

<sup>1</sup> **Relevant changes made in the manuscript**

<sup>2</sup> New text is given in *italic*. Numbering of the figures corresponds to the revised manuscript  
<sup>3</sup> version. See also the revised version of the manuscript with highlighted changes com-  
<sup>4</sup> pared to the original version.

<sup>5</sup> **Section 1: Introduction** In the introduction, material concerning altocumulus in gen-  
<sup>6</sup> eral and the Wegener-Bergeron-Findeisen process was added.

<sup>7</sup> New text: *According to Warren et al. (1998a,b) altocumulus and altostratus clouds*  
<sup>8</sup> *together cover 22 % of the earth's surface. For single-layered altocumulus clouds, ...*

<sup>9</sup> *... This was previously reported from Fleishauer et al. (2002) and Carey et al. (2008).*  
<sup>10</sup> *Fleishauer et al. (2002) also emphasized a lack of significant temperature inversions or*  
<sup>11</sup> *wind shears as a major feature of these clouds. Kanitz et al. (2011) show that the ratio of*  
<sup>12</sup> *ice-containing clouds increases with decreasing temperature. However, the numbers are*  
<sup>13</sup> *different for different locations with similar dynamics but with different aerosol burden,*  
<sup>14</sup> *e.g., at northern and southern midlatitudes, underlining the question for the influence*  
<sup>15</sup> *of ice-nucleating particles (INP). ...*

<sup>16</sup> *... One idea is that freezing is caused by soil dust with biological particles dominating*  
<sup>17</sup> *the freezing behaviour (O'Sullivan et al., 2014) which could explain on the one hand the*  
<sup>18</sup> *atmospheric abundancy of biological material and on the other hand the relatively high*  
<sup>19</sup> *freezing temperatures above  $-15^{\circ}\text{C}$  of ambient measurements. Seeding from ice clouds*  
<sup>20</sup> *above can be excluded for the cases presented which means that ice has formed at the*  
<sup>21</sup> *cloud temperatures observed. ...*

<sup>22</sup> *... However, despite its important contribution, ice nucleation does not determine*  
<sup>23</sup> *the entire microphysics of mixed-phase clouds alone. It is rather the complex trans-*  
<sup>24</sup> *fer between the three phases of water: water vapor, liquid water and ice described by*  
<sup>25</sup> *the Wegener-Bergeron-Findeisen (WBF) mechanism (Wegener, 1911; Bergeron, 1935;*  
<sup>26</sup> *Findeisen, 1938). It is well-known that due to the different saturation pressures of water*  
<sup>27</sup> *vapor with respect to liquid water and ice, a mixed-phase cloud is in a non-equilibrium*  
<sup>28</sup> *state which, nevertheless, may lead to a quasi-steady existence (Korolev and Field, 2008).*  
<sup>29</sup> *The main drivers for this phase transfer are vertical velocity (leading to supersaturation*  
<sup>30</sup> *and subsequent droplet formation) and ice particle formation and growth (WBF starts)*  
<sup>31</sup> *leading to sedimentation of the typically fast growing ice particles (WBF ends due to*  
<sup>32</sup> *removal of ice). The motivation of this work is to shed more light on the relative contri-*  
<sup>33</sup> *butions of the different processes involved in these complex interactions. ...*

<sup>34</sup> **Section 2: Observations** In section 2, more observational data is presented in the  
<sup>35</sup> revised manuscript (two additional figures and the corresponding text) and the error  
<sup>36</sup> range of the observations is discussed shortly.

<sup>37</sup> *... Liquid water content (LWC) is between  $0.1\text{ g/m}^{-3}$  to  $1\text{ g/m}^{-3}$  whereas ice water*  
<sup>38</sup> *content (IWC) is about 3-4 orders of magnitude smaller and reaches its maximum value*  
<sup>39</sup> *within the virgae (see Fig. 2). ...*

<sup>40</sup> *... This is supported by Fig. 3 where the cloud radar (right panel) mainly shows parti-*  
<sup>41</sup> *cles falling from the top layer. Therefore, particles are mainly moving downwards (green*

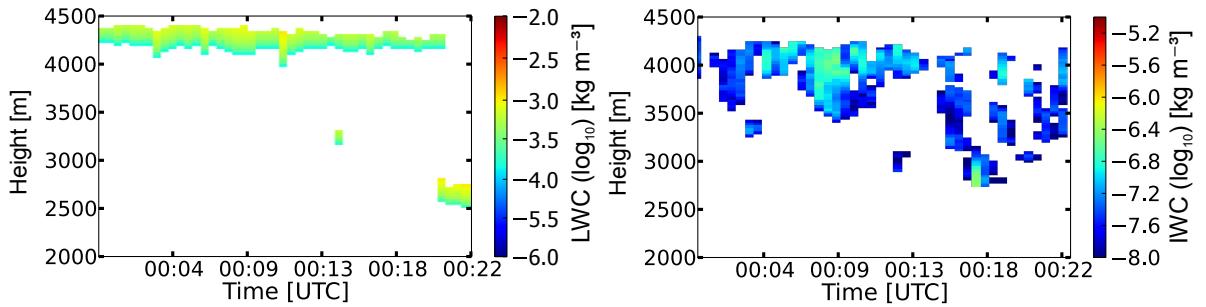


Figure 2: Cloudnet derived water contents for case 1. Left: Liquid water content, right: ice water content (both in logarithmic scale).

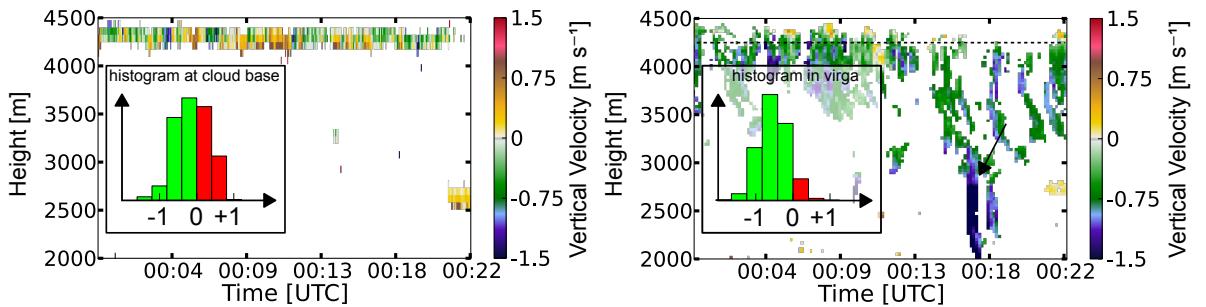


Figure 3: Vertical velocity for case 1. Left: derived from lidar (valid for more numerous smaller droplets at cloud base), right: derived from radar observations (valid for large particles; virgae).

42 color) and can be identified as ice particles by their size. Only at the very top at about  
 43 4300 m particles are small enough to still be lifted upwards (yellow colors). The Doppler  
 44 lidar (left panel), however, shows the motion of small cloud droplets at the predominantly  
 45 liquid cloud top. Hence, in this plot the cloud-top turbulence becomes visible. ...  
 46 ... and a LWC of up to  $0.1 \text{ g/m}^{-3}$  which is much smaller than for case 1. ...  
 47 ... and an IWC of up to  $0.01 \text{ g/m}^{-3}$  which means that in some parts of the cloud, ice  
 48 and liquid water reach the same order of magnitude (see Fig. 5). ...  
 49 ... Accuracy of the IWC is +/- 50 %. For the LWC calculated by the scaled adiabatic  
 50 approach the same order of magnitude applies. Vertical wind speeds are measured directly  
 51 by evaluation from the recorded cloud radar and Doppler lidar spectra. Errors are +/-  
 52 0.15 m/s for the cloud radar and +/- 0.05 m/s for the Doppler lidar. These errors are  
 53 mainly due to the pointing accuracy of the two systems. ...

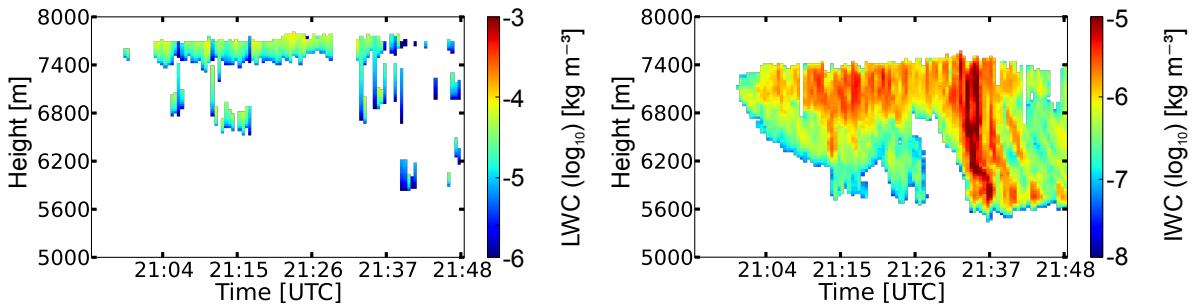


Figure 5: Cloudnet derived water contents for case 2. Left: Liquid water content, right: ice water content (both in logarithmic scale).

54 **Section 3: Model description and initialization**

55 • The model description was extended with respect to model geometry, time step  
 56 and driving velocity.

57 • The reasons for neglecting collision processes of ice particles was explained and  
 58 supporting literature was cited.

59 • Figure 7 showing the vertical profiles of temperature as well as relative humidities  
 60 with respect to liquid water and ice for both cases was added.

61 ... with radii of 100 m and 1000 m, respectively, resulting in a radius ratio of 1:10  
 62 which is typical for this setup. However, the geometric configuration of the model is  
 63 not intended to match the geometry of the clouds (and the cloud-free spaces between  
 64 the clouds) but is rather meant to provide the possibility of horizontal exchange between  
 65 clouds and a cloud-free background. ...

66 ... A time step of 1 s was used for the dynamics as well as for the microphysics.

67 However, in contrast to other Asai-Kasahara model studies, updrafts are not initialized  
 68 by a heat and/or humidity pulse in certain layers for a given period of time. Instead,  
 69 vertical velocity (updrafts and downdrafts) in the inner cylinder is prescribed, which is  
 70 more similar to a kinematic model like the Kinematic Driver Model KiD (Shipway and  
 71 Hill, 2012). In that way dynamics can be controlled to make sure that it is close to the  
 72 observations. ...

73 ... For this case study, collision processes between ice particles and drops (riming) and  
 74 between ice particles and ice particles (accretion) are not taken into account. One the  
 75 one hand, this is to exclude further uncertainties which would be introduced by the colli-  
 76 sion/collection kernel for those interactions, one the other hand, only small or neglectable  
 77 effects are expected. Clouds are shallow which means that there is not much time for  
 78 the ice particles to interact with droplets (especially when the ice is preferentially formed

79 near cloud base and sediments out soon). In addition, for case 1 ice particle concentrations  
80 are low which highly limits the probability of collisions. At the low temperatures of  
81 case 2 sticking efficiency is expected to be low. This assumption is corroborated by the  
82 findings of Smith et al. (2009) stating that water vapor deposition (and sublimation),  
83 balanced by sedimentation are more important than accretional growth. ...

84 ... To cover case 1, the parameterization is extrapolated to  $-5^{\circ}\text{C}$  despite the fact that  
85 the underlying measurements were only taken at  $-9^{\circ}\text{C}$  and below. ...

86 ... The drop size threshold was chosen to restrict freezing to droplets and to prevent  
87 (large) non-activated aerosol particles at high relative humidity (but subsaturated wrt  
88 water) outside the cloud from freezing. ...

89 ... (ranging from 15 to  $3000\mu\text{m}$  with a single description) and columns (for size ranges  
90 of 30 to  $100\mu\text{m}$ , 100 to  $300\mu\text{m}$ , and above  $300\mu\text{m}$  in diameter) are calculated from the  
91 mass-dimension power laws ...

92 ... Fig. 7 shows profiles of temperature and relative humidities with respect to liquid  
93 water and to ice, respectively, for both cases. ...

94 **Section 4: Model results: Dynamics** Reasons for preferred ice formation near liquid  
95 cloud base were explained.

96 ... If active INP are available ice formation can take place within the liquid part of  
97 the cloud. The INP are partly already active near liquid cloud base which means that  
98 they trigger freezing as soon as the droplets are formed. Less efficient INP become active  
99 after further cooling above cloud base. After ice formation rapid depositional growth  
100 takes place and the ice particles almost immediately start to sediment. ...

101 ... The LWC maxima are within a factor of 2 for varying  $h_{\text{bot}}$ . A similar trend is  
102 observed for the ice phase (see also Fig. 10), but IWC maxima differ only by about 25 %.

103 ...

104 ... This also means that near cloud base much more active INP are available and  
105 that a further cooling within the clouds only slightly increases the number of active INP  
106 leading again to a preferential ice nucleation near liquid cloud base. Due to the lower  
107 temperatures and the more massive ice formation, ...

108 ... ...

109 ... ...

110 **Section 5: Sensitivity studies** Drying of the layer below liquid cloud base due to  
111 ice particle growth with subsequent sedimentation and consequences for LWC were ex-  
112 plained.

