SIMULATION OF OROGRAPHIC CIRRUS IN THE GLOBAL CLIMATE MODEL ECHAM5

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A comparison of satellite data with simulations from global circulation models shows that there is a lack of cirrus cloud amount in large-scale models above and in the lee of mountains. The formation of orographic cirrus clouds due to gravity waves is usually not parameterized in large-scale models. To improve the simulation of such orographically excited cirrus clouds a coupling of the gravity wave dynamics and the cloud microphysics has been implemented in the climate model ECHAM5. As homogeneous freezing of solution droplets strongly depends on the vertical velocity, an increased vertical velocity due to gravity wave activity in the upper troposphere leads to the formation of cirrus clouds with higher ice crystal number densities. A comparison of the new parameterization with measurements shows a better agreement with observations.

1 INTRODUCTION

Cirrus clouds play an important role in the climate system. They cover approx. 30% of the earth and can influence the radiative budget of the earth in two different ways. Ice crystals scatter part of the incoming solar radiation back to space. This leads to a cooling of the underlying atmosphere (albedo effect of clouds). On the other hand, ice crystals reduce the outgoing longwave radiation and can lead to a warming (greenhouse effect of clouds). Which process is dominant depends on the properties of the cirrus cloud like ice crystal number density, thickness of the cloud and ice water content. In general it is thought that optically thin cirrus have a warming effect and optically thick cirrus a cooling effect. Thus, a net global warming of the Earth-atmosphere system due to cirrus clouds is possible (Chen et al., 2000). However, an estimate of the global influence of cirrus clouds on the radiative budget is very complex as the formation processes and the life cycle of cirrus clouds are not very well known (Spichtinger et al., 2005a,b) and especially the transition from the cooling to the warming regime is not yet completely understood. Recent studies indicate that the ice crystal number density plays a crucial role for the transition from warming to cooling due to cirrus clouds (Fusina et al., 2007).

An important factor for triggering the formation of ice is the vertical velocity. It induces adiabatic cooling and thus an increase of the relative humidity with respect to ice. Mesoscale velocity fluctuations in the range of 10-50 cm/s amplify homogeneous nucleation (Haag and Kärcher, 2004; Hoyle et al., 2005). Amongst others, these mesoscale fluctuations in the vertical velocity can be induced by gravity waves. One important source of gravity waves are mountains producing orographic waves. There are lots of mountainous regions in the world,

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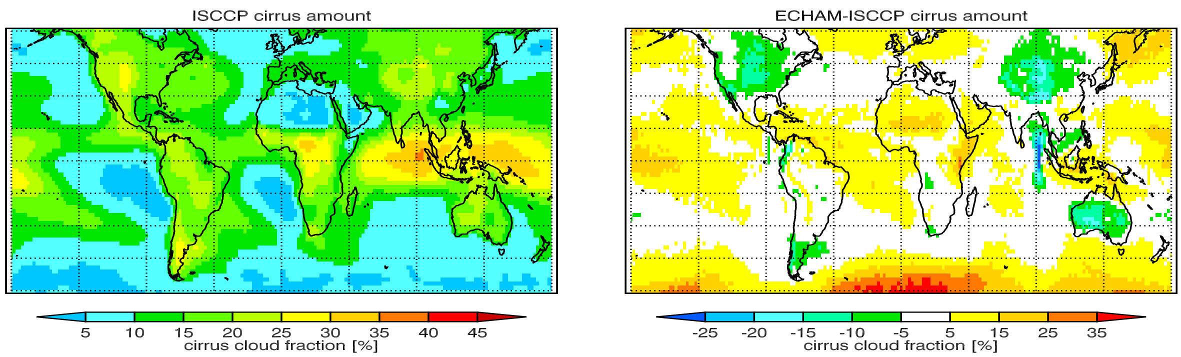

Fig. 1: Annual mean ISCCP Cirrus cloud amount (percentage of a gridbox covered with cirrus) for the years 1983-2005 (left) and the difference between a three year ECHAM5 simulation and ISCCP. Cirrus clouds are defined as clouds above 440 hPa and an optical depth $\tau < 3.6$.

where an influence of the gravity waves on the formation of clouds has to be considered (Kärcher and Ström, 2003). Dean et al. (2005) analyzed satellite data from the ISCCP project and compared them with the results of the 19-level HadAM3 version of the United Kingdom Met Office Unified Model. They showed that the model does not simulate sufficient high cloud cover over land especially in the regions of the mountains. Therefore they proposed a parameterization of orographic clouds described in Dean et al. (2007).

