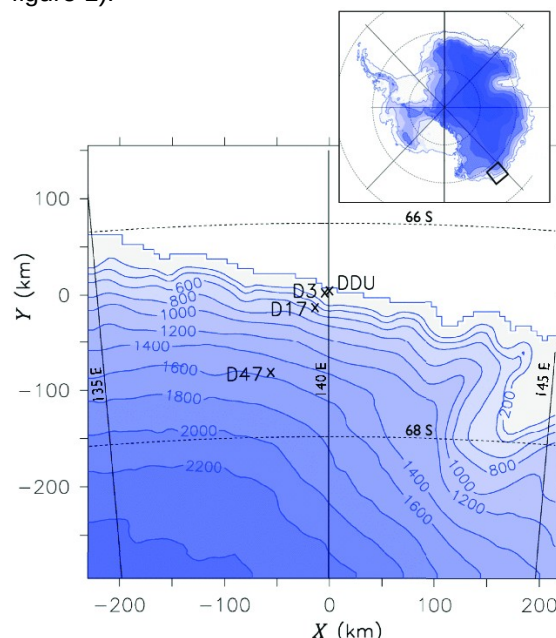


Figure 1. MAR integration Domain, Adélie Land. DDU stands for Dumont d'Urville french permanent station in Antarctica.

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We focus on January 2011, a period during which observers were on the field. This allowed us to evaluate in an easier way the possible occurrence of additional unknown processes. Indeed blowing snow is a rather unknown process so that errors may arise rapidly in its description. A similar study was already performed for January 2010 (Gallée et al., 2012), and the instruments used were FLOWCAPT which are able to detect blowing snow events only, but not to quantify the blowing snow fluxes. A new generation of FLOWCAPT was used in January 2011, and it is able to provide blowing snow fluxes, as shown elsewhere (Trouvilliez et al., this issue).

### 3 THE REGIONAL CLIMATE MODEL MAR

The coupled atmosphere / blowing snow / snow pack model is an improved version of the regional climate model MAR. An overview of MAR is given here, focused on the description of the blowing snow submodel and its coupling with the snowpack and atmospheric submodels. A full description of atmospheric dynamics is given in Gallée and Schayes (1994). The original version of the snow and blowing snow sub-models is described in Gallée et al. (2001) and a preliminary long-term validation based on a comparison with snow stake measurements is described in Gallée et al. (2005).

MAR atmospheric dynamics are based on the hydrostatic approximation of the primitive equations. This is acceptable when the vertical extent of the circulation (here the katabatic flow) is much smaller than the size of the grid (here no finer than 5 km). Nevertheless, it should be noted that non-hydrostatic processes may be responsible for a weak deceleration of the katabatic flow (Cassano and Parish, 2000). The vertical coordinate is the normalized pressure, with the model top situated at the 1 Pa pressure level. Parametrization of turbulence in the surface boundary layer (SBL) takes into account the stabilization effect by the blowing snow flux, as in Gallée et al. (2001). Turbulence above the SBL is parametrized using the local  $E - \varepsilon$  model of Bintanja (2000). In particular, it contains a parametrization of the turbulent transport of snow particles that is consistent with classical parametrizations of their sedimentation velocity. The influence of changes in the water phase on turbulence is included following Duynkerke and Driedonks (1987).

Prognostic equations are used to describe five water species, as in Gallée (1995): specific humidity, cloud droplets and ice crystals,

raindrops and snow particles. A sixth equation has been added describing the number of ice crystals. Cloud microphysical parametrizations are based on the studies of Kessler (1969), Lin et al. (1983), Meyers et al. (1992) and Levkov et al. (1992), and the influence of hydrometeors on air specific mass is included in the model as in Gallée et al. (2001). This allows the influence of the weight of eroded particles on katabatic flow dynamics to be taken into account. Furthermore, sublimation of airborne snow particles is a direct contribution to the heat and moisture budget of the atmospheric layer in which these particles are simulated. This is important because blowing snow particles may reach a significant height above the surface (Mahesh et al. 2002, Scarchilli et al., 2010). Latent heat losses due to the sublimation of blowing snow particles are taken into account in the energy budget of the atmospheric layer in which the particles are found. Contrary to Lenaerts et al. (2010, 2012a and b), they are not included in the surface budget, because they could be responsible for the underestimation of surface temperature and subsequent underestimation of surface sublimation and spurious stabilization of the SBL.

The radiative transfer through the atmosphere is parametrized as in Morcrette (2002) and is the same as that used in ERA-40 re-analyses. As blowing snow particles are small (Walden et al., 2003), they may have an impact on the radiative transfer. In MAR, the influence of snow particles on atmospheric optical depth is included (Gallée and Gorodetskaya, 2010).