113 ... As mentioned earlier, ice particle growth is not restricted to the liquid part of the  
114 cloud but also occurs in the layer below liquid cloud base, which is still supersaturated  
115 with respect to ice. This leads to a decrease in relative humidity in this part of the cloud,  
116 which in turn weakens or suppresses droplet formation by shifting liquid cloud base to  
117 higher altitudes. The lower LWC for the runs with higher IWC therefore cannot only be  
118 attributed to the WBF processes but also to this indirect effect. ...

119 **Section 6: Conclusions** ... However, below liquid cloud base supersaturation with  
120 respect to ice decreases. ...

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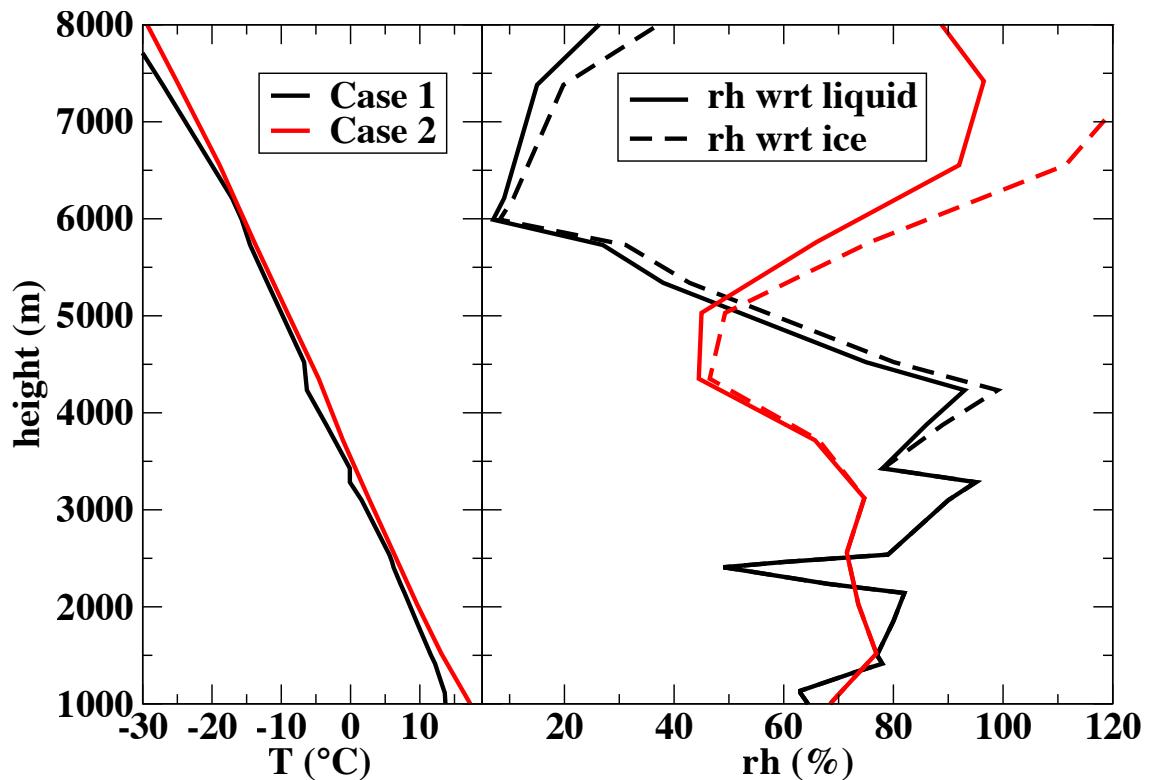


Figure 7: Vertical profiles of temperature (left) and relative humidity (right) with respect to liquid water (full lines) and ice (dashed lines) based on a radiosonde observation (Meiningen) for case 1 (black) and from GDAS (grid point Leipzig) for case 2 (red).

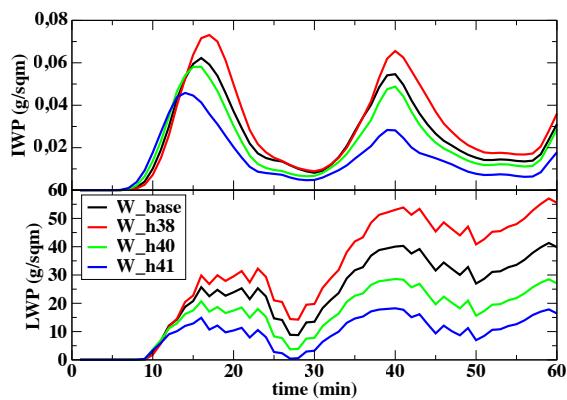


Figure 10: Liquid (lower panel) and ice water paths (upper panel) for case 1. Comparison of the different values for  $h_{bot}$ .

# Ice phase in Altocumulus Clouds over Leipzig: Remote sensing observations and detailed modelling

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**Abstract.** The present work combines remote sensing observations and detailed cloud modeling to investigate two altocumulus cloud cases observed over Leipzig, Germany. A suite of remote sensing instruments was able to detect primary ice at rather warm-high temperatures of  $-6^{\circ}\text{C}$ . For comparison, a second mixed phase case at about  $-25^{\circ}\text{C}$  is introduced. To further look into the details of cloud microphysical processes a simple dynamics model of the Asai-Kasahara type is combined with detailed spectral micro-physics forming the model system AK-SPECS. Vertical velocities are prescribed to force the dynamics as well as main cloud features to be close to the observations. Subsequently, sensitivity studies with respect to ice microphysical parameters are carried out with the aim to quantify the most important sensitivities for the cases investigated. For the cases selected, the liquid phase is mainly determined by the model dynamics (location and strength of vertical velocity) whereas the ice phase is much more sensitive to the microphysical parameters (ice nuclei (IN)nucleating particle (INP) number, ice particle shape). The choice of ice particle shape may induce large uncertainties which are in the same order as those for the temperature-dependent IN-INP number distribution.

Fleishauer et al. (2002) also emphasized a lack of significant temperature inversions or wind shears as a major feature of these clouds. Kanitz et al. (2011) show that the ratio of ice-containing clouds increases with decreasing temperature. However, the numbers are different for different locations with similar dynamics but with different aerosol burden, e.g., at northern and southern midlatitudes, underlining the question for the influence of ice-nucleating particles (INP). The observations with the highest temperatures are close to the limit at which the best atmospheric ice nuclei are known to nucleate ice in the immersion mode. This can only be attributed to the aerosol particles which are formed out of or at least contain biological material such as bacteria (Hartmann et al., 2013), fungi, or pollen. This is corroborated by the review of Murray et al. (2012) stating that only biological particles are known to form ice above  $-15^{\circ}\text{C}$ . However, these observations are from laboratory studies and it is still unclear whether or to which what extent these extremely efficient ice nuclei are abundant in atmosphere, especially above the boundary layer. One idea is that freezing is caused by soil dust with biological particles dominating the freezing behaviour (O'Sullivan et al., 2014) which could explain on the one hand the atmospheric abundance of biological material and on the other hand the relatively high freezing temperatures above  $-15^{\circ}\text{C}$  of ambient measurements. Seeding from ice clouds above can be excluded for the cases presented; however, preconditioning of ice nuclei (IN) could be a reason for these high ice activation temperatures, which means that ice has formed at the cloud temperatures observed.

Ice nucleation still is a large source of uncertainty in cloud modeling. Recently, several studies use combinations of vertically fine resolved models with rather detailed representation of the ice nucleation processes. Often, wave clouds are used as comparison since they represent rather ideal condi-

## 1 Introduction

Altocumulus clouds According to Warren et al. (1998a,b) altocumulus and altostratus clouds together cover 22 % of the earth's surface. For single-layered altocumulus clouds, observations by Buehl et al. (2013) show the typical feature with a maximum of liquid water in the upper part of the cloud (increasing with height) and an ice maximum in the lower part of the cloud, mostly below liquid cloud base down in the virga. This was previously reported from Fleishauer et al. (2002) and Carey et al. (2008).

tions when they are not influenced by ice seeding from layers above. Field et al. (2012) apply a 1D kinematic model with bulk microphysics but prognostic IN-INP. Eidhammer et al. (2010) use a Langrangian parcel model for the comparison of the ice nucleation schemes of Phillips et al. (2008) and DeMott et al. (2010) under certain constraints. A 1D column model with a very detailed 2D spectral description of liquid and ice phase is employed by Dearden et al. (2012). Sun et al. (2012) use a 1.5D model with spectral microphysics for shallow convective clouds for a sensitivity study of immersion freezing due to bacteria and its influence on precipitation formation.

Most ice microphysics descriptions in models lack from the fact that ice nuclei are not represented as a prognostic variable. These models diagnose the number of ice particles based on thermodynamical parameters such as temperature and humidity (MEYERS et al., 1992) and are, therefore, not able to consider whether IN-INP were already activated at previous time steps in the model.

However, despite its important contribution, ice nucleation does not determine the entire microphysics of mixed-phase clouds alone. It is rather the complex transfer between the three phases of water: water vapor, liquid water and ice described by the Wegener-Bergeron-Findeisen (WBF) mechanism (Wegener, 1911; Bergeron, 1935; Findeisen, 1938). It is well-known that due to the different saturation pressures of water vapor with respect to liquid water and ice, a mixed-phase cloud is in a non-equilibrium state which, nevertheless, may lead to a quasi-steady existence (Korolev and Field, 2008). The main drivers for this phase transfer are vertical velocity (leading to supersaturation and subsequent droplet formation) and ice particle formation and growth (WBF starts) leading to sedimentation of the typically fast growing ice particles (WBF ends due to removal of ice). The motivation of this work is to shed more light on the relative contributions of the different processes involved in these complex interactions.

The paper is structured as follows. Section 2 describes the remote sensing observations of two mixed-phase altocumulus cloud cases above Leipzig. The dynamical model as well as the process descriptions and initial data used for this study are specified in section 3. Section 4 refers to changes in the dynamic parameters of the model to identify base cases. The results for the which describe the observations sufficiently well to perform sensitivity studies with respect to the microphysical parameters. The results for those sensitivity studies are presented in section 5 and section 6 closes with a discussion of the results.

## 2 Remote sensing observations

Altocumulus and altostratus clouds are regularly observed with the Leipzig Aerosol and Cloud Remote Observations

System (LACROS) at the Leibniz Institute for Tropospheric Research TROPOS. LACROS combines the capabilities of Raman/depolarization lidar (Althausen et al., 2009), a MIRA-35 cloud radar (Bauer-Pfundstein and Görtsdorf, 2007), a Doppler lidar (Bühl et al., 2012), a microwave radiometer, a sun-photometer and a disdrometer to measure height-resolved properties of aerosols and clouds. The Cloudnet framework (Illingworth et al., 2007) is used to derive microphysical parameters like liquid-water content (Pospichal et al., 2012) or ice-water content (Hogan et al., 2006). The following two cases have been selected to illustrate this variety and to serve as examples to be compared to model results.

### 2.1 Case 1: Warm mixed-phase cloud

One of the warmest mixed-phase clouds within the data set was observed on 17 September 2011 between 00:00 and 00:22 UTC (see Fig. ?? 1). The liquid part of the cloud extends from about 4250 m to 4450 m height at temperatures of about  $-6^{\circ}\text{C}$  according to the GDAS (Global Data Assimilation System) reanalysis data for Leipzig. Liquid water-Liquid water content (LWC) is between  $0.1 \text{ g/m}^{-3}$  to  $1 \text{ g/m}^{-3}$  whereas ice water content (IWC) is about 3-4 orders of magnitude smaller and reaches its maximum value within the virgæ (see Fig. 2). Liquid water path (LWP) measured by a microwave radiometer varies between 20 and  $50 \text{ g/m}^2$  (mostly about  $25 \text{ g/m}^2$ ) whereas ice water path (IWP) is only slightly above the detection limit of about  $0.01 \text{ g/m}^2$  implying a rather large uncertainty with correspondingly large error bars. Virgæ (falling ice) are observed down to about 3000 m, which is close to the  $0^{\circ}\text{C}$  level. This is supported by Fig. 3 where the cloud radar (right panel) mainly shows particles falling from the top layer. Therefore, particles are mainly moving downwards (green color) and can be identified as ice particles by their size. Only at the very top at about 4300 m particles are small enough to still be lifted upwards (yellow colors). The Doppler lidar (left panel), however, shows the motion of small cloud droplets at the predominantly liquid cloud top. Hence, in this plot the cloud-top turbulence becomes visible. Vertical windspeeds range from about  $-1.5 \text{ m/s}$  to  $1.0 \text{ m/s}$  with pdf maxima at  $-0.5 \text{ m/s}$  and  $0.5 \text{ m/s}$ , respectively (Fig. ?? 3).

### 2.2 Case 2: Colder mixed-phase cloud

A much colder case could be was observed on 2 August 2012 between 21:00 UTC and 21:40 UTC (see Fig. ?? 4). Liquid water was measured around 7500 m at about  $-25^{\circ}\text{C}$  with an a LWP between  $10$  and  $30 \text{ g/m}^2$  and a LWC of up to  $0.1 \text{ g/m}^{-3}$  which is much smaller than for case 1. As can be expected due to the lower temperature, the ice phase was much more massive than in case 1 and reached down to about 5500 m with an IWP of about  $1-10 \text{ g/m}^2$  and an IWC of up to  $0.01 \text{ g/m}^{-3}$  which means that in some parts of the cloud,

ice and liquid water reach the same order of magnitude (see Fig. 5). Vertical wind speeds were in the same range as for the warmer case described above (Fig. ?? 6).