The comparison of the cirrus cloud cover simulated with the ECHAM5 model used in this study (Lohmann et al., 2007) with observations from the International Satellite Cloud Climatology Project (ISCCP) (Rossow and Schiffer, 1999) also shows a lack of cirrus cloud cover over continents and in the mountainous regions, as shown in figure 1. We therefore present a new concept of coupling the gravity wave dynamics and cloud microphysics in the climate model ECHAM5 (Roeckner et al., 2003). In our parameterization we explicitely calculate a vertical velocity induced by gravity waves which is used directly in the parameterization of homogeneous freezing. Since a double-moment scheme for the ice phase is implemented in ECHAM5, the new scheme influences not only the ice water content but also the ice crystal number concentration.

2 PARAMETERIZATION OF CIRRUS CLOUDS: HOMOGENEOUS FREEZING

Homogeneous freezing of supercooled solution droplets plays an important role for the formation of cirrus in the upper troposphere. The lack of efficient ice nuclei, high ice crystal number densities frequently measured in young cirrus clouds and the frequently observed high relative humidities with respect to ice indicate the importance of homogeneous freezing as an important mechanism for the formation of cirrus (Sassen and Dodd, 1989). The formation of gravity waves with high vertical velocities leads to very high supersaturations with respect to ice and one can assume that homogeneous freezing is the dominant freezing mechanism, although heterogeneous nucleation could modify homogeneous freezing events (Kärcher and Ström, 2003).

Kärcher and Lohmann (2002) developed a parameterization for the formation of cirrus due to homogeneous freezing of supercooled solution droplets. This parameterization is implemented in the version of ECHAM5 used for this study (Lohmann et al., 2007).

The number of newly frozen ice particles depends on a critical ice supersaturation S_{cr}, which only depends on temperature (Koop et al., 2000), the water vapor number density at ice saturation n_{sat} and the vertical velocity

w. Furthermore, the maximal number of newly frozen ice crystals cannot exceed the number of hygroscopic aerosol particles N_a. Hence, one can deduce the approximate scaling relationship for the number of newly frozen ice crystals due to homogeneous freezing N_i^{hom} as:

$$N_i^{hom} \propto w^{3/2} n_{sat}^{-1/2}. \quad (1)$$

The positive correlation between N_i^{hom} and w shows that the number density of freshly formed ice crystals increases with increasing vertical velocity. Higher vertical velocities lead to higher supersaturations allowing more ice crystals to form before the supersaturation is depleted efficiently. At lower temperatures the depositional growth is less efficient, thus the growing ice crystals need longer to take up the available water vapor and to reduce the supersaturation (Pruppacher and Klett, 1997). Therefore, the high supersaturations can exist over a longer time period and more ice crystals can be formed (Kärcher and Lohmann, 2002).
So far, the vertical velocity used in this parameterization consists of two parts: A large-scale, grid mean vertical velocity w_l and a contribution from the turbulent kinetic energy (TKE), in order to represent the subgrid-scale variabilities in the vertical velocity. The total vertical velocity used in this parameterization is then given by

$$w_{l+t} = w_l + 0.7\sqrt{TKE} = w_l + w_t. \quad (2)$$

3 CALCULATION OF THE VERTICAL VELOCITY

The calculation of the vertical velocity induced by gravity waves is based on the parameterization of orographic gravity waves from Lott and Miller (1997) which is part of the standard ECHAM5 model. Gravity waves can be excited when stably stratified air flows over mountains. Such waves can propagate to considerable altitudes before they dissipate (McFarlane, 1987). An important property of such vertically propagating waves is the transport of momentum from the Earth's surface to the regions where they dissipate. This transport of momentum significantly influences the large-scale circulation in the stratosphere (McFarlane, 1987).
The parameterization of the gravity wave drag is based on the linear theory for monochromatic waves in the hydrostatic regime. As a detailed derivation of the linear theory is beyond the scope of this work, only the main issues are explained here. For more details see e.g. Smith (1979). In order to derive a vertical velocity induced by gravity waves the 2-dimensional equations of motion for an incompressible atmosphere are considered. Additionally, Boussinesq approximation is used and the Coriolis force is neglected. Furthermore, it is assumed that the flow follows the shape of the terrain at the lower boundary which is described by $z = h(x) = h_m \sin(kx)$, whereas h_m is the height of the mountain. The maximal vertical velocity induced by gravity waves can then be calculated as

