Answer to Anonymous Referee 1

The authors are grateful for the time and thought that Anonymous Referee 1 put into the review and comments regarding our paper. We incorporate most of those comments into our revised manuscript, which has led to substantial improvements. Detailed responses to all comments follow below. The original comments from Anonymous Referee 1 are in italics and our responses as well as changes in the manuscript in plain text.

This work examines the uncertainties of Lagrangian parcel modelling of cirrus clouds to the details of model configuration (resolution, small-scale temperature fluctuations, initial water vapour content, and nucleation mechanism). The analyses are carefully done and scientifically sound. The manuscript contributes to progress in cirrus cloud modelling, and it is suitable for ACP. I recommend publication of the manuscript, subject to revisions.
In general, the manuscript is difficult to read. For instance, the abstract provides too many technical details and does not clearly highlight the main results, which are (based on my understanding):

· The model calculations are sensitive to the temperature fluctuations, upstream specific humidity, and nucleation mechanism, and the uncertainties associated with these factors are highly non-linearly linked.
· High resolution is required in order to account for the small-scale (high-frequency) temperature fluctuations.
I suggest the authors to rewrite the abstract to communicate these points more effectively to the readers.

Response:

We have rewritten the abstract to more clearly highlight these results. We think that a major outcome of the study is the illustration of the large day-to-day variability of the vertical velocity variance, which needs to be taken into account for the construction of small-scale temperature fluctuations in future studies. This remains an important point in the abstract.

Changes in manuscript on lines 2-24 on pages 1 and 2 of the revised manuscript in blue:

Here we model cirrus clouds along air mass trajectories, whose extinction has been measured with an elastic backscatter Lidar at Jungfraujoch research station in the Swiss Alps, with a microphysical stacked box model. The sensitivities of these simulations to input data uncertainties (trajectory resolution, unresolved vertical velocities, ice nuclei number density and upstream specific humidity) are investigated.
Variations of the temporal resolution of the wind field data (COSMO-model at 2.2 km resolution) between 20 s and 1 h have only a marginal impact on the trajectory path, while the representation of the vertical velocity variability and therefore the cooling rate distribution are significantly affected. A temporal resolution better than 5 minutes must be chosen in order to resolve cooling rates required to explain the measured extinction. A further increase of the temporal resolution improves the simulation results slightly. The close match between the modeled and observed extinction profile for high resolution trajectories suggests that the cooling rate spectra calculated by COSMO-2 suffice on the selected day. The modeled cooling rate spectra are, however, characterized by significantly lower vertical velocity amplitudes than those found previously in some aircraft campaigns (SUCCESS, MACPEX). A climatological analysis of the vertical velocity amplitude in the Alpine region based on COSMO-2 analyses and balloon sounding data suggests large day-to-day variability in small-scale temperature fluctuations. This demonstrates the necessity to apply numerical weather prediction models with high spatial and temporal resolutions in cirrus modeling, whereas using climatological means for the amplitude of the unresolved air motions does generally not suffice.
The box model simulations further suggest that uncertainties in the upstream specific humidity

(±10 % of the model prediction) and in the ice nuclei number density (0–100 L^{-1}) are more important for the modeled cirrus cloud than the unresolved temperature fluctuations, if temporally highly resolved trajectories are used.

In addition, although the main results (as stated above) are important, they are not especially new (I expect these results before reading the manuscript). Also, I am concerned that some of the model results may not be robust, i.e. very specific to the particular cloud studied here. Thus, the additional case (currently in the appendix) is helpful. Having these two cases, the authors could focus the discussions on the results that are robust (or not robust), and by doing so clarify the main conclusions of the paper.

Response:

We have so far found no publication where these uncertainties are systematically examined for a Lagrangian perspective, though they have been demonstrated separately for a variety of case studies. The systematic comparison of these uncertainties for a single cloud is new. We emphasize in the paper, that the main result might not be representative for all atmospheric conditions. Therefore we added the more active case in the Appendix. During this work we have done simulations for different times during 2011-11-22, which behaved more or less similar. Therefore for brevity only the results for this single time slot are shown. We have added some discussion on the representativity of the particular case in the conclusions.