Accuracy of the IWC is +/- 50 %. For the LWC calculated by the scaled adiabatic approach the same order of magnitude applies. Vertical wind speeds are measured directly by evaluation from the recorded cloud radar and Doppler lidar spectra. Errors are +/- 0.15 m/s for the cloud radar and +/- 0.05 m/s for the Doppler lidar. These errors are mainly due to the pointing accuracy of the two systems.

### 3 Model Description and initialization

For the model studies an Asai-Kasahara type model is used (Asai and Kasahara, 1967). The model geometry is axisymmetric and consists of an inner and an outer cylinder with radii of 100 m and 1000 m, respectively, resulting in a radius ratio of 1:10 which is typical for this setup. However, the geometric configuration of the model is not intended to match the geometry of the clouds (and the cloud-free spaces between the clouds) but is rather meant to provide the possibility of horizontal exchange between clouds and a cloud-free background.

The vertical resolution is constant with height and is chosen to be  $\Delta z = 25$  m to give a sufficient resolution of the cloud layer and to roughly match the vertical resolution of the observations. In contrast to a parcel model, the vertically resolved model grid allows for a description of hydrometeor sedimentation. This is important especially for the fast growing ice crystals to realistically describe their interaction with the vapor and liquid phase (Bergeron-Findeisen Wegener-Bergeron-Findeisen process). A time step of 1 s was used for the dynamics as well as for the microphysics.

However, in contrast to other Asai-Kasahara model studies, updrafts are not initialized by a heat and/or humidity pulse in certain layers for a given period of time. Instead, vertical velocity (updrafts and downdrafts) in the inner cylinder is prescribed, which is more similar to a kinematic model like the Kinematic Driver Model KiD (Shipway and Hill, 2012). In that way dynamics can be controlled to make sure that it is close to the observations.

The cloud microphysics is described by the mixed-phase spectral microphysics module SPECS (Simmel and Wurzler, 2006; Diehl et al., 2006). SPECS provides a joint spectrum for the liquid phase (soluble wetted aerosol particles as well as cloud and rain drops) and one spectrum for the ice phase.

For this case study, collision processes between ice particles and drops (riming) and between ice particles and ice particles (accretion) are not taken into account. One the one hand, this is to exclude further uncertainties which would be introduced by the collision/collection kernel for those interactions, one the other hand, only small or neglectable effects are expected. Clouds are shallow which means that

there is not much time for the ice particles to interact with droplets (especially when the ice is preferentially formed near cloud base and sediments out soon). In addition, for case 1 ice particle concentrations are low which highly limits the probability of collisions. At the low temperatures of case 2 sticking efficiency is expected to be low. This assumption is corroborated by the findings of Smith et al. (2009) stating that water vapor deposition (and sublimation), balanced by sedimentation are more important than accretional growth.

#### 3.1 Description of ice microphysics

In the following, the differences in the description of the microphysics compared to Diehl et al. (2006) are described.

##### 3.1.1 Immersion freezing

For this study, immersion freezing is assumed to be the only primary ice formation process. Since during the above mentioned observations no *in situ* measurements of the IN-INP are available, the parameterization of DeMott et al. (2010) is used assuming that all IN-INP are active in the immersion freezing mode. The parameterization of DeMott et al. (2010) is based on an empirical relation of IN-INP and the number of aerosol particles with radii  $> 250$  nm ( $N_{AP,r>250\text{ nm}}$ ). To cover case 1, the parameterization is extrapolated to  $-5^{\circ}\text{C}$  despite the fact that the underlying measurements were only taken at  $-9^{\circ}\text{C}$  and below. As base case  $N_{AP,r>250\text{ nm}} = 10^5$  kg $^{-1}$  air is used as input data for the parameterization resulting in about 0.01 active IN-INP per liter for  $-6^{\circ}\text{C}$  (case 1) and about 0.5 IN-INP per liter for  $-25^{\circ}\text{C}$  (case 2), respectively, at standard conditions. This corresponds to a relatively low number of larger aerosol particles but is well within the range observed by DeMott et al. (2010).

For the potential IN-INP a prognostic temperature resolved field with 20 temperature bins with a resolution of 1 K is introduced into SPECS. It ranges from  $-5^{\circ}\text{C}$  to  $-25^{\circ}\text{C}$  to cover the temperature range for the selected cases and can easily be changed for other case studies. This is a simplified version of the method used by Fridlind et al. (2007). The potential IN-INP field is initially defined in every grid cell (layer) and is transported vertically with the given up-/downdrafts and horizontally exchanged between inner and outer cylinder in the same way as the other hydrometeor fields (drops and ice crystals). Immersion freezing occurs as soon as liquid drops above a certain size limit are present and the temperature of a certain potential IN-INP bin is reached. Then the respective amount of drops freezes (if available) instantaneously and is transferred from the liquid to the frozen spectrum. If more drops larger than the size threshold of  $10\text{ }\mu\text{m}$  than active IN-INP are present, the IN-INP are distributed evenly over all drop size bins above the threshold value. The drop size threshold was chosen to restrict freezing to droplets and to prevent (large) non-activated aerosol particles at high relative humidity (but subsaturated

wrt water) outside the cloud from freezing. If ice crystals melt below the freezing level, they contribute to the potential ~~IN-INP~~ field at that level.

### 3.1.2 Ice particle shape

It is well known that ice particle shape highly influences water vapor deposition (described by changing the capacitance of the particle) as well as terminal fall velocity of the ice particle. Therefore, instead of the previously chosen spherical ice particle shape, ice particles now can be prescribed as hexagonal columns or plates. The aspect ratio can be either constant for all size bins or be changed with size following the approach of Mitchell (1996). Typically, with increasing particle size, the deviation from an uniform aspect ratio increases. In our simulations, a constant uniform aspect ratio (ar=1) is used as base case. From Mitchell (1996) the size-varying aspect ratios for plates ~~and columns are (ranging from 15 to 3000  $\mu\text{m}$  with a single description) and columns (for size ranges of 30 to 100  $\mu\text{m}$ , 100 to 300  $\mu\text{m}$ , and above 300  $\mu\text{m}$  in diameter) are calculated from the mass-dimension power laws and used for sensitivity studies.~~

The (relative) capacitance needed for the calculation of deposition growth of the ice crystals is modeled using the method of Westbrook et al. (2008) for the aspect ratios given above. Ice crystal terminal fall velocities are calculated according to Heymsfield and Westbrook (2010) using the same aspect ratios.

## 3.2 Model initialization

### 3.2.1 Thermodynamics

The Asai-Kasahara model has to be initialized with vertical profiles of temperature and dewpoint temperature either from reanalysis data (here GDAS) or radiosonde profiles from nearby stations (here Meiningen, Thuringia). [Fig. 7 shows profiles of temperature and relative humidities with respect to liquid water and to ice, respectively, for both cases.](#) For case 1, profiles from both methods show a similar general behaviour but the radiosonde profile of Meiningen measured at 00 UTC is used since it provides a finer vertical resolution than the GDAS reanalysis data ~~(cp. Fig. 7)~~. However, for case 2 the Meiningen RS profile misses the humidity layer at the level where the clouds were observed ~~and, therefore,~~. [This means that the profile is not representative for the given meteorological situation. Therefore,](#) GDAS reanalysis data for Leipzig at 21 UTC were chosen. Finally, both profiles used show a sufficiently humid layer where the clouds were observed, so that lifting of these layers lead to supersaturation and subsequent cloud formation.

[In contrast to other Asai-Kasahara model studies, updrafts are not initialized by a heat and/or humidity pulse in certain layers for a given period of time. Instead, As mentioned above,](#) vertical velocity (updrafts and downdrafts) in the in-

ner cylinder is prescribed at cloud level ranging from  $h_{bot}$  to  $h_{top}$ . The center of this interval is given by  $h_{mid} = (h_{top} + h_{bot})/2$  and its half-depth by  $h_{depth} = (h_{top} - h_{bot})/2$ .  $h_{bot}$  ranges from 3800 m to 4100 m for case 1 and from 7000 m to 7300 m for case 2. The respective values for  $h_{top}$  are 4500 m and 7700 m. The vertical dependency (compare Fig. 8, left) is given by

$$f_h(h) = \frac{h_{depth}^2 - (h - h_{mid})^2}{h_{depth}^2} \quad \text{for } h_{bot} \leq h \leq h_{top} \quad (1)$$

resulting in the time- and height-dependent function

$$w(h, t) = w_{mid}(t) f_h(h) \quad \text{for } h_{bot} \leq h \leq h_{top} \quad (2)$$

and  $w(h, t) = 0$  otherwise, defining  $w_{mid}(t)$  as the updraft velocity at  $h_{mid}$ . In order to match the observed wind field distributions rather closely,  $w_{mid}(t)$  is chosen as a stochastic function

$$w_{mid}(t) = w_{ave} + f_{scal} \frac{\delta(t)^3}{|\delta(t)|} \quad (3)$$

where  $w_{ave}$  is the average ('large-scale') updraft velocity at  $h_{mid}$  varying between 0.1 m/s and 0.4 m/s,  $f_{scal}$  is the scaling factor determining the range of updraft velocities (chosen as 4 m/s to obtain a difference of minimum and maximum velocity of 2 m/s), and  $\delta(t)$  is a random number ranging from -0.5 to +0.5 obtained from a linear stochastic process provided by FORTRAN. After 30 s model time a new  $\delta(t)$  is created. Different realizations of the stochastic process are tested (see below). E.g.,  $w_{mid}(t)$  ranges from -0.7 m/s to 1.3 m/s if  $w_{ave} = 0.3$  m/s and  $f_{scal} = 4$  m/s as it is shown in the temporal evolution and the histogram in [Figure Fig. 8](#).

Due to the height dependent vertical velocity  $w$ , a horizontal transport velocity  $u_k$  (exchange between inner and outer cylinder) is induced in the Asai-Kasahara formulation for a given model layer  $k$ .

$$u_k = - \frac{w_{k+\frac{1}{2}} \rho_{k+\frac{1}{2}} - w_{k-\frac{1}{2}} \rho_{k-\frac{1}{2}}}{f_r \Delta z \rho_k} \quad (4)$$

Full indices  $k$  indicate values at level centers whereas half indices  $(k + \frac{1}{2}, k - \frac{1}{2})$  describe values at level interfaces.  $f_r = 2/r_i$  is a geometry parameter with the radius  $r_i = 1000$  m of the inner cylinder.

The prescribed velocity field leads to the following effects (all descriptions are related to the inner cylinder if not stated otherwise explicitly):

- In the updraft phase: In the upper part (between  $h_{mid}$  and  $h_{top}$ ) of the updraft, mixing occurs from the inner to the outer cylinder whereas in the lower part (between  $h_{low}$  and  $h_{mid}$ ), horizontal transport is from the outer cylinder into the inner one
- For downdrafts it is the other way: This means that below  $h_{mid}$  drops and ice particles are transported from the inner cylinder to the outer one and are therefore removed from the inner cylinder

- below  $h_{low}$  or above  $h_{top}$ , no horizontal exchange takes place.

The question arises to which extent this dynamical behaviour <sup>420</sup> reflects the real features of the observed clouds and whether <sup>375</sup> this is critical for the topics aimed at in this study.

Prescribing vertical velocity in any way also means that a <sup>425</sup> feedback of microphysics on dynamics due to phase changes (e.g., release of latent heat for condensing water vapor or <sup>450</sup> freezing/melting processes) is not considered by the model. <sup>380</sup>

### 3.2.2 Aerosol distribution

Since no in situ aerosol measurements are available, literature data is used. The Raman lidar observations do not <sup>430</sup> show any polluted layers for both cases; therefore data from LACE98 (Petzold et al., 2002) are used <sup>435</sup> which should be representative for the free troposphere over Leipzig. For case 1 values for the lower free troposphere (M6), for case 2 those from the upper free troposphere (M1) are used <sup>445</sup> (see Petzold et al., 2002, Tab. 6) (see Petzold et al., 2002, Tab. 6)

## 4 Model results: Dynamics

In a first step, the aim is to achieve a sufficient agreement concerning macroscopic cloud features as well as (liquid phase) microphysics as far as they were observed. The following parameters describing model dynamics (updraft velocity) are varied to identify a 'best case' which in the second <sup>445</sup> step can be used to perform sensitivity studies with respect to (ice) microphysics (see also Tables 1 and 2).