$$w_{gw} = k \cdot U \cdot \delta h(z) \quad (3)$$

where $\delta h(z)$ is the vertical displacement (amplitude) of the flow which depends on the air density ρ, the Brunt-Väisäla frequency N and the horizontal wind U projected in the plan of the gravity wave stress. To account for the breaking of gravity waves, an instability criterion based on Lindzen (1981) is defined: A minimum Richardson number Ri_{min} that includes the gravity wave influence on the static stability and wind shear is evaluated. It is assumed that instability occurs for $Ri_{min} < 0.25$. This condition takes into account the occurrence of both convective overturning and shear instability. If Ri_{min} reaches its critical value saturation occurs and the amplitude $\delta h(z)$ is restricted to the value at which instability occurs. For the new total vertical velocity we obtain

$$\begin{aligned} w_{ges} &= \underbrace{w_l}_{large-scale} + \underbrace{0.7\sqrt{TKE}}_{turbulence} + \underbrace{w_{gw}}_{gravity\ waves} \quad (4) \\ &= w_l + w_t + w_{gw}. \end{aligned}$$

The calculation of the vertical velocity contains a horizontal wavenumber k which describes the width of the mountain. In ECHAM5 the orography is represented as elliptical mountains (Baines and Palmer, 1990; Lott and Miller, 1997) with an aspect ratio $r = a/b$ where a and b are the semi axis of the ellipse. Thus, the horizontal wavelength of the excited gravity wave depends on the aspect ratio of the mountain and the angle between the incident flow and the orography. Furthermore flow can be blocked at the windward side of the mountain, such that only flow from the higher levels can flow over the mountains which reduces the effective height as seen by the flow and also the horizontal wavelength which is excited.

4 RESULTS

In order to investigate the influence of gravity waves on the formation of cirrus clouds simulations with the global climate model ECHAM5 (Roeckner et al., 2003) with a horizontal resolution of T63 (1.875° x 1.875°) and 31 vertical levels using a timestep of 12 minutes were carried out for three years after a spin-up time of three month. Climatological sea surface temperature and sea-ice extent were used. One reference run (REF) was performed, where the previous vertical velocity described by eq. (2) is used. In a second simulation (GWD) the original vertical velocity is replaced by the vertical velocity that contains a contribution from the gravity waves and is described by eq. (4).
Additionally, a nudged simulation was performed in order to compare the simulation to observations from the INCA (Interhemispheric differences in cirrus properties from anthropogenic emissions) campaign (Gayet et al., 2004), which took place during March/April 2000 at Punta Arenas, Chile and September/October 2000 at Prestwick, Scotland. Nudging is a special assimilation technique where the dynamical model variables are relaxed to observations or meteorological analysis (Davies, 1976; Jeuken et al., 1996).

4.1 GLOBAL SIMULATION

Figure 2 shows a three-year mean of the vertical velocities and the ice crystal number density for the REF and GWD simulation averaged over the upper troposphere from 165 - 285 hPa. In the REF simulation very low values for the vertical velocity are simulated with maxima up to 20 cm/s in the tropics. In the GWD simulation one can see a completely different distribution of the vertical velocities. There are high values in the range of 5 cm/s to 100 cm/s over the mountains where gravity waves can be excited. This leads to a completely new distribution of the vertical wind field which also influences the ice crystal number concentration. The ice crystal number concentration in the REF simulation lies between 1 and 6 cm^{-3}. Only in the tropics values of up to 15 cm^{-3} occur due to convection. There is a lack of cirrus over continents in general and especially over mountains. In the GWD simulation the model produces much higher concentrations due to the higher vertical velocities. Thus, ice crystals form over the mountains and the ice crystal number concentrations lie between 1-5 cm^{-3} over the oceans and up to 40 cm^{-3} over the mountains. Due to the development of orographic cirrus we can expect a higher cirrus cloud amount in this region and the lack of cirrus clouds over continents can be reduced. Furthermore we see slight advection of ice crystals formed in orographic waves downstream for example to the adjacent ocean at the tip of south America.

