ROUGHNESS LENGTH FOR MOMENTUM AND HEAT OVER ANTARCTICA IN A REGIONAL ATMOSPHERIC CLIMATE MODEL

C.H. Reijmer[1], E. van Meijgaard[2] and M.R. van den Broeke[1]
[1]Institute for Marine and Atmospheric Research Utrecht,
Utrecht University, Utrecht, the Netherlands
[2] Royal Netherlands Meteorological Institute, de Bilt, the Netherlands.

1 INTRODUCTION

Atmospheric models for weather and climate prediction (henceforth atmospheric models) are a very suitable tool to obtain a continent wide picture of processes involved in the interaction between the atmosphere and the (snow) surface. Two of the processes involved are the surface turbulent fluxes of heat and moisture, which are the fluxes to and from the surface caused by an atmospheric vertical temperature and humidity gradient. To calculate the surface turbulent fluxes knowledge of the surface roughness lengths for momentum (z_{0m}), heat (z_{0h}) and moisture (z_{0q}) is necessary. They are defined as the height at which, respectively, wind speed, temperature and specific humidity assume their surface values. In atmospheric models the roughness lengths for land surfaces are prescribed surface characteristic fields based on empirical results. Owing to the limited amount of measurements, z_{0h} and z_{0q} are often set equal to z_{0m} or $0.1 \times z_{0m}$. Over Antarctica this results in too much evaporation and sublimation, especially in mountainous areas (Van Lipzig *et al.*, 2002) and it may also result in a bias in the sensible heat flux (Cassano *et al.*, 2001). This emphasises the necessity of using different parameterisations for z_{0h} and z_{0q}.

In this study we examine the effect of changes in z_{0m} and z_{0h} on the general structure of the atmosphere, and on the surface energy fluxes over Antarctica by means of a regional atmospheric climate model.

2 EXPERIMENTAL SET UP

We use the Regional Atmospheric Climate Model (RACMO) (Christensen *et al.*, 1996) with a ~55 km horizontal resolution and 20 hybrid-levels in the vertical. The parameterisations of the physical processes are taken from the ECHAM4 model (Roeckner *et al.*, 1996) with some adjustments to improve the representation of the physical processes over Antarctica (Van Lipzig *et al.*, 1999). The formulation of the dynamical processes is adopted from the High-Resolution Limited Area Model (HIRLAM) (Gustafsson, 1993). The model is initialized once and forced every six hours at the lateral boundaries and at the sea surface by European Center for Medium-Range Weather Forecasts (ECMWF) operational analyses. The inner part of the model is allowed to evolve freely.

RACMO distinguishes between three surface types in the description of the roughness lengths; sea, sea ice and land surfaces. The ice shelves are treated as grounded ice and are therefore part of the Antarctic continent and treated as land. For snow covered land the z_{0m}-field is based on a climatological value for snow and corrections due to variations in orography (Figure 1). z_{0h} is taken equal to z_{0m} and z_{0q} is assumed equal to z_{0h}.

A total of four experiments were carried out in which z_{0m} and/or z_{0h} over land were altered with respect to a control experiment (CTL) (Table 1). In CTL the z_{0m}-field of the ECMWF model is adopted (henceforth CTL-field). In all experiments the assumption is made that z_{0q} equals

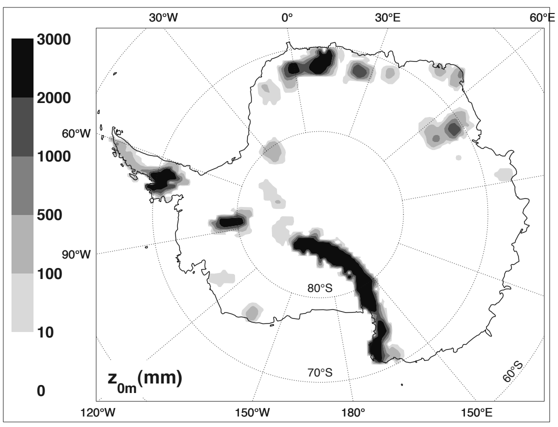

Fig. 1. Surface roughness length for momentum (z_{0m}) for Antarctica as used in experiments CTL, CNS and AND based on the ECMWF field maximized at 3 m.

[0]*Corresponding author address:* C.H. Reijmer, Inst. for Marine and Atmosph. Res. Utrecht, Utrecht Univ., Princetonplein 5 , 3584 CC Utrecht, the Netherlands; e-mail: c.h.reijmer@phys.uu.nl

Table 1. Summary of the experiments. ECMWF is the ECMWF z_{0m}-field limited to 3 m (Figure 1), Andreas is the surface renewal model of Andreas (1987) with $z_{0m} = 10^{-3}$ m.

