Flow Across the Antarctic Plateau

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1 Introduction

Precipitation is an important parameter to control the growth and decay of the Antarctic ice shield. Due to lack of adequate measuring facilities, only few reliable observation data on precipitation sums are available. At present, precipitation climatology for Antarctica is only interpreted from annual ice accumulation observations (King and Turner, 1997). Therefore, precipitation simulation for Antarctic conditions with numerical weather prediction models (see e.g. Bromwich et al. (2001) and Powers et al. (2003) for the US American Antarctic Mesoscale Prediction System (AMPS)) and with climate models (e.g. van Lipzig et al., 2002; Bromwich et al., 2004) has gained much attention during the last years.

A striking feature in Antarctic precipitation climatology is the sharp inland decrease in precipitation amount from the order of 500 mm water equivalent to less than 50 mm on the central Antarctic plateau. The precipitation distribution in the coastal regions is strongly influenced by topography, namely the escarpment of the plateau with more than 2000 m height difference.

In this contribution, the influence of the plateau and its precipice on the distribution of clouds and precipitation will be investigated. To that end we perform and evaluate simulations with LM of DWD for Antarctic conditions. A weather situation is selected in which the air flow approaches the plateau nearly perpendicular. The effect of the excited gravity waves on the precipitation distribution will be investigated with the help of two-dimensional simulations of an idealized flow over a plateau.

2 Model Setup

The LM version V3.15 is implemented for the Antarctic region. For the case studies presented the domain is centered around the Neumayer Station (70°39'S, 8°15'W) with 321 × 201 gridpoints of about 7 km mesh size. The atmosphere is divided into 35 vertical layers of unequal thicknesses. The simulation is started on 10 January, 2002 0000 UTC and run for 48 hours. The initial and boundary data are obtained by interpolating ECMWF analysis and forecast data onto the LM grid.

The simulation of the idealized flow is performed with the two-dimensional version of LM (here: V2.19) for a channel of 22000 km length in x-direction. This length is sufficient to find in the interior a reasonably large area where gravity waves spread without any serious boundary effects. The topography is prescribed in form of a cosine-shaped slope towards the plateau of 2000 m height. As in the three-dimensional simulations, a 7 km mesh size and 35 vertical layers are chosen. The model run is started from a prescribed field and run for 10 days to reach a quasi-steady state; this state will be interpreted later. At the inflow boundary, the values are kept constant; at the outflow boundary, we assume a vanishing gradient in x-direction.

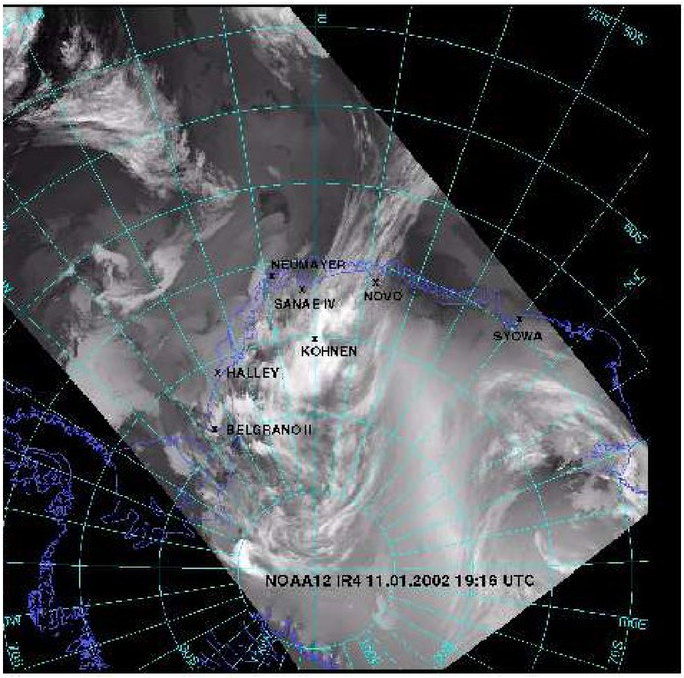

Figure 1: IR satellite image valid at 11 January, 2002 1916 UTC.