In MAR, surface processes are modelled using the "soil-ice-snow-vegetation-atmosphere transfer" scheme (SISVAT, De Ridder and Gallée, 1998, Gallée et al., 2001). In particular, the snow surface albedo depends on the snow properties (dendricity, sphericity and size of the snow particles). The influence of snow erosion / deposition on surface roughness ( $z_0$ ) is taken into account by allowing the aerodynamic roughness length to increase linearly as a function of the wind speed 10 m a.g.l. ( $V_{10}$ ), when  $V_{10} > 6 \text{ m s}^{-1}$ . The time scale for sastrugi formation is assumed to be half a day, as suggested by Andreas (1995), and the asymptotic value of  $z_0$  may increase linearly as a function of the wind speed  $V$  ( $z_{0,lim} = 10 \text{ mm}$  for  $V = 20 \text{ m s}^{-1}$ ; note that the friction velocity corresponding to  $V = 20 \text{ m s}^{-1}$  is generally slightly greater than  $1 \text{ m s}^{-1}$ ).  $z_0$  is allowed to decrease when precipitation occurs with no erosion of the snow by the wind. Indeed the

newly deposited snow progressively buries the sastrugi. Andreas et al. (2005, their Fig. 1) found values of  $z_0$  ranging between approximately  $10^{-4}$  and 100 mm, for friction velocities no greater than  $0.6 \text{ m s}^{-1}$ . The scatter is very high and is explained by the high dependency of  $z_0$  on sastrugi history. Our parametrization includes that effect in a simple way, and is calibrated to obtain the best simulation of wind speed. Sastrugis contribute to surface roughness (sastrugi form drag) and hence to the loss of kinetic energy available for erosion. The contribution is represented by a decrease in the snow erosion flux and is parametrized as in Marticorena and Bergametti (1995). The increase in roughness length through the building of sastrugis is a negative feedback, and is not included e.g. in the study of Lenaerts et al. (2010, 2012a and b).

Densification of snow by the wind is included in SISVAT as in Gallée et al. (2001) with a slight modification. Snowpack densification is allowed for erodible snow layers even deep within the snow pack to account for the redistribution of snow inside a grid cell. This is because our regional climate model simulates snow pack behaviour averaged over a whole grid cell. In turn, an increase in the density of the surface snow pack is responsible for an increase in the friction velocity threshold before erosion. This is a negative feedback.

Unlike in previous versions of our model, the density of deposited blown snow particles is parametrized as a function of the wind speed, as in Kotlyakov (1961):

$$\rho = 104 (V_{10} - 6)^{0.5} \quad (1)$$

where  $\rho$  is the snow density in  $\text{kg m}^{-3}$  and  $V_{10} > 6 \text{ m s}^{-1}$ .

#### 4 COMPARISON BETWEEN MAR AND THE OBSERVATIONS AT D47 (ADELIE LAND).

Here model results for january 2011 in Adélie Land are discussed. We focuss mainly on the wind speed and the horizontal blowing snow flux at D47 (see figure 1 for the location of D47). The simulation is started one month before the period of interest, i.e., on 1st december 2010, in order to get a behaviour of the snow pack in relative equilibrium with atmospheric conditions.

#### 4.1 Wind Speed and Temperatures

Simulated wind speed and temperatures are well correlated with the observations at D47, with a correlation coefficient amounting respectively to 0.82 and 0.94. The Nash test (Nash and Sutcliffe, 1970) is relatively lower for the wind speed (0.37) than for temperature (0.48). The monthly mean temperature is well simulated at D47, But this is less the case for the simulated mean wind speed, which is underestimated by roughly 2 m/s.

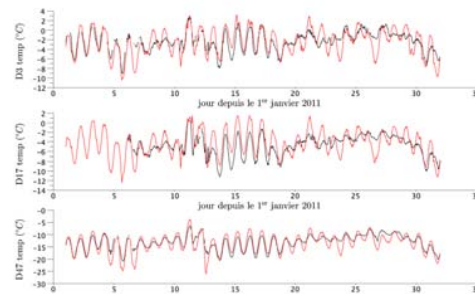


Figure 2. Comparison between simulated (dark) and observed temperature (red) at D3 (top), D17 (mid) and D47 (bottom), in January 2011.

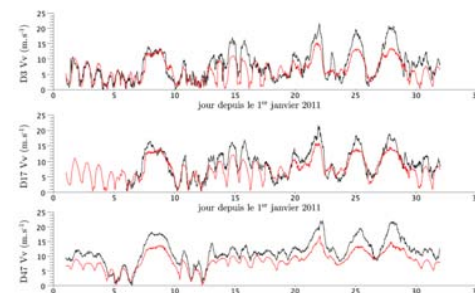


Figure 3. Comparison between simulated (dark) and observed wind speed (red) at D3 (top), D17 (mid) and D47 (bottom), in January 2011.