Experiment	z_{0m}	z_{0h}
CTL	ECMWF	z_{0m}
CNS	ECMWF	10^{-3} m
CNSC	10^{-3} m	10^{-3} m
AND	ECMWF	Andreas
ANDC	10^{-3} m	Andreas

z_{0h}, z_{0m} and z_{0h} are limited to 3 m to constrain it to values smaller than the altitude of the lowest model level. Each experiment consists of a summer and a winter month, January and July 1998.

For z_{0m} two and for z_{0h} three formulations are tested (Table 1). In AND and ANDC z_{0h} is a function of the atmospheric conditions by using the surface renewal model of Andreas (1987). The surface renewal model predicts ln($z_{0h}\,/\,z_{0m}$) as a function of the roughness Reynolds number (Re_*):

$$Re_* = \frac{u_*\, z_{0m}}{\nu} \ ,$$

$$\ln\left(\frac{z_{0h}}{z_{0m}}\right) = a_1 + a_2\ \ln(Re_*) + a_3\ \ln(Re_*)^2 \ . \quad (1)$$

Here, u_* is the friction velocity and ν is the kinematic viscosity (1.35$\cdot$ 10^{-5} $m^2\,s^{-1}$). Andreas (1987) defines three regimes, a smooth regime ($Re_* \leq$ 0.135), a transition regime (0.135 $< Re_* <$ 2.5) and a rough regime (2.5 $\leq Re_* \leq$ 1000). The coefficients a_1, a_2 and a_3 differ per regime. In the description of Andreas (1987) z_{0q} is not equal to z_{0h}. Here, we assume that they are equal which may result in a slight underestimation of the moisture fluxes but differences are small. In experiment AND, z_{0m} in equation 1 is set to a constant value of 10^{-3} m, neglecting the orographic influence incorporated in z_{0m} on z_{0h}. This is justified by the fact that the characteristic length scale of the diffusion process responsible for the transfer of heat and moisture is determined by the size of small scale surface elements and does not depend on larger scale inhomogeneities like mountains (Smeets, 2000). Note that since the ECMWF z_{0m}-field is $\geq 10^{-3}$ m over the Antarctic continent, in all experiments the proposed changes in z_{0h} and z_{0m} make them smaller (or remain equal) compared to CTL. The results of the experiments are presented in terms of changes with respect to CTL.

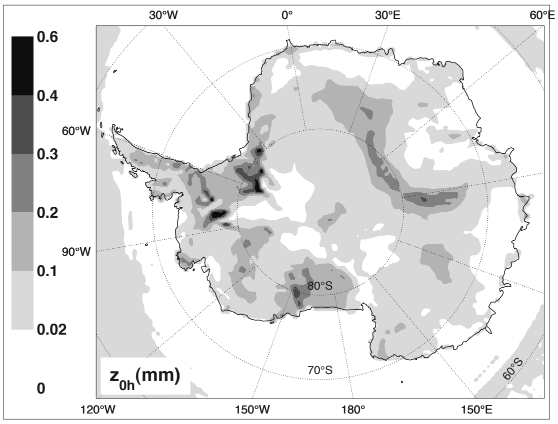

Fig. 2. Monthly averaged surface roughness length for heat (z_{0h}) for July 1998 for ANDC.

3 RESULTS

3.1 Spatial variations

Figure 1 presents the z_{0m}-field as used in experiments CTL, CNS and AND. The climatological value of z_{0m} for snow without orographic effects is 10^{-3} m, a value found over large parts of the continent. Values as large as 3 m are found over the Trans-Antarctic mountain range, the Antarctic Peninsula and in Dronning Maud Land, areas where the orography is expected to have a large impact on the resolved flow.

The z_{0h} values in CNS, CNSC, AND and ANDC are considerably smaller than in CTL. In experiments AND and ANDC z_{0h} depends on the near surface wind speed via u_*, and varies between ∼0.01 and 0.6$\cdot 10^{-3}$ m (Figure 2). The dependence on wind speed results in a decrease in z_{0h} with increasing wind speed. Figure 2 presents the monthly averaged z_{0h} for ANDC for July 1998. The figure shows lower values of z_{0h} in the escarpment region of the East Antarctic plateau where wind speeds are higher. The importance of the topography in forcing the katabatic wind is also visible through the outlines of the topography of the East Antarctic plateau in the pattern of z_{0h}. In AND (not shown) z_{0h} exhibits a similar pattern as in ANDC but with slightly lower values due to lower values of u_*. Since z_{0m} is smaller in ANDC compared to AND the lower values of z_{0h} and u_* in ANDC are due to the fact that the impact of a reduced z_{0m} on u_* is larger than the effect of an increase in wind speed caused by a reduction in z_{0m} on u_*.