In both types of simulation we use the *cloud ice scheme* for parameterization of microphysics in grid scale clouds, as described in Doms et.al. (2005). The precipitation concentrations are calculated either according to the column equilibrium approach or by solving the full prognostic budget equation (Baldauf and Schulz, 2004).

3 Situation from January, 2002

The weather situation from 10 to 12 January, 2002, in the larger surrounding of Neumayer Station was characterized by a huge frontal system moving from the Drake passage in south-eastern direction toward the Antarctic coast and penetrating into Dronning Maud Land (DML); see the cloud bands in the satellite image valid for 11 January, 2002 1916 UTC given in Fig. 1.

The horizontal distribution of mean sea level pressure, given in Figure 2 (left) for simulation valid at 11 January, 2002 0000 UTC, shows the low pressure system with center over the Weddell Sea. The turning of the near surface wind direction to the left indicates the position of a cold front/occluded front. East of the front the flow at about 15°E over the ocean is nearly perpendicular to the plateau; close to the coast and inland the flow is deflected due to the mountains. As a result of this flow field, (see the horizontal distribution of relative humidity in Fig. 2 (right)) moist air is advected aloft by the northerly flow in the warm sector.

The meteorological observatory of the Neumayer Station provides 3-hourly routine synoptic observations. In Fig. 3 the observed vertical profiles of temperature and of relative humidity are given together with a time series of simulated profiles taken at the grid point nearest to the station. The thick green lines mark the simulated profiles for the time closest to the launch of the radiosonde.

The temperature profiles agree reasonbly well in the free atmosphere and show a stable stratification. In the lower troposphere, the simulated profiles evolve towards nearly isothermal

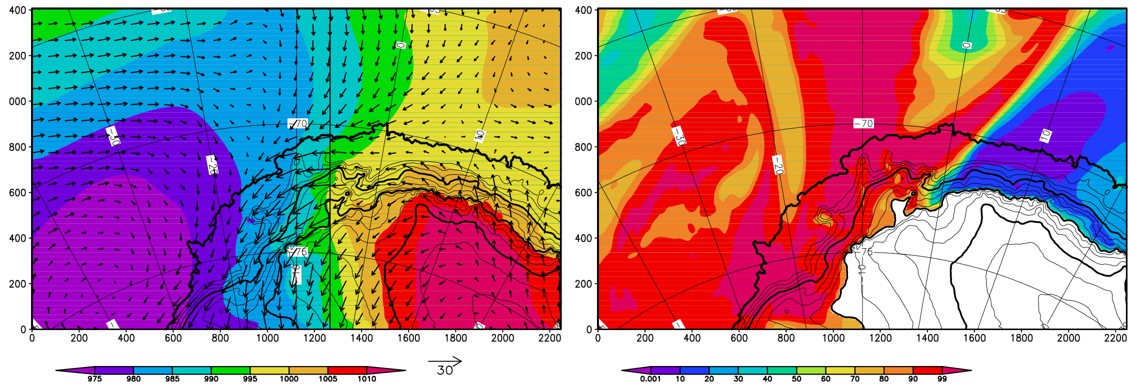

Figure 2: Horizontal distribution of simulated mean sea level pressure (in hPa) and near surface horizontal wind field (left) and of relative humidity (in %) at 2000 m above sea level (right). No relative humidity data are plotted for surface heights larger than 2000 m. Data follow from 24h simulation valid at 11 January, 2002 0000 UTC. Black lines give topographical heights in 250 m intervals starting at 0 m. Black vertical line at ca 1260 km in left figure marks position of vertical cross section for Fig. 5.