Note that the Nash test is better for wind speed than for temperature at D17 in January 2011 (respectively 0.60 and 0.00). This behaviour was also found for January 2010 by Gallée et al. (2012) and may be explained by an underestimation of the cloud cover by the model, leading to an overestimation of the radiative heating during daytime and of the radiative cooling during nighttime.

The better behaviour of the simulated temperatures at D47 than at D17 may be explained by the weaker influence of cloud cover and its subsequent underestimation by the model there.

Finally we note that the strong wind speed events are not well simulated by the model at D17 and at D47. The reason is possibly an underestimation of the size of the turbulent eddies by the E-e turbulent model used in MAR, precluding the transport from the top of the katabatic layer towards the surface of air parcels having a high momentum. In particular MAR is worse at D47 than at D17 regarding that point and this shortcoming will defavourably influence the simulation of the horizontal blowing snow flux.

#### 4.2 Horizontal Blowing Snow Flux.

The comparison between the simulated and observed blowing snow flux at D47 is shown in Figure 4 as a function of the wind speed.

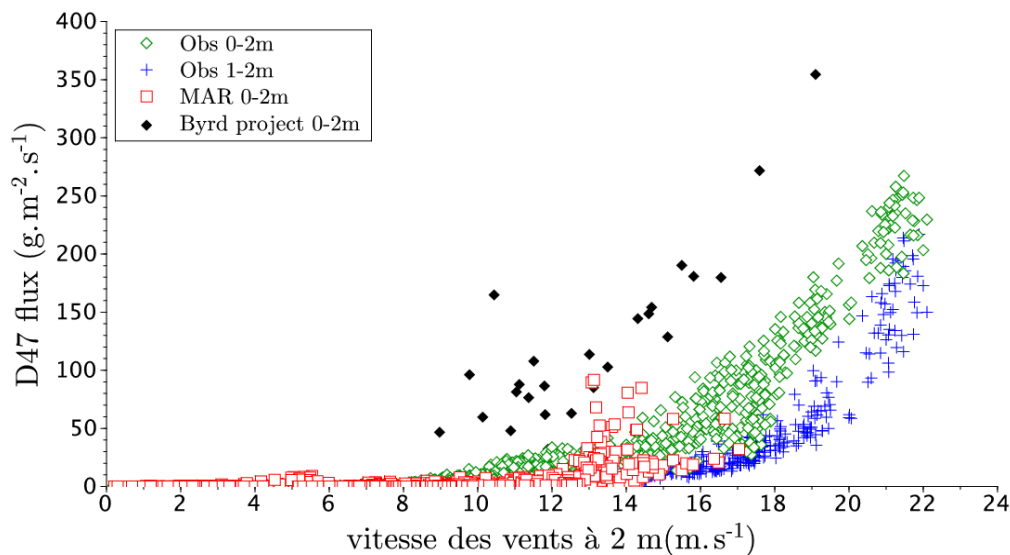


Figure 4. Horizontal blowing snow flux vs wind speed at D47. Comparison of the simulated horizontal blowing snow flux averaged between 0 and 2 m (red squares), the observed blowing snow flux averaged between 0 and 2 m (green diamonds), and the observed blowing snow flux averaged between 1 and 2 m (blue crosses). The observations made during the Byrd project (black diamonds) are also displayed on the figure.

It is found that for the same wind speed the model underestimates the horizontal blowing snow flux. Possible reasons for that underestimation are an overestimation by the model of the threshold friction velocity before erosion and/or an overestimation of the sastrugis form drag. The first reason is difficult to assess despite the fact that rare

measurements have shown that the simulated surface density is in agreement with the observation. The second reason is related to a deficit of the surface shear stress available for snow erosion. Indeed a preliminary analysis of the simulated roughness length reveals that it is slightly larger than the observed one. As the form drag is the main contributor of the roughness length it is concluded that a further calibration of the roughness length in MAR is needed.

#### 4.3 Conclusions of MAR simulation over Adélie Land.

MAR has been set up over Adélie Land, Antarctica, for a period lasting 2 months (december 2010 – january 2011).