4.2 COMPARISON WITH MEASUREMENTS

In order to test the new parameterization, the results of the nudged simulation are compared with measurements taken during the INCA campaign. The INCA campaign took place in April 2000 in Punta Arenas, Chile and in October 2000 in Prestwick, Scotland. INCA was an aircraft field experiment with the DLR (German Aerospace Center) Falcon aircraft. Vertical velocities were measured with a 5-hole probe (Bögel and Baumann, 1991) only during constant altitude flight sections. The accuracy of

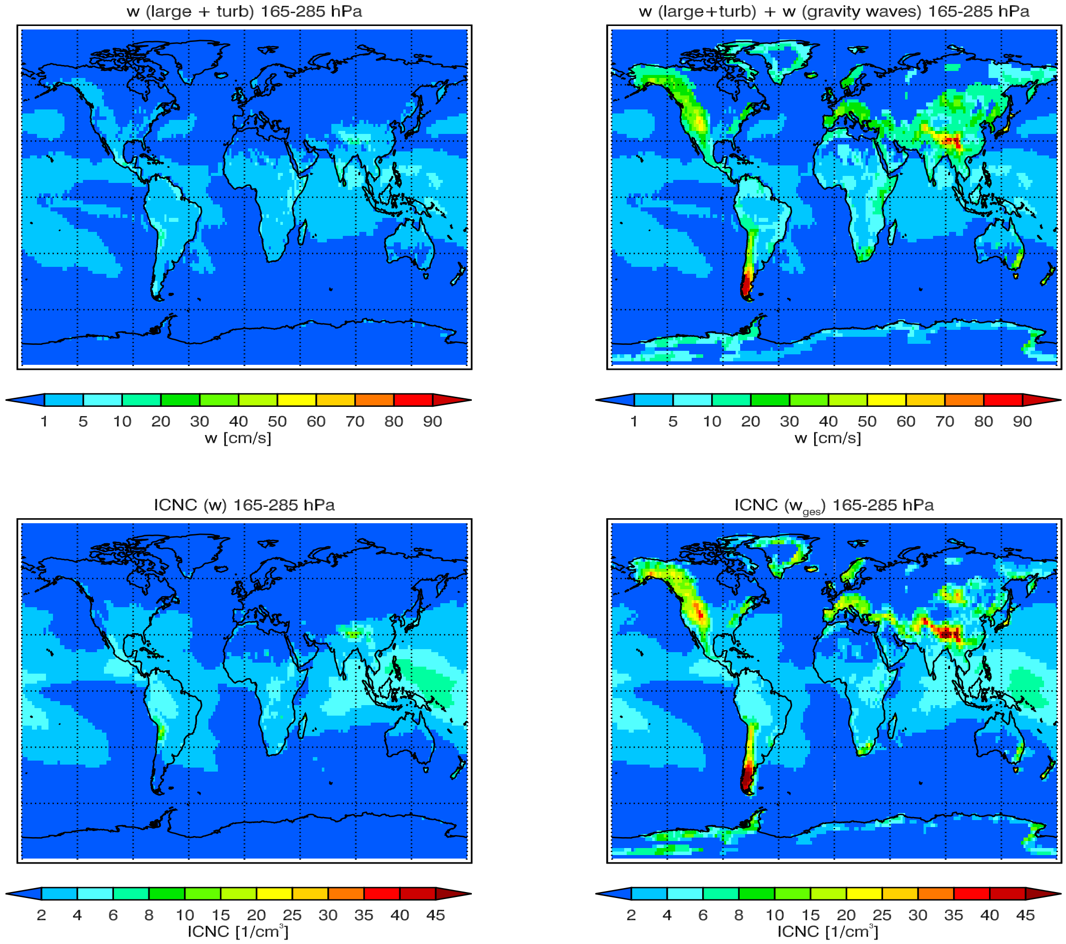

Fig. 2: Global distribution of the annual mean vertical velocity [cm/s] (upper panels) and annual mean of in cloud ice crystal number concentration [cm^{-3}] (lower panels) in the upper troposphere (165-285 hPa) for the REF simulation (left column) and the GWD simulation (right column).

the vertical velocity is estimated to be on the order of 0.1 m/s. Ice particle concentrations were measured during INCA with a combination of two instruments, the FSSP-300 and 2D-C optical probes (Gayet et al., 2002, 2004). The particle concentrations used for this comparison refer to the particle size range 3 – 800 micrometer in diameter. As a nudged simulation is used, one can assume that the large-scale flow in the model is similar to the observed one during the measurement period; thus, it makes sense to compare the simulated values with the measured ones. For comparison of the histograms of the vertical velocity and ICNC all values at altitudes higher than 280 hPa and temperatures less than 235 K measured during the southern and northern hemispheric campaign in the area of the measurements were taken. The experimental data represent about 40 flight hours taken during a 4 week period, in each hemisphere. Although these data do not represent climatological averages, their probability frequency distributions should be representative for this region and season and thus can be compared to the results from a nudged simulation. The two regions where measurements were taken are shown in Figure 3. The grey shaded areas in the map show the points where