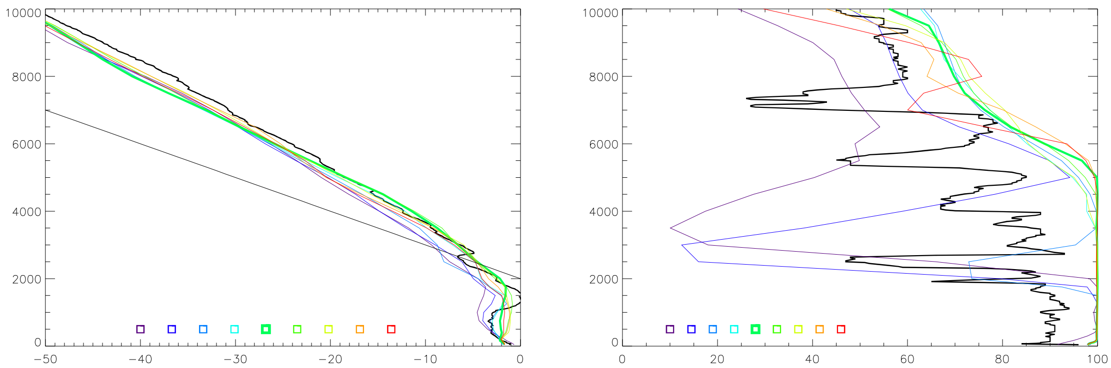

Figure 3: Vertical profiles of temperature (in °C; left) and of relative humidity (in %; right). Thick black lines give results from radiosonde launched at Neumayer Station on 10 January, 2002 1100 UTC. Coloured lines give simulated profiles from the model run started at 10 January, 2002, 0000 UTC for the grid point closest to Neumayer Station; data are valid from 00 h (purple) to 24 h (red) simulation time in three hourly intervals. Thin black straight line gives a dry adiabatic temperature profile.

ones; however, they do not show the observed inversion between 1000 to 1500 m height. The observed profile of relative humidity shows values of about 80 to 90 % in the lower and mid troposphere and a decrease above. In between, dry layers are observed with changes of up to 40 % over a distance less than 100 m. It is expected that such variations cannot be simulated with LM let alone due to the larger depth of the vertical layers. Although the simulations start with a dry mid troposphere, a water saturated lower and mid troposphere develops, probably due to the persistent advection of moist air and only few ice formation.

Figure 4 (left) shows the horizontal distribution of the simulated 6 hours precipitation sums. The distribution reflects the forcing due to the synoptic situation and topography. The latter is well seen in the precipitation enhancement on the upslope side of the plateau. The peak values with precipitation sums above 30 mm may be overestimated, since the annual mean precipitation sums amount here to only several hundreds of mm. From synoptic observations at the Neumayer Station, continuous moderate snow fall was reported on 10

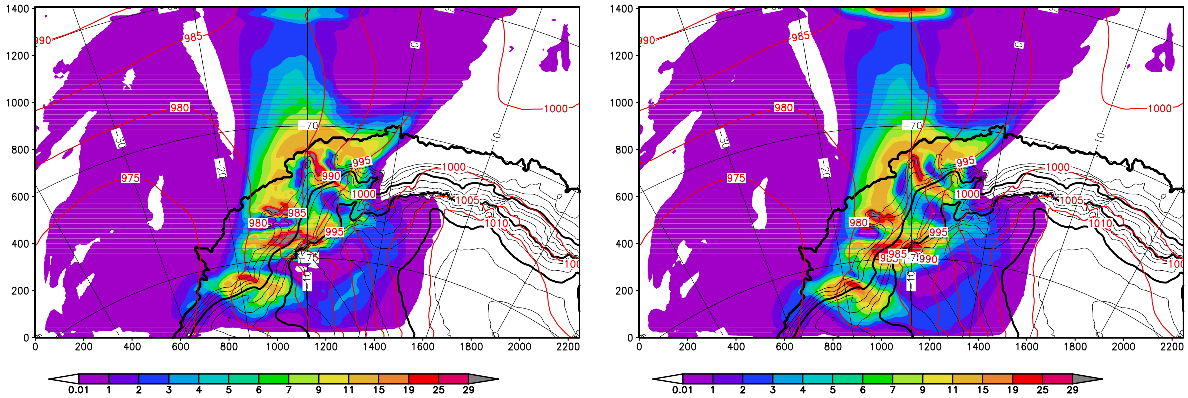

Figure 4: Horizontal distribution of simulated 6 hours precipitation sums valid for the 6 hours interval 10 January, 1800 UTC to 11 January, 0000 UTC. Left: Precipitation fluxes are calculated using the column equilibrium approach. Right: Precipitation concentrations are calculated using the full precipitation mass budget equation. Red lines denote mean sea level pressure (in hPa) for 11 January, 2002 0000 UTC.