3.2 Near surface conditions

Wind speed Changes in z_{0m} and z_{0h} have a large impact on the exchange of momentum, heat and moisture between surface and atmosphere and, consequently, on the structure of the overly-

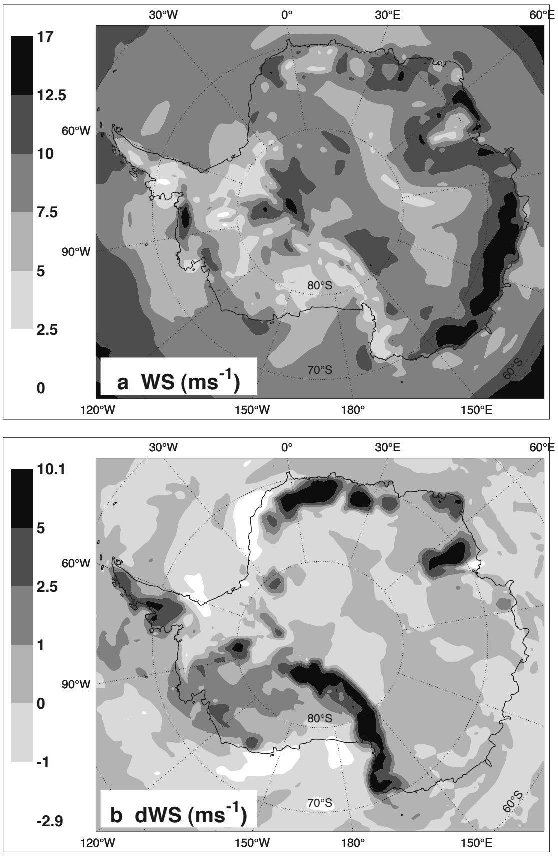

Fig. 3. Monthly averaged 10 m wind speed (WS) for CTL (a) and wind speed difference (dWS) (ANDC - CTL) (b) for July 1998.

ing atmosphere. The basic effect of lowering z_{0m} is a reduction of the friction exerted by the surface on the atmospheric flow resulting in an increase in the near surface wind speed (Figure 3). The largest increase occurs in the escarpment regions where the decrease in z_{0m} is largest. The effect on wind speed of changing z_{0h} is an order of magnitude smaller than the effect of changing z_{0m}. Monthly averaged regional changes of $\pm 2\ \mathrm{m\,s^{-1}}$ occur due to changes in z_{0h} while a lowering of z_{0m} may result in regional wind speed increases up to $10\ \mathrm{m\,s^{-1}}$. Averaged over the continent the 10 m wind speed increases from 4.8 to $5.3\ \mathrm{m\,s^{-1}}$ in January and from 8.2 to $9.0\ \mathrm{m\,s^{-1}}$ in July when lowering z_{0m} from the CTL-field to a constant value. On a continental scale, lowering z_{0h} has only a marginal effect on wind speed.

Temperature The effect of changes in z_{0m} and z_{0h} on near surface temperature is more complicated and is only to some extend directly related to changes in z_{0m} and z_{0h}. Small changes in the large-scale circulation patterns owing to changes in the surface roughness lengths changing the advection patterns of heat also affect the temperature. The monthly averaged regional changes over the continent with respect to CTL may range between ± 3°C in January and ± 10°C in July. The large variations in July are due to the fact that the horizontal and vertical temperature gradients in winter are larger than in summer. Averaged over the continent the surface temperature decreases and the temperature at the lowest model level increases (except in CNS) compared to CTL. This results in an increase in the temperature gradient between the surface and the lowest model level and an increase in near surface static stability which is largest for AND and ANDC.

Turbulent fluxes Changing z_{0m} and z_{0h} has a direct effect on the magnitude of the turbulent fluxes of heat (H) and moisture (LE) as well as an indirect effect by changing the near surface wind speed, temperature and specific humidity. Lowering z_{0m} and z_{0h} has the effect of reducing the magnitude of the turbulent fluxes owing to the decrease in u_* and increase in static stability of the boundary layer. Lowering z_{0h} has the largest effect in AND and ANDC. Over the Antarctic plateau changes in H and LE are small. Over large parts of the continent LE is positive (towards the surface) in July (0 - 5 $\mathrm{W\,m^{-2}}$) indicating that deposition occurs in all experiments. The