- $h_{low}$ : ranging from 3800 m to 4100 m for the warmer and from 7000 m to 7300 m for the colder case. This parameter influences the vertical cloud extent and, therefore, liquid water content and liquid water path. <sup>450</sup>
- $w_{ave}$ : ranging from 0.1 m/s to 0.4 m/s. Higher average updraft also leads to higher LWC. Due to the lateral mixing processes the model setup requires a positive updraft velocity in average to form and maintain clouds. <sup>455</sup>
- $\delta$ : Four different realizations of the stochastic process are used. This influences the timing of the cloud occurrence as well as LWC and LWP but not systematically. <sup>460</sup>

All model results shown refer to the inner cylinder. <sup>410</sup>

### 4.1 Case 1: Warm mixed-phase cloud

Figs. 9 and 11 show time-height plots of the liquid (contours, linear scale) and ice (colours, logarithmic scale) water <sup>470</sup> mixing ratio content for case 1 illustrating the cloud sensitivity with respect to variation of cloud base ( $h_{bot}$ ), average vertical updraft ( $w_{ave}$ ), and the realization of the stochastic

process, respectively. Liquid clouds form in the updraft regions (cp. Fig. 8) whereas in the downdrafts the liquid phase vanishes at least partly. ~~Ice forms mainly at cloudbase and immediately starts~~ If active INP are available ice formation can take place within the liquid part of the cloud. The INP are partly already active near liquid cloud base which means that they trigger freezing as soon as the droplets are formed. Less efficient INP become active after further cooling above cloud base. After ice formation rapid depositional growth takes place and the ice particles almost immediately start to sediment. Due to the supersaturation with respect to ice even below liquid cloud base, ice particles still grow while sedimenting, reaching their maximum size before, finally, subsaturated regions are reached and ~~evaporation sublimation~~ sets in. Figs. 10 and 12 show the time evolution of liquid (lower panel) and ice water path (upper panel) for the same parameters varied, reflecting the same temporal patterns. Table Tab. 1 summarizes the maximum values for liquid and ice water mixing ratio (LWMR content (LWC/IWMIWC)), liquid and ice water path (LWP/IWP) as well as cloud droplet and ice particle number concentration (CDN/IPN) for all dynamics sensitivity runs for case 1.

One can clearly observe, that a lower  $h_{bot}$  (Fig. 9) results in a lower cloud base, larger vertical cloud extent as well as more liquid water. The ~~same trend with similar intensity~~ LWC maxima are within a factor of 2 for varying  $h_{bot}$ . A similar trend is observed for the ice phase (see also Fig. 10) but IWC maxima differ only by about 25 %. However, the values of the two maxima of the condensed phase after about 15–20 min and about 40 min model time are quite different. The first maximum is more pronounced for the ice phase whereas the second one is larger for the liquid phase. While the liquid phase is dominated by the updraft velocity (see Fig. 8) the ice phase additionally depends on INP supply. In the first ice formation event at 15 min, all INP active at the current temperature actually form ice leading to an INP depletion. Due to the horizontal exchange with the outer cylinder the INP reservoir is refilled, but only to a certain extent when the second cloud event after 40 min sets in. Due to the limited INP supply the second ice maximum is weaker than the first one. The stochastic velocity fluctuations cause fluctuations in relative humidity, which are directly reflected by the liquid phase parameters whereas the ice phase generally reacts much slower. Sensitivity of CDN and IPN with respect to change of  $h_{bot}$  does not seem to be systematic.

Increasing the average updraft velocity  $w_{ave}$  leads to a similar increase of liquid water and ice as lowering  $h_{bot}$  (see Figs. 11, upper panel and 12, left). This can be expected since more water vapor flows through the cloud and is able to condense. However, a certain limit seems to be reached for W\_w04, since the increase of LWP slows down (see maximum value at 40 min in Fig. 12, left). This is due to the enhanced horizontal exchanged following eq. (4). Additionally, the stronger updrafts allow the ice particles a longer presence

time in the vicinity of the cloud and, therefore, an enhanced 525 growth at comparably high supersaturation with respect to ice before sedimentation sets in at larger sizes. This also leads 475 to an accumulation of ice particles and, therefore, to a higher IPN. Surprisingly, CDN only depends depends only weakly and not systematically on  $w_{ave}$  which is in contrast to the 530 typical enhancement of CDN with increasing updraft velocities.

480 Figs. 11 (lower panel) and 12 (right) show that different realizations of the stochastic process (as explained above in section 3.2.1) lead to different temporal cloud evolutions. 535 However, differences in maximum LWP and  $LW_{MR}$  are much smaller than those discussed above. Variations in 485 maximum IWP and  $IW_{MR}$  as well as CDN and IPN are in the range of about 30 %. This is also true for average LWP ranging from 18 g/m<sup>2</sup> for W\_r1 to 26 g/m<sup>2</sup> for W\_r3. However, despite the different maxima and temporal evolutions of IWP, average IWP is almost identical for the different 490 stochastic realizations (0.023 g/m<sup>2</sup>). This shows that changing the stochastic realization influences cloud evolution in detail (timing) but does not change the overall picture.

500 With maximum values between 17 and 57 g/m<sup>2</sup> the modeled liquid water path is in the same range as the observed 545 values (20–50 g/m<sup>2</sup>), especially for the 'wetter' runs (smaller  $h_{bot}$ , larger  $w_{ave}$ ). Average LWP typically is about half (40–60 %) of the maximum value for most of the runs which also fits well into the observations. Ice forms within the liquid 550 layer and sediments to about 3800 m for most runs which is less than for the observations. The (maximum) modeled ice 555 mixing ratio is in the same order of magnitude as the observed one (about 10<sup>-7</sup> kg/m<sup>3</sup>). The same holds for the ice water path with values of about 0.01 g/m<sup>2</sup> for both, model and observation. For the other values, no observational data is available for comparison.

## 4.2 Case 2: Colder mixed-phase cloud

510 Due to the colder lower temperatures of case 2 much more INP are active and much more ice is produced than in case 1 (see Figs. 13–16 as well as Tab. 2). Therefore This 560 also means that near cloud base much more active INP are 515 available and that a further cooling within the clouds only slightly increases the number of active INP leading again to a preferential ice nucleation near liquid cloud base. Due to the lower temperatures and the more massive ice formation, 565 the virgae reach down to more than 1500 m below liquid cloud base which is in concordance with the observations. The principal behaviour with respect to the sensitivity parameters is similar as in case 1: The liquid phase is enhanced by either decreasing  $h_{bot}$  or increasing  $w_{ave}$ , showing the 'saturation' effect slightly more pronounced as in case 1. Different 570 stochastic realizations only weakly influence the maximum and average values of the liquid phase but change the timing of occurrence. Generally, the variability of the ice phase is weaker than in case 1. The different stochastic realizations

show the highest variability in  $IW_{MR}$  and IWP. Different variations of  $h_{bot}$  show almost identical IWPs, whereas changing  $w_{ave}$  at least slightly influences maximum  $IW_{MR}$  and IWP, which again can be attributed to the ice particle accumulation in the updraft. Liquid water path is smaller than in case 1 and reaches maximum values between 10 and 43 g/m<sup>2</sup> which well covers the observed maximum value of about 20 g/m<sup>2</sup>. Cloudnet observations show an IWC of 10<sup>-7</sup> – 10<sup>-5</sup> kg/m<sup>3</sup> which is an increase by a factor of 10–100 compared to case 1. Similar values are obtained by the model results underlining the strong temperature dependency of the ice nucleation process.

## 5 Sensitivity studies

In the previous section it could be shown that dynamical parameters can be chosen in a way that the model results (in terms of LWP, IWP as well as cloud geometry) are in good agreement with the observations. This allows to perform sensitivity studies with respect to cloud microphysics. To cover the proper sensitivities we have to answer the question which microphysical parameters are expected to have a large influence on mixed phase microphysics and are rather uncertain to be estimated. This leads to (temperature-dependent)  $IN$  number ( $N_{TN}$ )  $IN$  number ( $N_{LN}$ ) which directly influences ice particle number but mostly is poorly known. To be consistent with the freezing parameterization of the model,  $N_{TN}$   $N_{LN}$  is varied by changing  $N_{AP,r>250\text{ nm}}$  which additionally is easier to observe in most cases. A second parameter is the shape of the ice particles which does not influence the primary freezing process but the subsequent growth by water vapor deposition onto existing ice particles and, therefore, the total ice mass produced. Their relative importance shall be quantified and also be compared to the influence of dynamics discussed above.

### 5.1 $IN$ -INP number

Changing  $N_{AP,r>250\text{ nm}}$  leads to a temperature-dependent change of  $IN$ -INP number which is relatively small for warmer conditions. However, the effect increases with decreasing temperature. This is illustrated by the following numbers. The parameterization of DeMott et al. (2010) gives about 0.009 active  $IN$ -INP per liter at standard conditions ( $N_{TN}$ ,  $N_{LN}$ ) when  $N_{AP,r>250\text{ nm}} = 10^5 \text{ kg}^{-1}$  at  $T = -5^\circ\text{C}$ . A tenfold increase to  $N_{AP,r>250\text{ nm}} = 10^6 \text{ kg}^{-1}$  results in about 0.012 active  $IN$ -INP per liter which is a rise of only about 35 %. For  $T = -7^\circ\text{C}$ ,  $IN$ -INP number rises by about 65 % for a tenfold increase of  $N_{AP,r>250\text{ nm}}$ . This shows that for those rather warm high temperatures considered for case 1, a massive change in  $N_{AP,r>250\text{ nm}}$  leads to relatively small changes in  $N_{TN}$ ,  $N_{LN}$  and only a small effect on the ice phase can be expected. This is confirmed by Fig. 17 (left) showing liquid and ice water mixing ratios

575 contents for W\_in6. **Ice mass IWC** is enhanced by less than 60 % for W\_in6 and by about 160 % for W\_in7 which is consistent for the given temperature range (see Tab. 3). Similar values are obtained for the change in IPN. This directly leads to the conclusion that the individual ice particles grow independently from each other. Their individual growth history is (in contrast to drop growth) only influenced by thermodynamics as long as their number is low enough which seems to be the case here.

580 This is confirmed by Fig. 18 showing drop and ice particle size distributions at the time when the maximum IWP is reached (16 min for case 1, 17 min for case 2). For case 1 (upper panel), the liquid phase (contours) is unaffected by the **IN-INP** enhancement. Despite the increase of ice particle number and mass the shape of the ice particle size distribution (colors) is not changed. The smallest ice particles 585 can be observed at three discrete height (and temperature) levels caused by the temperature resolved parameterization of the potential **IN-INP** described in section 3.1.1. In reality this part of the spectrum showing rather freshly nucleated and fast growing ice particles should be continuous over the height range from about 4100 m to 4400 m. Nevertheless, the total number of ice particles formed is described correctly.

590 One can conclude that increasing **IN-INP** number therefore increases ice particle number as well as ice mass proportionally. Generally, the ice mass remains small and the liquid phase is not affected by the ice mass increase. Those results are supported by Fig. 19 (left) showing an unchanged LWP and a proportionally growing IWP for increased **IN-INP** 595 numbers.

600 For the colder case 2 the parameters are varied in the same way. However, one big difference is that a tenfold increase of  $N_{AP,r>250\text{ nm}}$  at  $T = -25^\circ\text{C}$  results in a much larger change in active **IN-INP**. Their number rises by 300 % 605 from about 0.5 per liter to about 2 per liter following the parameterization. This is reflected by the IPN values in **Table Tab. 4**. Fig. 17 (right) and **Table Tab. 4** show that ice mass increases in such a way that liquid water is depleted partially (C\_in6 by about 50 %) or almost totally (C\_in7) due 610 to the **Bergeron-Findeisen-Wegener-Bergeron-Findeisen** process. Compared to C\_base, ice is enhanced by a factor of 3–4 for C\_in6 and about 10 for C\_in7 whereas IPN increases by a factor of 12. This can also be seen in the IWP (Fig. 19, right, red lines) showing a limited increase for C\_in7, especially for 615 the first maximum after 17 min. This means that the results for C\_in6 are still consistent with an independent growth of the individual ice particles (as described above) despite the relatively high ice occurrence.

620 This is verified by the size distributions in Fig. 18 (lower panel). As in case 1 the ice particle size distributions only differ by the number/mass, but not by shape. Additionally, the decrease in the liquid phase is reflected also in the drop spectrum showing a more shallow liquid part of cloud as well 625 as droplet distribution shifted to smaller sizes.

630 However, for C\_in7 the ice particles compete for water vapor which becomes clear from (i) the depletion of liquid water (resulting in a lower supersaturation with respect to ice) and (ii) the ice mass enhancement factor being below the value expected from the ice nucleation parameterization and below that of IPN. This means that despite the higher number of **IN-INP** and, therefore, ice particles, the amount of ice is limited by the thermodynamic conditions which results in the production of more but smaller ice particles, similar to the Twomey effect for drop activation.

635 As mentioned earlier, ice particle growth is not restricted to the liquid part of the cloud but also occurs in the layer below liquid cloud base, which is still supersaturated with respect to ice. This leads to a decrease in relative humidity in this part of the cloud, which in turn weakens or suppresses droplet formation by shifting liquid cloud base to higher altitudes. The lower LWC for the runs with higher IWC therefore cannot only be attributed to the WBF processes but also to this indirect effect.

## 5.2 Ice particle shape

640 As discussed previously, for most of the cases (except for C\_in7) changing the parameters in the section above does neither influence the ice particles themselves nor their individual growth. Additionally, due to their low number, there is almost no competition of the ice particles for water vapor, and, therefore, ice water content scales linearly with ice particle number. In contrast to this, changing the ice particle shape from quasi-spherical ( $\text{ar}=1$ ) to columns or plates with size-dependent axis ratios deviating from unity results in an increase of water vapor deposition on the individual ice particles leading to enhanced ice water content due to larger individual particles when ice particle numbers remain unchanged. This is due to (i) enhanced relative capacitance resulting in faster water vapor deposition and (ii) lower terminal velocities of the ice particles leading to longer residence times in vicinity of conditions with supersaturation with respect to ice.