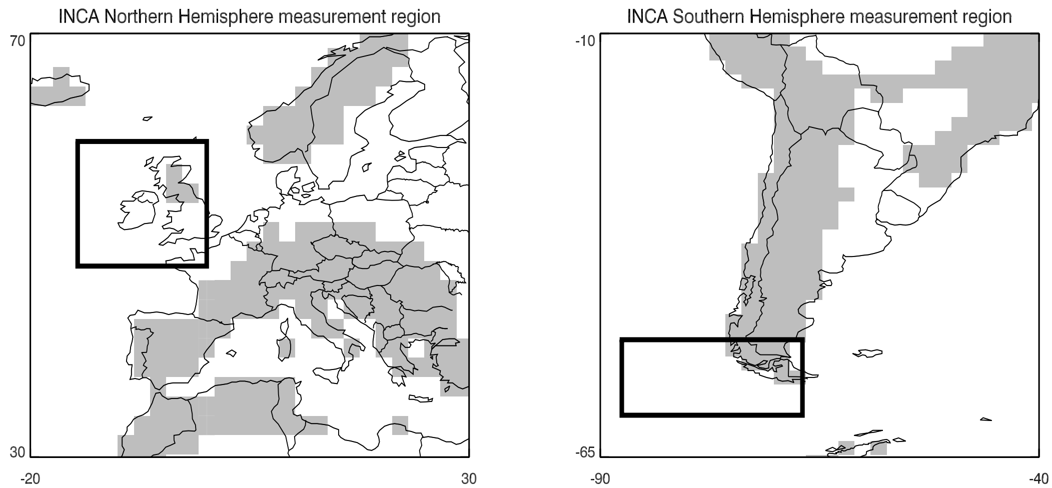

Fig. 3: Measurement region of the INCA campaign in the Northern and Southern Hemisphere. Grey shaded areas denote gridpoints where the gravity wave scheme can be activated.

the gravity wave scheme in the model can be activated. In the northern hemisphere there are only three gridpoints where the scheme can become activated and where gravity waves can develop. In the southern hemisphere there are nine active points. The histograms for the simulated values are calculated using data from a nudged simulation from March to May 2000 for the southern hemispheric case and from September to November 2000 for the northern hemispheric case for the upper troposphere from 165-285 hPa in the measurement regions. Figure 4 shows the comparison of the histogram for the measured and simulated values. For the northern hemispheric case one can see that the addition of a gravity wave induced vertical velocity leads to a better representation of the measured values. The values in the range of 0.2 to 2 m/s are shifted to a higher probability of occurrence but cannot reach the measured distribution. This could be due to the fact that in the measurement region there are only three gridpoints where the gravity wave scheme can be active and thus gravity waves can develop. We also should mention here that the development of turbulence in breaking gravity waves (i.e. nonlinear contributions) would lead to an additional vertical velocity which is not yet calculated. This lack of turbulence could lead to an underestimation of the probability of occurrence especially in the range of 10-100 cm/s. Using the new parameterization a higher probability of occurrence for the ice crystal number concentration in the range of 10 to 200 cm^{-3} can be simulated which is a better representation of the measured values. For the southern hemispheric case we also obtain an improvement due to the new parameterization. Gravity waves lead to enhanced vertical velocities which better represent the measurements especially in the range of 1 to 2 m/s, although it seems that the scheme produces too high vertical velocities. In this case an additional vertical velocity from turbulence also would enhance the probability of occurrence in the range of 10-100 cm/s. Higher ice crystal number concentrations are also simulated in better agreement with measurements.