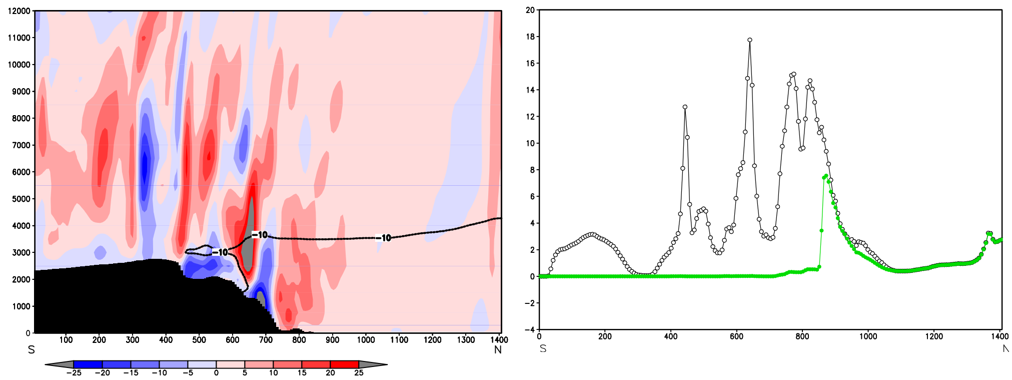

Figure 5: Left: Vertical cross section for vertical velocity w (in cm s^{-1}) in north-south direction along the line marked in Fig. 2 (left). Thick line gives – 10°C isotherm. Simulated data are valid for 11 January, 2002 0000 UTC. x-axis gives distance from southern domain boundary in km. Right: Surface precipitation sum (in mm) along the cross-section for period as in Fig. 4. Green line indicates rain, black line indicates rain plus snow.

and 11 January, 2002 from 10 January, 2002 1500 UTC to 12 January, 2002 0900 UTC. No precipitation sums are registered. In the region on the plateau, which does not show strong topographic variations and which is yet unaffected by the approaching front, remarkable horizontal variations in precipitation are found.

The precipitation variations in north–south direction are inspected by looking at a cross section of vertical velocity and of precipitation (Fig. 5) along the line marked in Fig. 2. Certainly the w-field is strongly affected by topography. Over land the near surface wind is frequently directed downward along the sloping surface and thus has negative vertical component in those regions. Nevertheless, a wavy pattern can be recognized, whereby the axes of the upwind and downwind cells are tilted with height slightly towards the north, that is in upstream direction. This distribution suggests the presence of gravity waves.

Due to the topographically induced rising of the comparatively warm and moist air, the simulated cloud water and cloud ice cells are in close connection with the upwind pattern (not shown), with maximum concentrations at the downstream side of the upwind cells. The simulated 6 hour sum of surface precipitation, given in Fig. 5 (right), shows three successive peaks, each around 15 mm. In the cold air over the slope and the plateau all simulated precipitation falls as ice as expected, while over the ocean most of the falling precipitation reaches the surface as rain.

4. Gravity Waves in an Idealized Flow Field

Apart from the major mechanisms influencing the distribution of precipitation, that are the approaching front and the topographical details, we suggest that the velocity field and the precipitation pattern over the continent (as seen in Figs. 4 and 5 (right)) are also influenced by the occurrence gravity waves. To find out the pure gravity wave phenomena for a flow over a plateau, the results from two-dimensional simulations with idealized initial and topographic conditions are now presented. A topography is prescribed in a form to resemble the Antarctic plateau in DML. The surface height increases from zero to 2000 m height over a distance of approximately 500 km. The following case study is calculated, however, for conditions of 45°N.