645 Fig. 20 (left) shows the results for the runs using hexagonal columns (W\_col) as prescribed ice particle type. Compared to the previous results (W\_base, W\_in6, W\_in7) more ice mass is produced (see **Table Tab. 3**) but still the liquid part of the cloud remains unaffected (compare also LWP and IWP in Fig. 19, left). Similar results are obtained for the assumption of plate-like ice particles (W\_pla). The mass increase results from the larger ice particle size due to the reasons discussed above which can be seen from Fig. 21 showing the size distributions for W\_col at different times. On the upper left panel W\_col is shown after 16 min corresponding to Fig. 18. Compared to W\_base, larger ice particles are produced leading to more ice mass (equivalent radius up to 300  $\mu\text{m}$  compared to 189–238  $\mu\text{m}$  for the base case). Additionally, due to the lower fall speed of the columns (1.03 m/s vs. 1.75–2.24 m/s), the maximum of the ice is at about 4200 m compared to 4100 m

for the base case. On the upper right panel, size distributions after 21 min are shown corresponding to the IWP maximum of W\_col. Ice particles have grown larger (equivalent radius up to  $378 \mu\text{m}$ , length of the columns increases from about 3 mm to 4.5 mm) and sedimentation has developed further with increasing terminal velocity (1.13 m/s). Similar results are obtained for plates (W\_pla) with terminal velocities of 0.89–1.21 m/s, equivalent radii of 300–476  $\mu\text{m}$  and maximum dimension of 1.8–3.2 mm.

The lower terminal velocity of columns and plates despite their larger size is leading to the stronger tilting of the virgæ. Additionally, ice particle number IPN is enhanced by about 30 % although ice nucleation is identical to W\_base. This can be attributed to the lower fall velocities, too, leading to an accumulation of ice particles. The differences between W\_col and W\_pla are caused by both, the higher relative capacitances of and lower terminal fall velocities of plates compared to columns (at least when their axis ratios are chosen following Mitchell (1996)).

For case 2 (C\_col and C\_pla), the liquid water reduction due to the Bergeron-Findeisen process is similar to C\_in6 (see Fig. 20, right, and Table Tab. 4). In contrast to the respective case 1 runs, less ice is produced than for C\_in7. The tilting of the virgæ is not as strong as in W\_col which is due to the larger ice particle sizes leading to higher terminal fall velocities (1.43–1.60 m/s). Additionally, the lower air density leads to an increase of terminal velocity of more than 10 % independently from shape. Fig. 21 (lower panels) shows the size distributions for C\_col at different times. Due to the longer growth time larger individual ice particles than in case 1 are produced (equivalent radius up to  $600 \mu\text{m}$  compared to  $300 \mu\text{m}$  for the base case).

To decide whether independent ice particle growth or competition occurs, further runs with less IN\_INP (C\_col\_in4 and C\_pla\_in4) are discussed (see Fig. 19, right). IWMR-IWC and IWP of these runs (in4) are about one third of the values of the respective runs with more IN\_INP (in5). For ice particle number, a factor of slightly more than three occurs which means that a weak competition for water vapor occurs for C\_col and C\_pla resulting in slightly smaller individual ice particles compared to C\_col\_in4 and C\_pla\_in4.

## 6 Conclusions

The model system AK-SPECS was applied to simulate dynamical and microphysical processes within altocumulus clouds. Sensitivity studies on relative contributions on cloud evolution as well as comparisons to observations were made.

Variation of the dynamic parameters as it was done in section 4 leads to systematic differences mainly in the liquid phase (LWMR\_LWC, LWP) which can easily be explained. More liquid water is produced when either cloud base is lowered (corresponding to a larger vertical cloud extent) or vertical wind velocity is increased. However, the effects of

the dynamics on the ice phase are surprisingly small, at least smaller than those on the liquid phase. Increasing vertical velocity leads to an accumulation of the smaller ice particles in the enhanced updraft.

On the other hand, much larger differences in terms of IWMR-IWC and IWP were found when microphysical parameters like IN\_INP number or ice particle shape were varied under identical dynamic conditions. This is valid for both cases studied. However, at least for the ice nucleation parameterization used, sensitivity of IN\_INP number strongly increased with decreasing temperature.

This means that relatively large differences concerning the ice phase can only be reached when either IN\_INP number differs considerably or ice particle shape is different (which should not be the case for relatively similar thermodynamical conditions). After Fukuta and Takahashi (1999) for case 1 with temperatures of about  $-6^\circ\text{C}$  column-like ice particles with  $ar = 0.1$  could be expected (corresponding to W\_col) whereas for case 2 ( $T < -24^\circ\text{C}$ ) hexagonal particles with  $ar = 1$  are most likely (e.g., C\_base). Those ice shapes were observed in laboratory studies at water saturation which was also valid for the observed cases when ice formed by immersion freezing within the liquid layer of the cloud. However, below liquid cloud base supersaturation with respect to ice decreases. These ice shapes can also explain why a depletion of the liquid phase was not observed in case 2 as it was predicted by the sensitivity studies using either columns or plates as prescribed shape. Generally, the liquid phase is affected considerably only when enough ice particles are present which typically is the case for cold conditions with a sufficient amount of IN\_INP and fast growing ice particle shapes (most effective for large deviations from spherical shapes).

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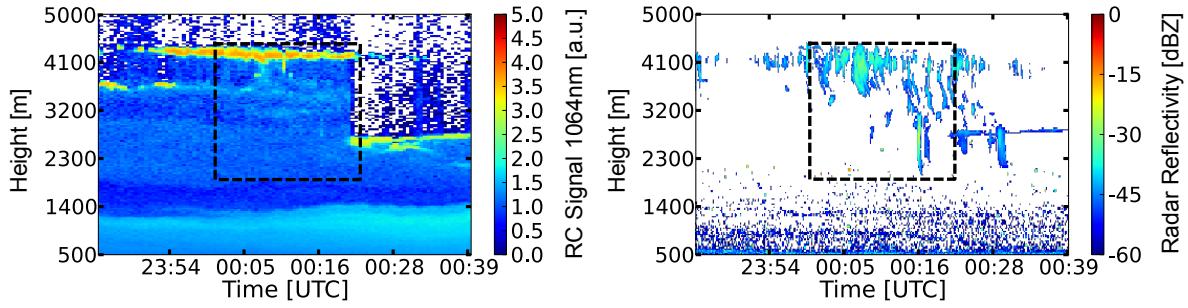
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**Table 1.** Overview of the model results for the dynamic sensitivity runs for the warmer case 1 (maximum values of L/IWMR/IWC: liquid/ice water mixing ratio content, L/IWP: liquid/ice water path, CDN: cloud drop number, IPN: Ice particle number).

run	parameter value differing from base case	LWMR-LWC g/kg m <sup>3</sup>	IWMR-IWC 10 <sup>-3</sup> g/kg m <sup>3</sup>	LWP g/m <sup>2</sup>	IWP 10 <sup>-3</sup> g/m <sup>2</sup>	CDN cm <sup>-3</sup>	IPN l <sup>-1</sup>
W_base	—	0.277 0.355	0.304 0.379	41.33	62.27	46.89	0.0197
W_h38	$h_{bot} = 3800$ m	0.332 0.426	0.329 0.408	57.05	73.11	48.63	0.0235
W_h40	$h_{bot} = 4000$ m	0.225 0.289	0.286 0.357	28.58	58.12	61.48	0.0240
W_h41	$h_{bot} = 4100$ m	0.170 0.219	0.259 0.324	18.23	45.81	59.53	0.0208
W_w01	$w_{ave} = 0.1$ m/s	0.147 0.187	0.160 0.200	17.41	31.73	43.36	0.0138
W_w02	$w_{ave} = 0.2$ m/s	0.232 0.297	0.241 0.300	32.86	47.18	54.57	0.0175
W_w04	$w_{ave} = 0.4$ m/s	0.297 0.382	0.359 0.448	44.48	78.25	52.66	0.0219
W_r1	stoch. realiz. r1	0.261 0.336	0.254 0.316	40.32	54.85	64.26	0.0163
W_r3	stoch. realiz. r3	0.296 0.381	0.252 0.314	42.88	54.48	43.03	0.0167
W_r4	stoch. realiz. r4	0.269 0.346	0.197 0.245	40.91	46.93	47.42	0.0151

**Table 2.** Overview of the model results for the dynamic sensitivity runs for the colder case 2 (maximum values of L/IWMR/IWC: liquid/ice water mixing ratio content, L/IWP: liquid/ice water path, CDN: cloud drop number, IPN: Ice particle number).

run	parameter value differing from base case	LWMR-LWC g/kg m <sup>3</sup>	IWMR-IWC g/kg m <sup>3</sup>	LWP g/m <sup>2</sup>	IWP g/m <sup>2</sup>	CDN cm <sup>-3</sup>	IPN l <sup>-1</sup>
C_base	—	0.215 0.377	0.026 0.041	29.35	10.71	70.56	0.462
C_h70	$h_{bot} = 7000$ m	0.258 0.452	0.030 0.048	43.06	11.34	71.33	0.432
C_h72	$h_{bot} = 7200$ m	0.169 0.296	0.022 0.035	18.71	10.11	90.51	0.396
C_h73	$h_{bot} = 7300$ m	0.122 0.215	0.018 0.028	10.54	9.27	77.61	0.337
C_w01	$w_{ave} = 0.1$ m/s	0.126 0.219	0.025 0.040	17.19	8.01	76.98	0.292
C_w02	$w_{ave} = 0.2$ m/s	0.181 0.316	0.027 0.044	25.89	9.42	74.40	0.415
C_w04	$w_{ave} = 0.4$ m/s	0.229 0.402	0.028 0.045	30.58	11.85	98.37	0.439
C_r1	stoch. realiz. r1	0.209 0.366	0.014 0.023	29.37	6.57	86.64	0.257
C_r3	stoch. realiz. r3	0.228 0.399	0.029 0.046	30.22	9.95	79.65	0.341
C_r4	stoch. realiz. r4	0.213 0.373	0.031 0.049	29.53	8.33	95.89	0.419



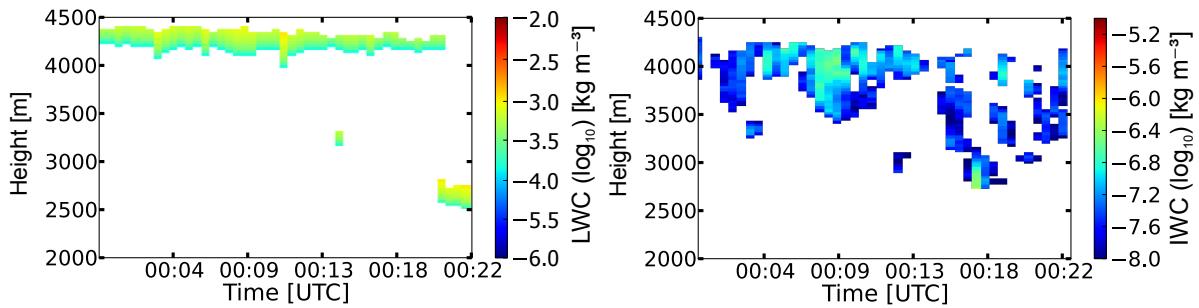
**Fig. 1.** Lidar and radar observations on 17 September 2011 (case 1). Left: Lidar range-corrected 1064 nm signal (in logarithmic scale, arbitrary units a. u.), right: radar reflectivity. The dashed box denotes the region for which case 1 observations are shown in the following figures.

**Table 3.** Overview of the model results for the microphysical sensitivity runs for the warmer case 1 (maximum values of L/IWMR/IWC: liquid/ice water mixing ratio content, L/IWP: liquid/ice water path, CDN: cloud drop number, IPN: Ice particle number).

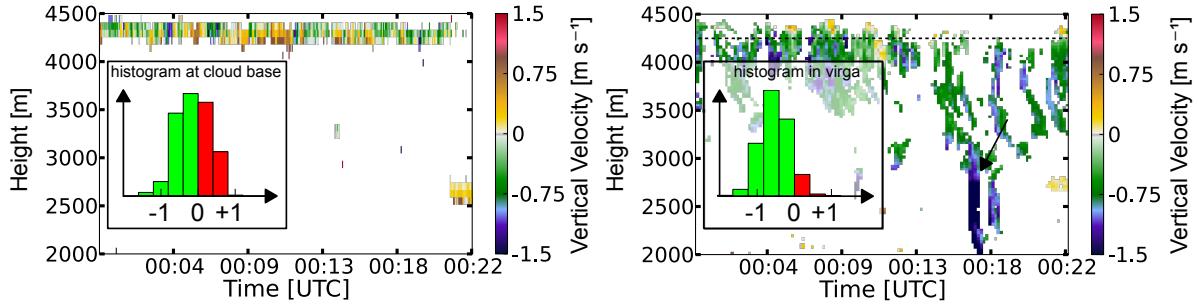
run	parameter value differing from base case	LWMR-LWC g/kg m <sup>3</sup>	IWMR-IWC 10 <sup>-3</sup> g/kg m <sup>3</sup>	LWP g/m <sup>2</sup>	IWP g/m <sup>2</sup>	CDN cm <sup>-3</sup>	IPN l <sup>-1</sup>
W_in6	$N_{AP,r>250nm} = 10^6 \text{ kg}^{-1}$	0.276 0.354	0.496 0.619	41.31	0.10	46.69	0.0296
W_in7	$N_{AP,r>250nm} = 10^7 \text{ kg}^{-1}$	0.276 0.354	0.801 1.000	41.24	0.17	41.61	0.0450
W_col	ice shape: columns	0.275 0.353	1.467 1.830	41.20	0.27	42.90	0.0257
W_pla	ice shape: plates	0.275 0.353	2.285 2.850	41.13	0.45	43.41	0.0267

**Table 4.** Overview of the model results for the microphysical sensitivity runs for the colder case 2 (maximum values of L/IWMR/IWC: liquid/ice water mixing ratio content, L/IWP: liquid/ice water path, CDN: cloud drop number, IPN: Ice particle number).