5 SUMMARY AND CONCLUSION

A coupling of gravity wave dynamics and cloud microphysics has been implemented in

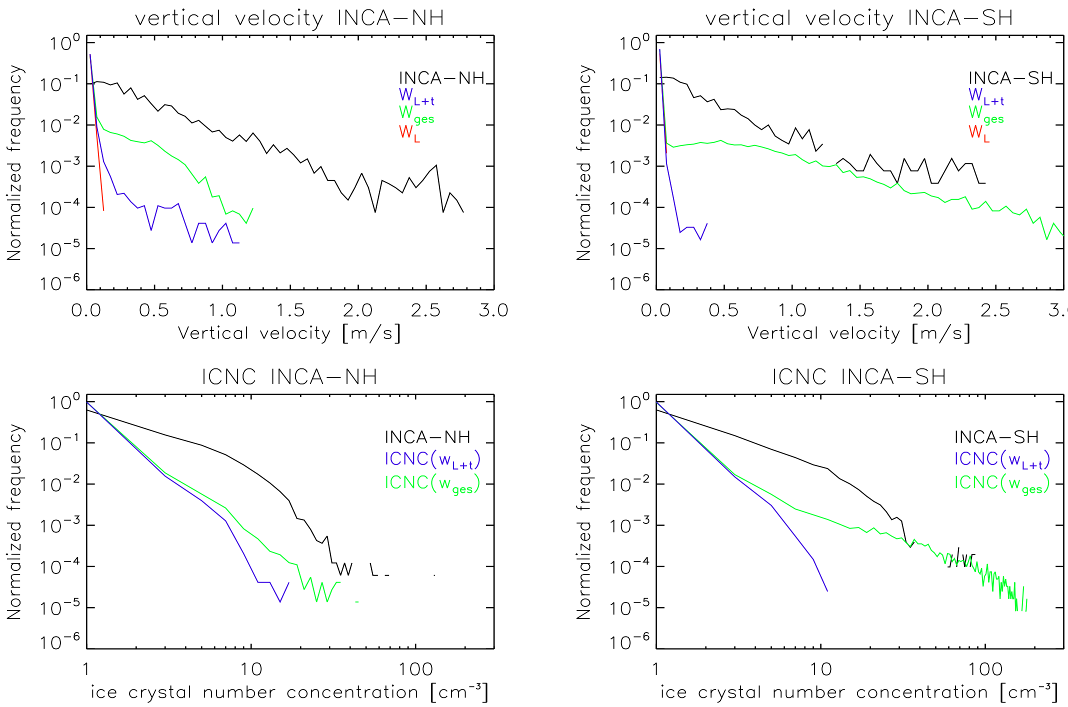

Fig. 4: Histogram of the measured and simulated vertical velocities [m/s] (upper panels) and ice crystal number concentration [cm^{-3}] (lower panels) sampled over the measurement regions in the Northern Hemisphere (left column) and the Southern Hemisphere (right column) shown in figure 3.

ECHAM5 in order to simulate sufficient amount of cirrus clouds in the lee of mountains. To account for the effect of gravity waves and to simulate the formation process of orographic cirrus an additional component for the vertical velocity has been added to the previously used formula in ECHAM5, which only contains a large-scale part and a contribution from TKE. The calculation of the vertical velocity induced by gravity waves is based on the parameterization of the gravity wave drag which calculates the momentum transfer from the earth surface to the atmosphere. The contribution of the vertical velocity from gravity waves leads to a much more realistic simulation of the vertical wind field. The probability of occurrence of the vertical velocity in the upper troposphere is enhanced in the range of 20-200 cm/s. This is exactly the range where a contribution due to gravity waves was expected. Good agreement with the measurements from the INCA campaign can be achieved in a direct comparison. Due to the new parameterization, the annual mean vertically integrated ice crystal number concentration could be enhanced from $1.5 \cdot 10^{10}$ m^{-2} to $1.67 \cdot 10^{10}$ m^{-2} which corresponds to an increase of $\sim$ 11%. Higher ice crystal number concentrations are simulated especially over mountains, which decreases the lack of cirrus over mountains.
Indeed, the new parameterization has a few limitations which should be mentioned here. Currently, the influence of the downdraft of a gravity wave on an orographic cirrus cloud is neglected. As the horizontal extend of an orographic cirrus cloud is limited by strong downdrafts, this limitation of the parameterization should be taken into account in a next step. Moreover, it has to be clarified whether the calculation of the vertical velocity based on a two-dimensional gravity wave scheme has to be modified as the vertical velocities seem to be slightly overestimated and the two-dimensional theory leads to an overestimation of the vertical velocities (Dörnbrack, 1998). Additionally,

it should be considered if the contribution from the TKE to the vertical velocity can be dropped or decreased whenever gravity waves occur.
The new distribution of the vertical velocity in the troposphere could also influence the formation of warm and mixed phase clouds via the activation of aerosols into cloud droplets. Thus, the calculation of a more realistic vertical wind field could therefore be of great importance for cloud processes in general.

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