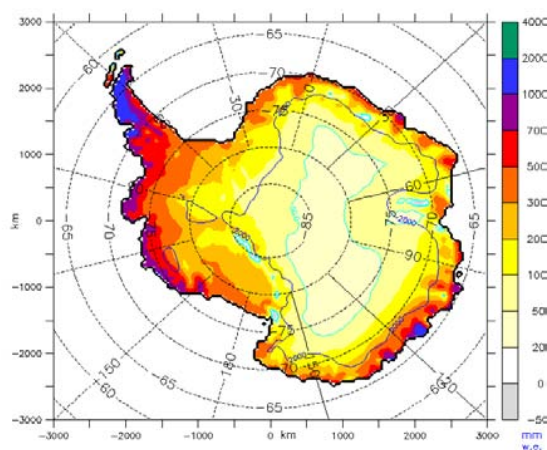
It is found that the simulated temperature and wind speed are generally in good agreement with the observations. Nevertheless the dependency of the horizontal blowing snow flux on the wind speed is only roughly half of that observed. Furthermore high wind speeds are underestimated by the model. Consequently MAR is able to provide a lower bound of the contribution of that process to the antarctic surface mass balance (ASMB).

## 5 SIMULATION OF THE ANTARCTIC SURFACE MASS BALANCE (ASMB).

Here we describe briefly the sensitivity of the MAR ASMB to the switching “on” or “off” of the blowing snow model.

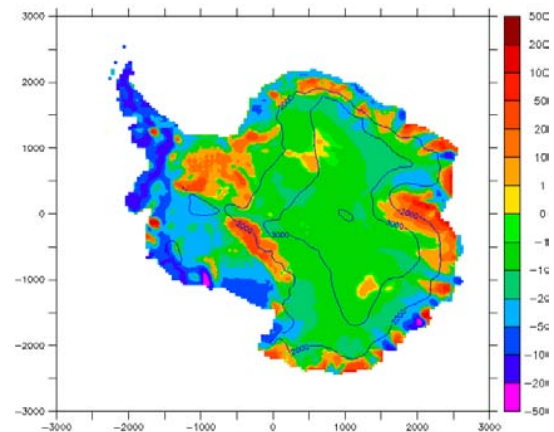
MAR is set up over the whole antarctic ice sheet with an horizontal resolution of 40 km. Sea-ice fraction, SST and lateral boundary conditions are prescribed from ERA – Interim. Meteorological fields in the lateral and upper sponge (from 20 km upwards above the surface) are also nudged to ERA – Interim data. The period 1990 – 2010 has been simulated. The initialization is performed once, on 1st january 1990 and the first year of the experiment is not included in the analysis. As the simulated SMB for the period 2004 – 2007 is representative of the whole 1991 – 2010 ASMB, a sensitivity test has also been performed by switching off the blowing snow model, for the years 2003 – 2007.

ASMB for years 1991 – 2010 is shown on figure 5 while MAR ASMB sensitivity to blowing snow is shown on figure 6 for years 2004 - 2007. The contribution of snow erosion and sublimation to the ASMB is generally negative, especially on the West Antarctic Ice Sheet, but areas characterized by a positive contribution exist, especially in some coastal areas of the East Antarctic Ice Sheet.. This behaviour is due to a weakening of the katabatic wind speed near the ice-sheet margin, mainly on the right side of topographic confluence zones, when looking downslope. In contrast the negative contribution intensifies on the left side, where katabatic air accumulates, causing an increase of the katabatic force and the subsequent increase of the katabatic winds.



MAR with Blowing Snow, 1991 – 2010 ASMB

Figure 5. Antarctic Surface Mass Balance simulated by MAR nested in ERA-Interim for the period 1990 – 2010. Blowing snow model is activated. Horizontal resolution is 40 km. Only the period 1991 – 2010 is considered.



MAR ASMB, sensitivity to Blowing Snow, 2004 – 2007

Figure 6. Antarctic Surface Mass Balance simulated by MAR nested in ERA-Interim for the period 2003 – 2007. Sensitivity to blowing snow. Horizontal resolution is 40 km. Only the period 2004 – 2007 is considered.

The ASMB averaged over the grounded Antarctic ice sheet is respectively 179.1 mm w.e. year<sup>-1</sup> and 193.1 mm w.e. year<sup>-1</sup> with and without blowing snow. This sensitivity is comparable to that obtained in previous studies. Nevertheless it could be actually much more than twice that value, since the simulated transport of snow by the wind is roughly half that observed and since the strong wind events responsible for a substantial fraction of the transport (see the observations on figure 4) are missing in MAR.

## 6 DISCUSSION

MAR has been coupled to a blowing snow model. The new model is validated over Adélie Land and it is found that the dependency of the simulated horizontal blowing snow flux on the wind speed is roughly half of that observed. Despite that fact MAR ASMB sensitivity to that process is significant, suggesting that it may be actually much larger than previously assessed.

## 7 ACKNOWLEDGMENT

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