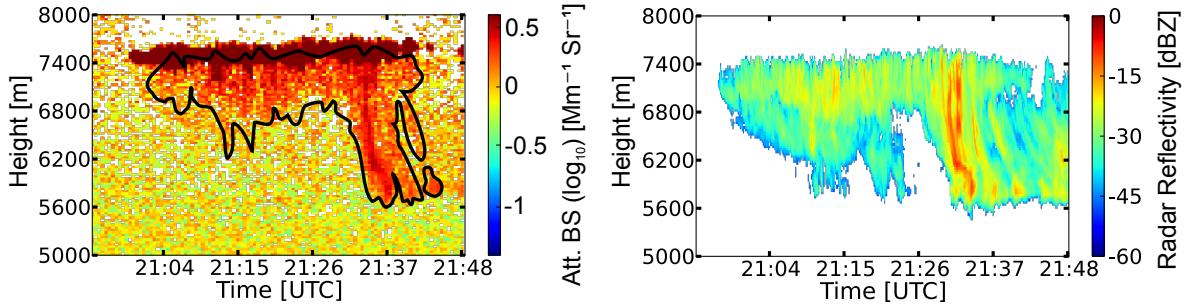
run	parameter value differing from base case	LWMR-LWC g/kg m <sup>3</sup>	IWMR-IWC g/kg m <sup>3</sup>	LWP g/m <sup>2</sup>	IWP g/m <sup>2</sup>	CDN cm <sup>-3</sup>	IPN l <sup>-1</sup>
C_in6	$N_{AP,r>250nm} = 10^6 \text{ kg}^{-1}$	0.128 0.224	0.089 0.140	13.09	34.75	80.29	1.380
C_in7	$N_{AP,r>250nm} = 10^7 \text{ kg}^{-1}$	0.021 0.036	0.265 0.446	2.58	57.98	46.67	5.208
C_col	ice shape: columns	0.135 0.237	0.139 0.223	14.33	46.78	78.40	0.462
C_col_in4	ice shape: columns, $N_{AP,r>250nm} = 10^4 \text{ kg}^{-1}$	0.216 0.378	0.048 0.076	30.01	14.93	74.75	0.139
C_pla	ice shape: plates	0.104 0.182	0.183 0.294	9.94	57.11	39.41	0.472
C_pla_in4	ice shape: plates, $N_{AP,r>250nm} = 10^4 \text{ kg}^{-1}$	0.207 0.362	0.064 0.102	27.80	19.21	74.44	0.129



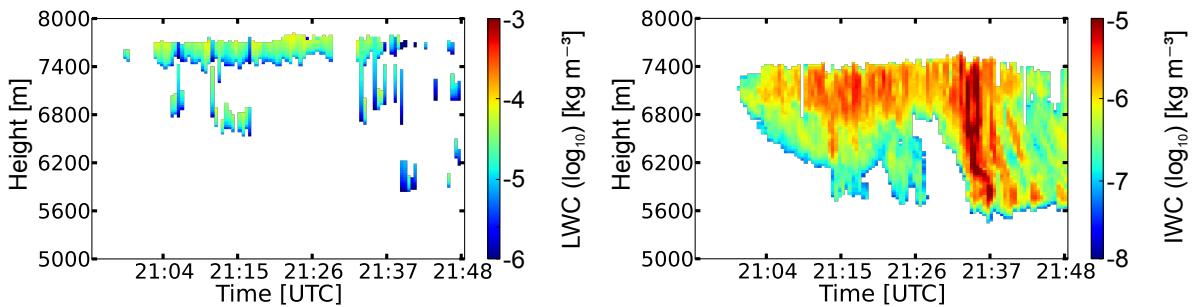
**Fig. 2.** Lidar observations on 17 September 2011 (Cloudnet derived water contents for case 4)-1. Left: Liquid water content IWC, right: range-corrected 1064 nm signal ice water content (both in logarithmic scale, arbitrary units a.u.).



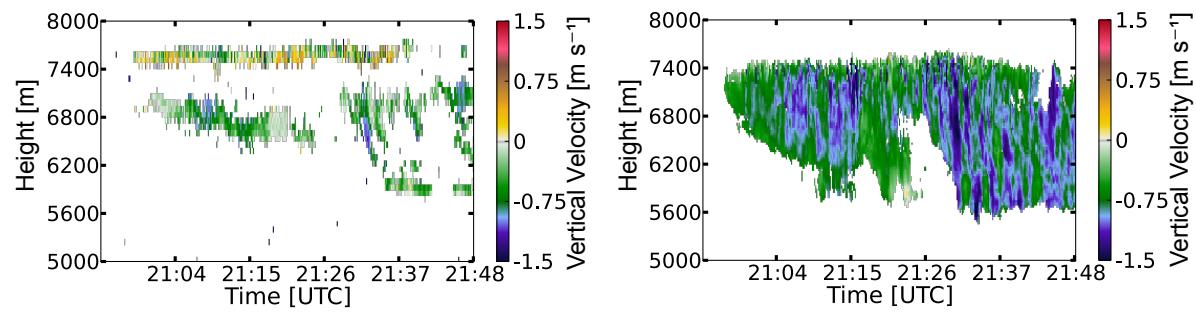
**Fig. 3.** Vertical velocity for case 1. Left: derived from [radar observations-lidar](#) (valid for [large particles; virga](#) [more numerous smaller droplets at cloud base](#)), right: derived from [lidar-radar observations](#) (valid for [more numerous smaller droplets at cloud base](#) [large particles; virga](#)).



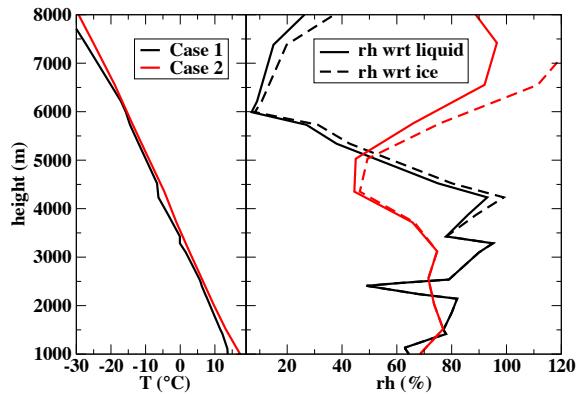
**Fig. 4.** Lidar and radar observations on 2 August 2012 (case 2). Left: [Ice water content IWC](#), right: [1064-532 nm attenuated backscatter coefficient](#), right: [radar reflectivity](#).



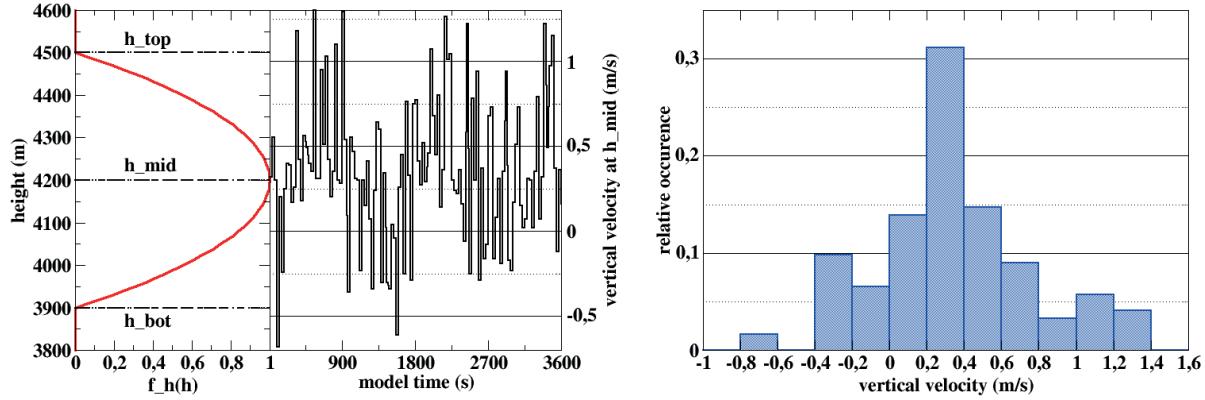
**Fig. 5.** [Vertical velocity](#)-Cloudnet derived water contents for case 2. Left: Liquid water content, [derived from radar observations](#) right: ice water content (both in logarithmic scale).



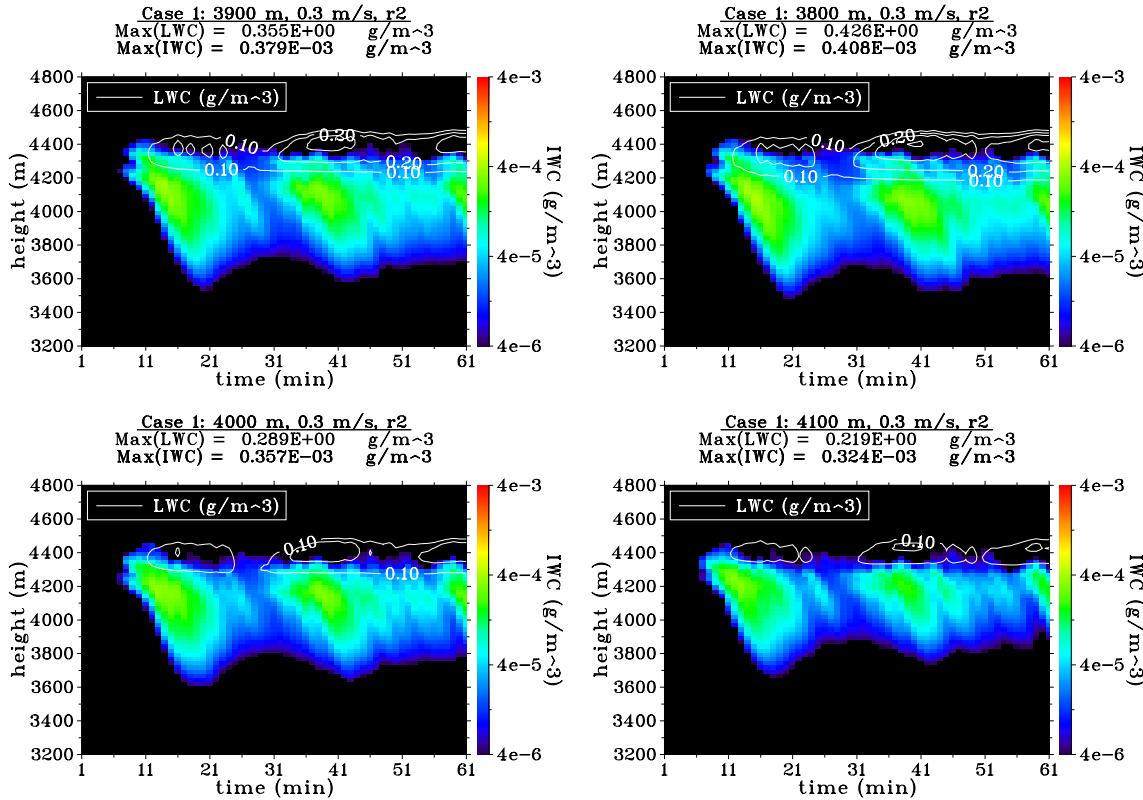
**Fig. 6.** Vertical velocity for case 2. Left: derived from lidar (valid for more numerous smaller droplets at cloud base), right: derived from radar observations (valid for large particles; virga).



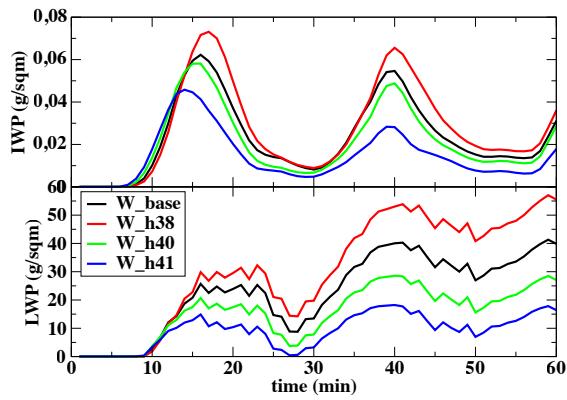
**Fig. 7.** Vertical profiles of temperature (left) and relative humidity (right) with respect to liquid water (full lines) and ice (dashed lines) based on a radiosonde observation (Meiningen) for case 1 (black) and from GDAS (grid point Leipzig) for case 2 (red).