The vertical cross section of the field of vertical velocity is given in Fig. 6 (left). A strong rising of air occurs immediately above the slope; further downstream one finds the bands of rising and sinking air with axes tilted upstream with height. Even though we consider a plateau, the cells are similar to the pattern found for mountain gravity waves excited by a single hill or a periodic sequel of hills, as assumed in typical idealized gravity wave studies (e.g. Smith, 1979). The w-fields in Fig. 5 (left) and in Fig. 6 (left) show a similar overall spatial pattern. They differ, however, insofar as that in the idealized case (i) the vertical velocities are generally weaker than in the case shown in Fig. 5), (ii) the cells above the plateau are much weaker than the cell over the slope, and (iii) the wave length, being of the order of 1000 km, is larger than in the case from Section 3. The differences may be attributed, at least partly, to the deviations in the topography, and certainly also to the deviations in the atmospheric general situation. Moreover, in the southern part of the model domain on the left hand side in Fig. 5 (left) the intensity of the wave seems to be damped; this, however, may also be due to boundary effects.

The precipitation pattern in the idealized simulation is shown in Fig. 6 (right). The highest precipitation sum is found above the escarpment, related to the strong upwind cell. Downstream, across the plateau, the intensity rapidly decreases below to about 1 mm, but due to the up-/downwind pattern, weak peaks are perceived.

5. Discussion

This study has reported on results from the first-time application of LM for Antarctic conditions. Bearing in mind that no specific modifications were introduced, the overall quality of the LM-simulations is satisfying.

The study reveals first informations on the order of magnitude and the horizontal distribution of precipitation on the Antarctic continent. The horizontal variability reflects strongly the synoptic and topographic forcing. On the plateau, where these forcings become weak, we do not find a monotonous decrease in precipitation. From the distribution of vertical velocity in combination with results of two-dimensional simulations we suggest the presence of topographically induced gravity waves. Weather situations, in which the northerly flow is nearly perpendicular to the plateau, are characteristic for the generation of gravity waves. The re-

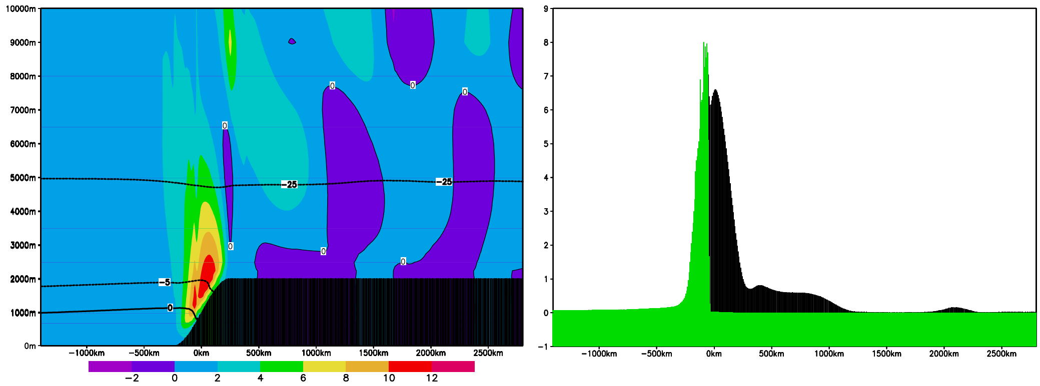

Figure 6: Left: Vertical cross section for vertical velocity w (in cm s^{-1}) for the idealized 2-dimensional quasi-steady state flow field. Horizontal flow is from left to right. x-axis gives distance from the center of the slope in km. Thick black line marks isotherms (in °C). Right: Surface precipitation sum (in mm within 6 hours) along the cross-section. Green shading marks rain, black shading marks rain plus snow.

lated upwind and downwind cells provoke a corresponding surface precipitation pattern with several precipitation peak values above the plateau. Although the peaks are strongly damped with increasing distance from the escarpment, they nevertheless inhibit a monotonous decrease in precipitation amount inland the Antarctic continent. This result from the idealized case study confirms the interpretation, that despite of the plateau-shaped topography, we should not expect a monotonously decreasing precipitation distribution downstream over the plateau in synoptic situations when the air flows perpendicular towards the plateau.