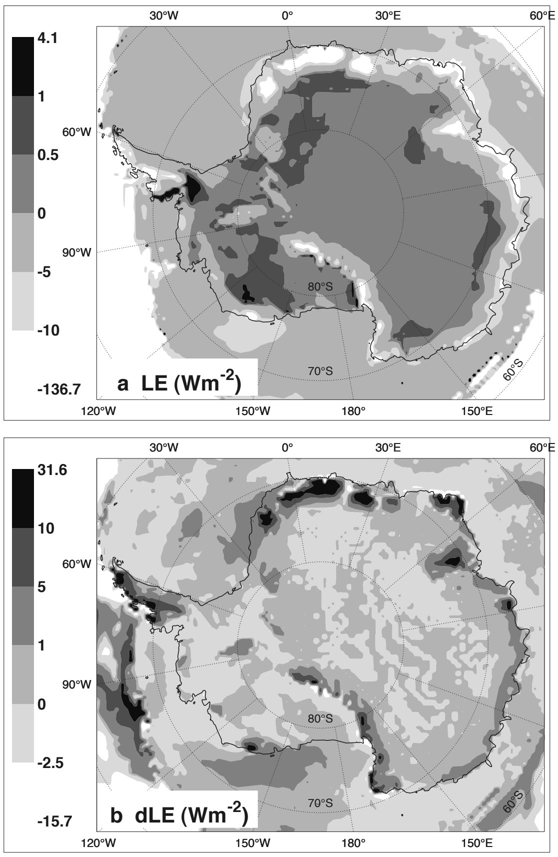

Fig. 4. Monthly averaged surface latent heat flux (LE) for CTL (a) and latent heat flux difference (dLE) (ANDC - CTL) (b) for July 1998.

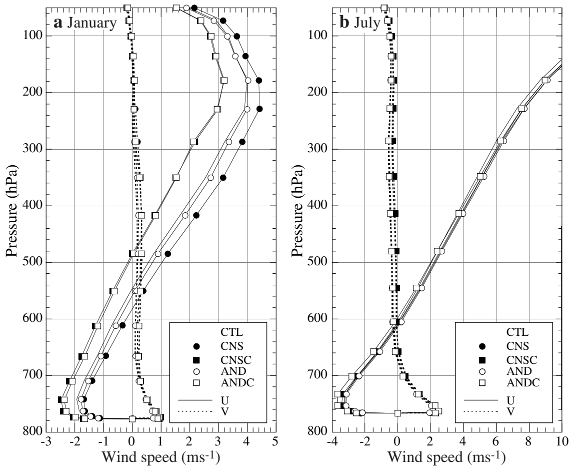

Fig. 5. Monthly and continentally averaged profiles of the zonal (straight lines, U) and meridional (dotted lines, V) component of the wind speed for January (a) and July (b) 1998.

amount of deposition decreases when decreasing z_{0m} and z_{0h}.

The reduction in H and LE is largest in the escarpment regions and mountainous areas where the change in z_{0h} is largest (Figure 4). LE is negative (away from the surface) in the escarpment region indicating sublimation. Reducing z_{0h} generally results in the disappearance of the areas with extreme amounts of sublimation as found by Van Lipzig *et al.* (2002). Extreme values of LE found in the escarpment regions in CTL are ~-45 W m^{-2} in January and ~-40 W m^{-2} in July. Reducing z_{0h} typically reduces these values to ~-30 W m^{-2} in January and ~-10 W m^{-2} in July.

3.3 Vertical profiles

The changes at the surface propagate to the overlying atmosphere, changing the profiles of wind, temperature and humidity. The wind speed profiles show the most pronounced changes, which are caused mainly by changes in z_{0m}. Figure 5 presents the continentally and monthly averaged profiles of the zonal and meridional component of the wind speed. The profiles show the expected increase in wind speed in the boundary layer. The variations caused by changes in z_{0h} (CNS and AND) are an order of magnitude smaller than the changes due to changing z_{0m} (CNSC and ANDC). The wind speed profiles also exhibit large variations above the boundary layer, especially in January. These variations are most pronounced in the zonal component of the wind speed. The profiles show that the layer where south-easterly surface winds prevail thickens considerably and the strength of the westerly large-scale flow decreases. In July this change is an order of magnitude smaller and not visible in Figure 5.

4 SUMMARY

The effects of changing the roughness lengths on average surface and atmospheric parameters are significant not only near the surface but also at higher levels in the atmosphere. The reduction of z_{0m} results in the expected increase in near surface wind speed which is largest in the escarpment regions where the changes in z_{0m} are largest. Changes in z_{0h} have little effect on the magnitude of the wind speed. The effect of a reduced z_{0m} is not confined to the boundary layer. On average the depth of the surface wind layer increases and the influence of the large-scale flow reduces. This effect is most pronounced in summer. Changes in the surface temperature and temperature profiles due to changes in the roughness lengths are not unequivocal. The general trend is a decrease in surface temperature and an increase in atmospheric temperature resulting in an increase in static stability of the boundary layer. Changes in temperature are not only caused by changes in roughness lengths but also by small changes in flow patterns changing the advection of heat and moisture plus changes in radiation caused by differing cloud cover. The surface heat fluxes are on average reduced by the changes in roughness length with the largest impact due to changes in z_{0h}.

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