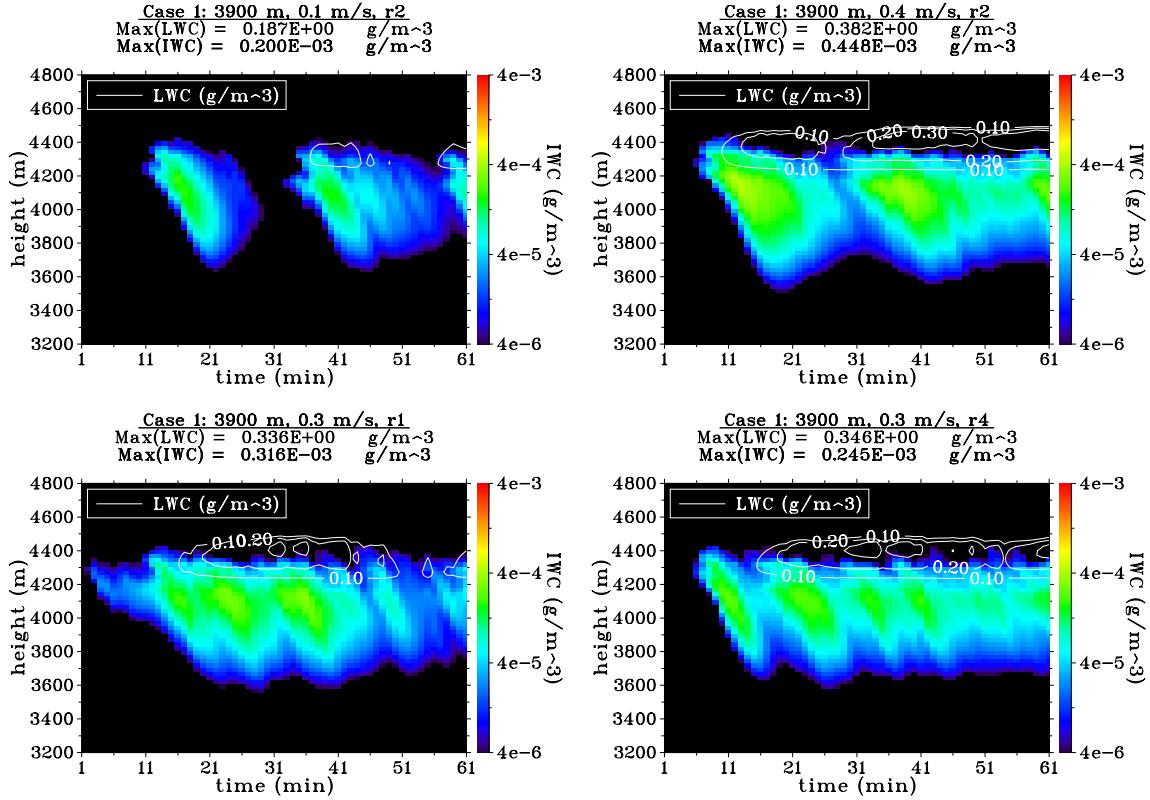
**Fig. 8.** Vertical velocity field of the inner cylinder for case 1. Left: Height dependence (red line) and temporal evolution of one realization of the stochastic vertical velocity field (black line) for  $w_{ave} = 0.3$  m/s at  $h_{mid}$ . Right: Histogram of velocity field. Vertical velocity for case 2 is identical but for heights between 7100 m and 7700 m.



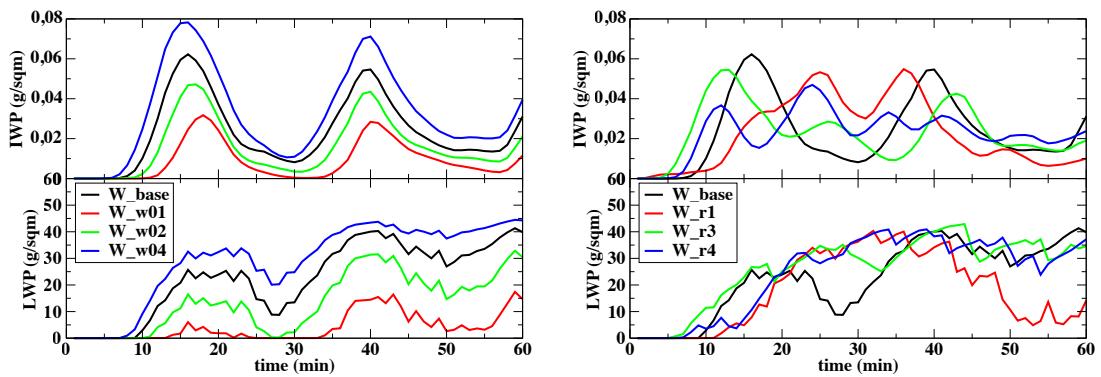
**Fig. 9.** Liquid water content (LWC) (contours) and ice-water mixing ratio (IWC) (colours, logarithmic scale) for case 1. Comparison of different values for  $h_{bot}$  (Upper left: W\_base,  $h_{bot} = 3900$  m, upper right: W\_h38,  $h_{bot} = 3800$  m, lower left: W\_h40,  $h_{bot} = 4000$  m, lower right: W\_h41,  $h_{bot} = 4100$  m).



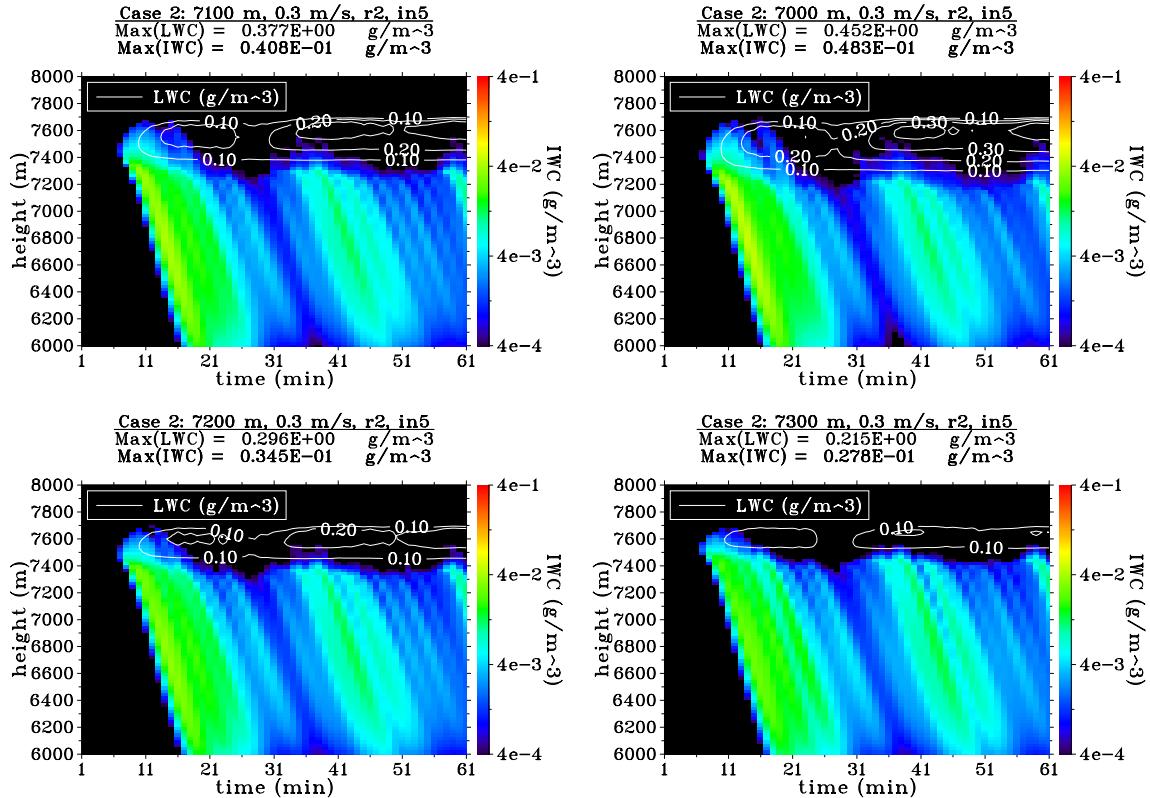
**Fig. 10.** Liquid (lower panel) and ice water paths (upper panel) for case 1. Comparison of the different values for  $h_{bot}$ .



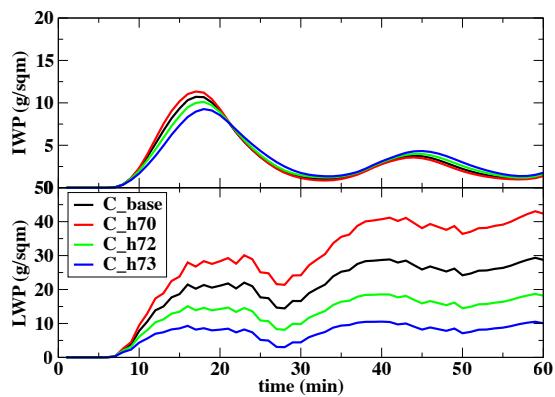
**Fig. 11.** Liquid LWC (contours) and ice water mixing ratio IWC (colours, logarithmic scale) for case 1. Comparison of different average updraft velocities  $w_{ave}$  (Upper panel: Left: W\_w01,  $w_{ave} = 0.1$  m/s, right: W\_w04,  $w_{ave} = 0.4$  m/s.) and different stochastic realizations (Lower: Left: W\_r1, r1, right: W\_r4, r4).



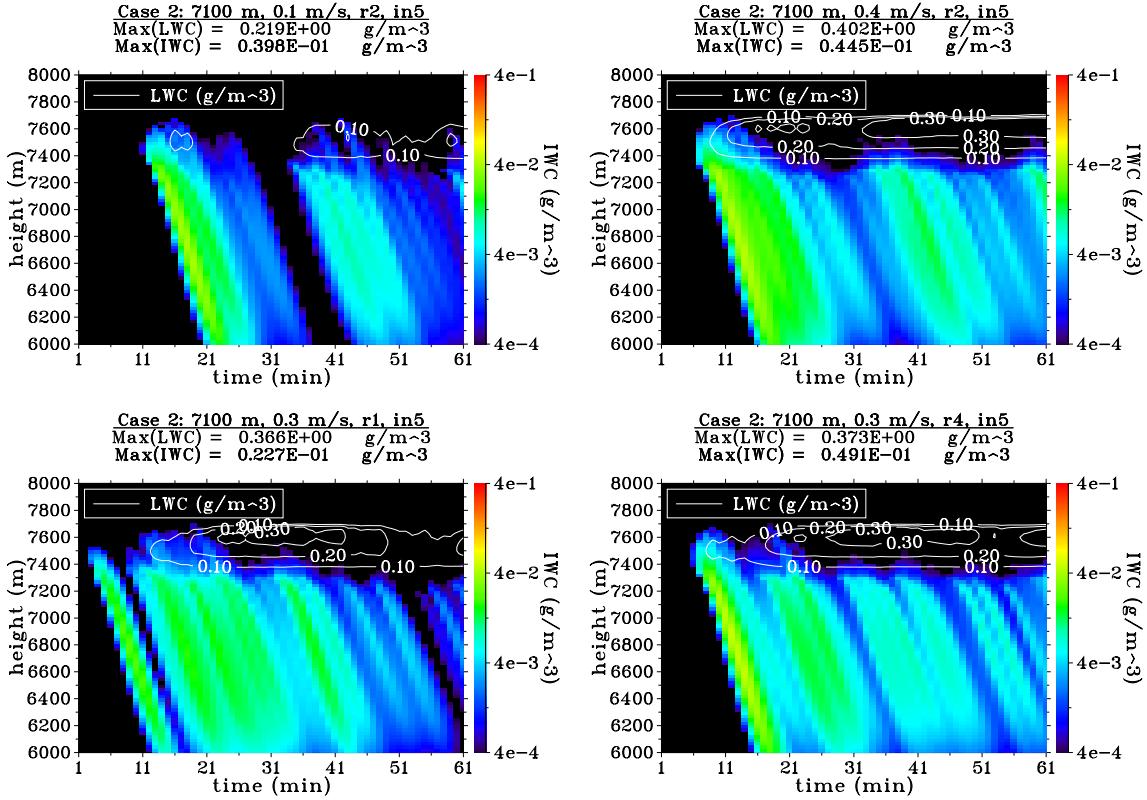
**Fig. 12.** Liquid (lower panels) and ice water paths (upper panels) for case 1. Comparison of the different values for  $w_{ave}$  (left) and the different stochastic realizations (right).



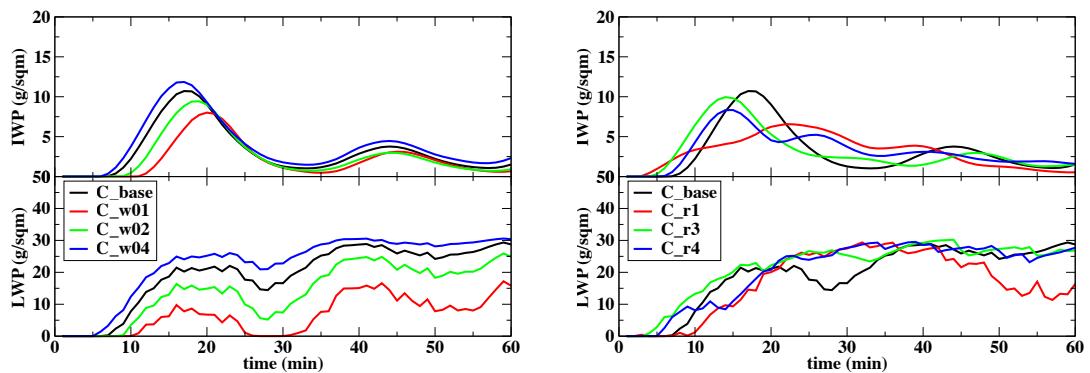
**Fig. 13.** Liquid-LWC (contours) and ice-water-mixing-ratio-IWC (colours, logarithmic scale) for case 2. Comparison of different values for  $h_{bot}$  (Upper left: C<sub>base</sub>,  $h_{bot} = 7100$  m, upper right: C<sub>h70</sub>,  $h_{bot} = 7000$  m, lower left: C<sub>h72</sub>,  $h_{bot} = 7200$  m, lower right: C<sub>h73</sub>,  $h_{bot} = 7300$  m.)