In the simulations discussed up to now, the precipitation flux is calculated by using the so-called column equilibrium approach. Fig. 4 (right) now shows the horizontal distribution of 6 hour precipitation sums, as follow if the full precipitation mass balance equation is solved. Both precipitation distributions given in Fig. 4 are very similar, since precipitation is mainly forced by the synoptic situation and topography. When using the prognostic treatment, however, the peak values of precipitation sums are damped and shifted downstream. With regard to the profile shown in Fig. 5 (right), the two peaks over the plateau are reduced to less than 15 mm, and all three maxima are shifted about 20 km downstream.

Certainly, several deficits in the simulations are obvious, although lacking the possibility of a proper verification. (i) The precipitation sums over the Antarctic plateau seem to be overestimated. (ii) Huge precipitation sums are found at the northern inflow boundary, see Fig. 4, in particular when using the solution of the full budget equation for precipitation mass; their origin should be looked for in the model physics of LM and of ECMWF-model, which provides the boundary data. (iii) Cloud ice is found mostly at levels where temperature drops below −25°C (not shown here) in the 3-dimensional as well as in the 2-dimensional simulations. This is in agreement with the LM results presented by Doms et al. (2004). It is speculated that the confine of cloud ice to such a threshold temperature may be related to an assumption in the cloud ice parameterization scheme: namely that cloud ice nucleation requires water saturation for $T > -25$°C, and only for $T \leq -25$°C ice saturation is sufficient for the initiation of cloud ice. This hypothesis is supported by the simulated vertical profile of relative humidity e.g. for 1200 UTC (see Fig. 3), which indicates a mostly water saturated troposphere for temperatures above about −20°C. Since the cloud microphysics parameterization used in the ECMWF model simulates clouds at temperature below 0°C already at water subsaturation, the prescription of ECMWF-model boundary data may cause a too dry model atmosphere for the temperature range $-25°C < T < 0°C$ with regard to cloud ice formation by LM.

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References

Baldauf, M. and J.-P. Schulz, 2004: Prognostic precipitation in the Lokal Modell (LM) of DWD. *COSMO Newsletter*, No. 4, pp. 177-180. availabe at `http://www.cosmo-model.org`.

Bromwich, D.H., A.J. Monaghan, J.J. Powers, J.J. Cassano, H. Wei, Y. Kuo, and A. Pellegrini, 2003: Antarctic Mesoscale Prediction System (AMPS): A case study from the 2000/2001 field season. *Mon. Wea. Rev.*, 131, 412-434.

Bromwich, D.H., Z.Guo, L.Bai, and A. Chen, 2004: Modeled antarctic precipitation. Part I: Spatial and temporal variability. *J. Climate.*, 17, 427-447.

Doms, G., J. Förstner, E. Heise, H.-J. Herzog, M. Raschendorfer, R. Schrodin, T. Reinhardt, and G. Vogel, 2005: *A Description of the Nonhydrostatic Regional Model LM, Part II: Physical Parameterizations.* DWD, GB Forschung und Entwicklung, 2005.

Doms, G., D. Majewski, A. Müller, and B. Ritter, 2004: Recent changes to the cloud-ice scheme. *COSMO Newsletter*, No. 4, pp 177-180. availabe at `http://www.cosmo-model.org`

King, J.C. and J. Turner, 1997: *Antarctic Meteorology and Climatology.* Cambridge: University Press, 409 pp.

van Lipzig, N.P.M., E. v. Meijgaard, and J. Oerlemans, 2002: The spatial and temporal variability of the surface mass balance in Antarctica: Results from a regional climate model. *Int. J. Climatol.*, 22, pp. 1197-1217.

Powers, J.J., A.J. Monaghan, A.M. Cayette, D.H. Bromwich, Y.-H. Kuo, and K.W. Manning, 2003: Real-time mesoscale modeling over Antarctica. *Bull.Amer.Meteor.Soc.*, 84, pp. 1533-1545.

Smith, R.B., 1979: The influence of mountains on the atmosphere. *Advances in Geophys., Academic Press*, Vol.21, pp. 87-230.