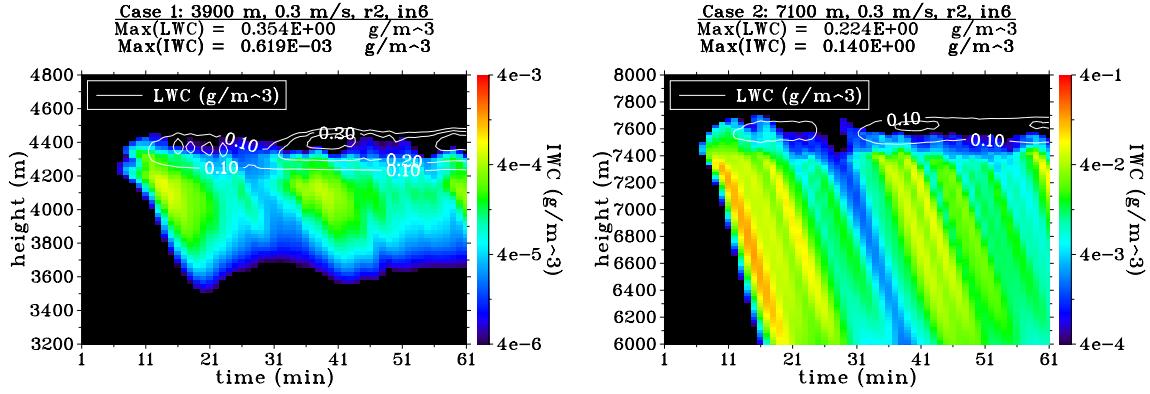
**Fig. 14.** Liquid (lower panel) and ice water paths (upper panel) for case 2. Comparison of the different values for  $h_{bot}$ .



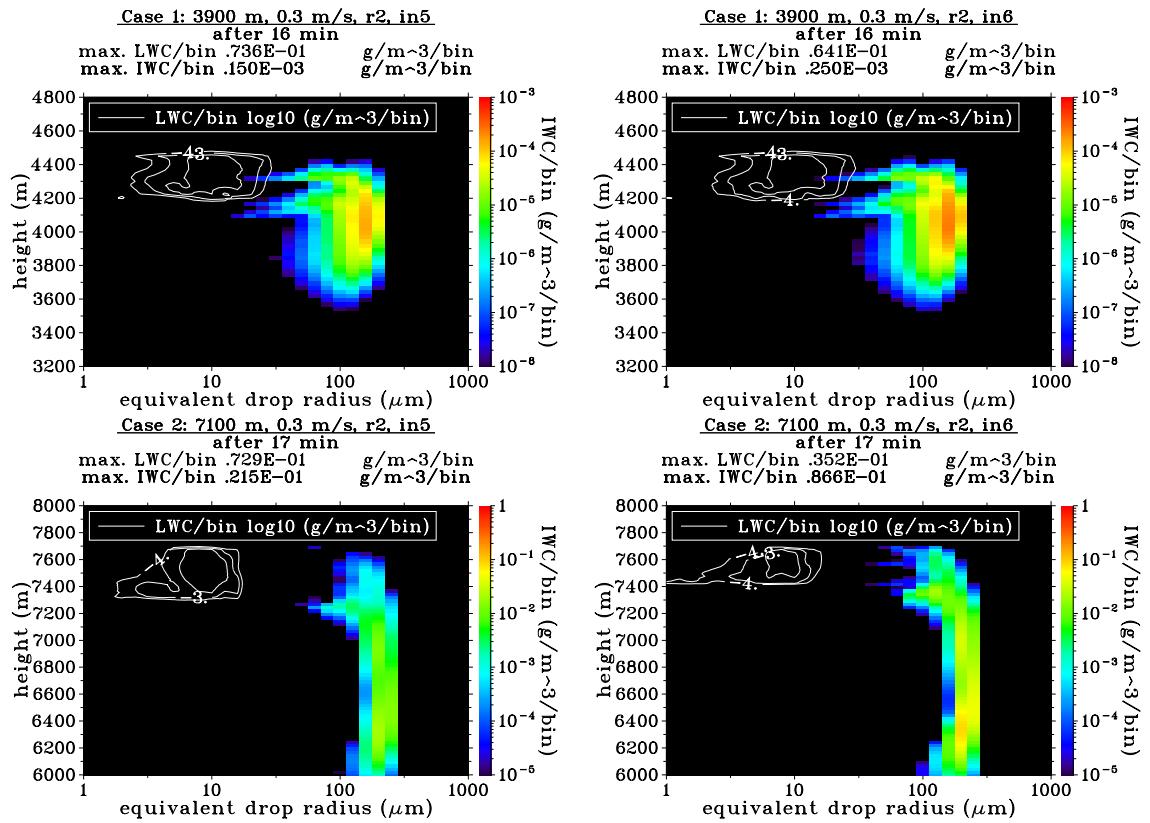
**Fig. 15.** Liquid LWC (contours) and ice water mixing ratio IWC (colours, logarithmic scale) for case 2. Comparison of different average updraft velocities  $w_{ave}$  (Upper: Left: C\_w01,  $w_{ave} = 0.1$  m/s, right: C\_w04,  $w_{ave} = 0.4$  m/s) and the different stochastic realizations (Lower: Left: C\_r1, r1, right: C\_r4, r4).



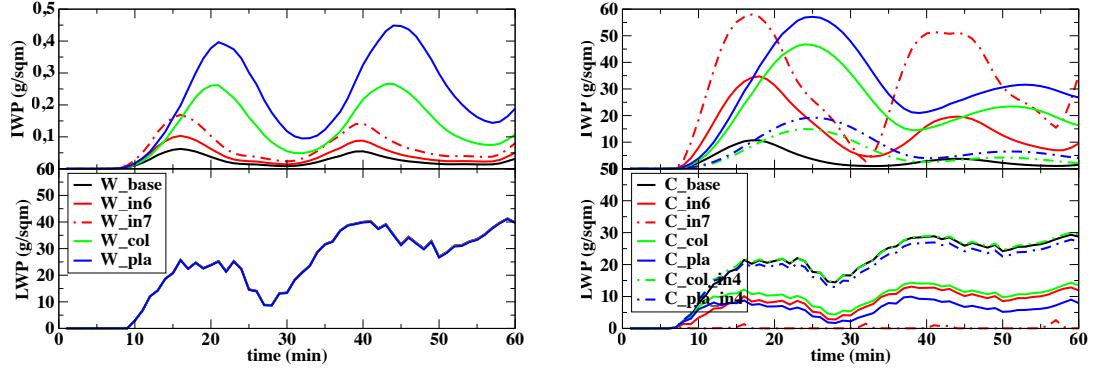
**Fig. 16.** Liquid (lower panels) and ice water paths (upper panels) for case 2. Comparison of the different values for  $w_{ave}$  (left) and the different stochastic realizations (right).



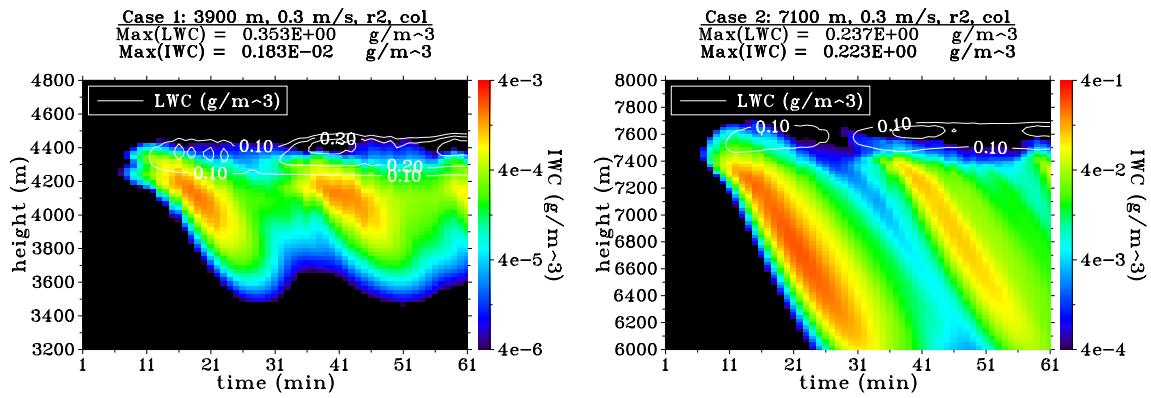
**Fig. 17.** Liquid LWC (colors) and ice-water mixing ratio IWC (contours, logarithmic scale) for case 1 (W\_in6, left) and case 2 (C\_in6, right). Enhancing IN by increasing  $N_{AP,r>250\text{ nm}}$  by a factor of 10.



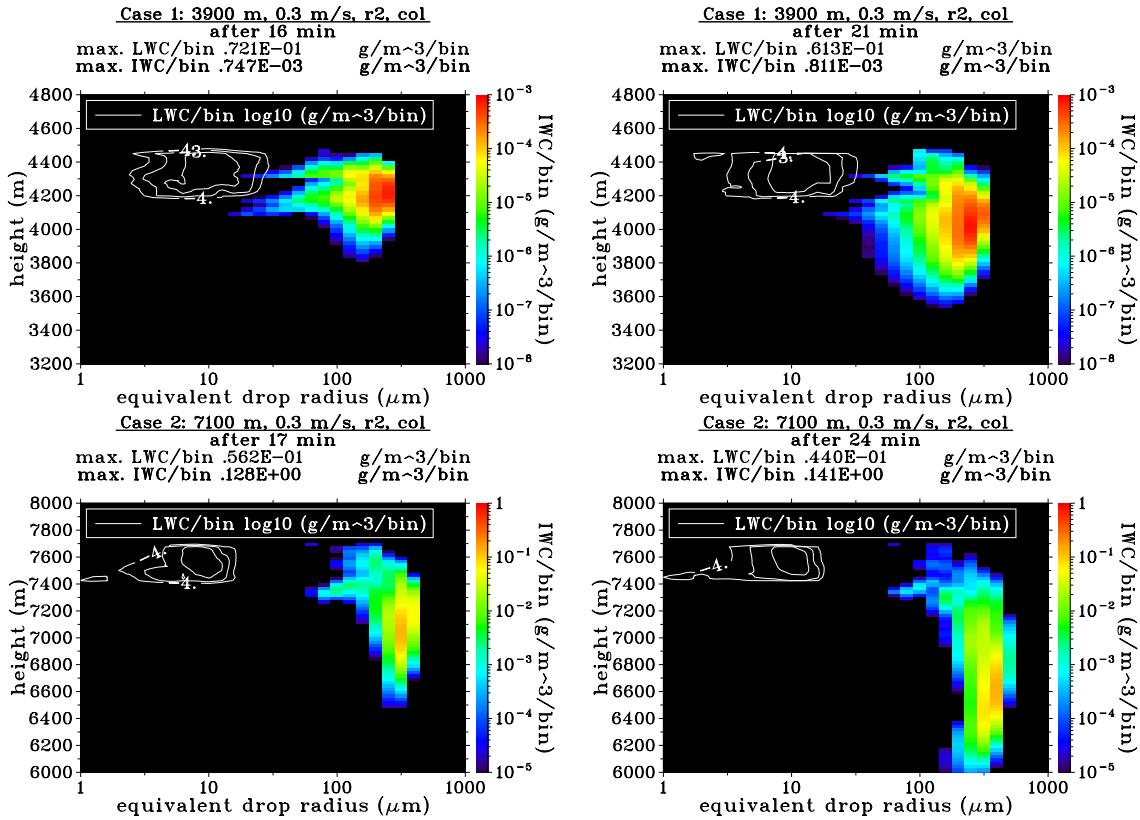
**Fig. 18.** Liquid LWC (colors, contours) and ice-water mass IWC per bin (contours, colors, both logarithmic scale) for case 1 (upper panel) and case 2 (lower panel) for the respective base case (left) and the case with enhanced IN number (right; in6) after 16 and 17 minutes model time, respectively, corresponding to the IWP maximum of the base case runs.



**Fig. 19.** Liquid (lower panel) and ice water paths (upper panel) for case 1 (left) and case 2 (right). Comparison of the sensitivities with respect to IN number and ice particle shape.



**Fig. 20.** Liquid LWC (color contours) and ice water mixing ratio IWC (color contours, logarithmic scale). Results for changing ice particle shape to hexagonal columns for case 1 (W\_col, left) and case 2 (C\_col, right).



**Fig. 21.** Liquid LWC (e~~on~~ors~~on~~ contours) and ice water mass per bin (e~~on~~contours~~on~~ colors, both logarithmic scale) for case 1 (upper panel) and case 2 (lower panel) assuming columns as ice particle shape at IWP maximum of the respective base case (left) and at IWP of the run (right).