Added section in manuscript on lines 689-701 on page 28 of the revised manuscript in blue:

Lagrangian cirrus cloud modeling shows large sensitivities to all investigated factors. However, the order of their importance can vary from case to case. The presented case study of an isolated temporally persistent cirrus cloud with rather small horizontal extent may only be representative for cirrus cloud formation under some specific conditions. In addition, the wave activity on the investigated day is clearly below the climatological average. Therefore we present a case with dynamically more active conditions in the appendix. For the active day, the modelled cirrus clouds shows different responses to modifications of the initial humidity and the assumed ice nuclei number density: variations of both parameters lead in general to a variation of the optical thickness of the cloud, while they affected also the vertical location of the cloud on the quiet day. Similar to the quiet day, simulations with ice nuclei number density in excess of 20 L^{-1} are found to be inconsistent with the observations. The best match with the observed extinction profile is obtained for an increased initial moisture content. A high sensitivity of Lagrangian cirrus cloud modeling to initial humidity was also found by Dinh et al. (2015) in simulations for cirrus clouds in the tropical tropopause layer.

Please see my specific comments below:

· Page 7538, line 15: "ice nuclei number density" is not quite correct. The simulations were carried out with homogeneous nucleation only, and with both homogeneous and heterogeneous nucleation with varying ice nuclei number densities. In section 2.3, please provide the number density of solution droplets used for the calculation of homogeneous nucleation.

Response:

This was corrected.

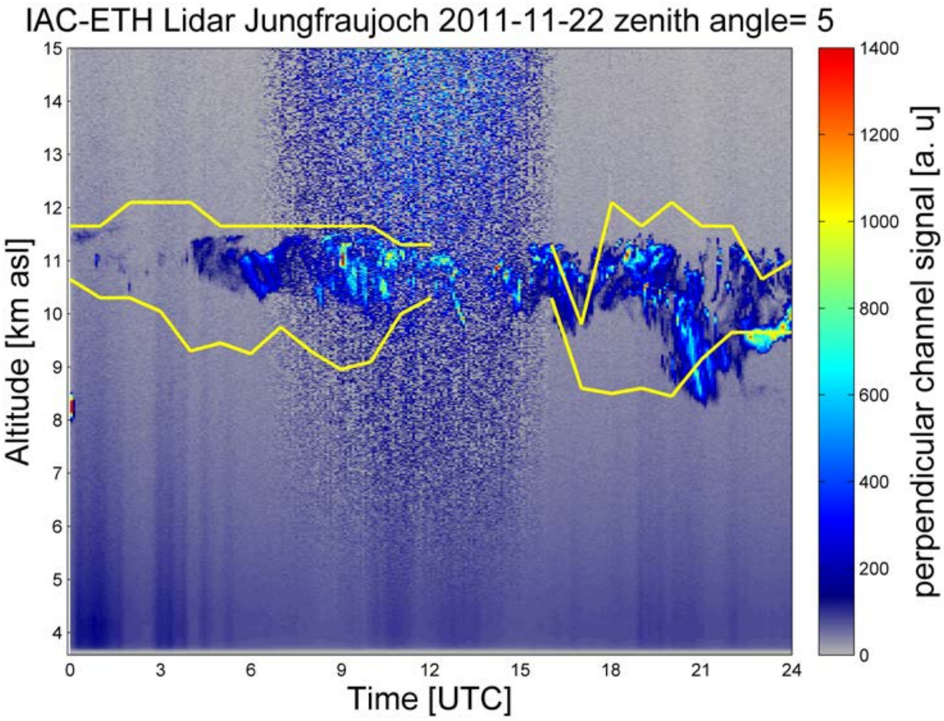
Changes in manuscript on lines 68-69 on page 3 of the revised manuscript in blue:

(d) simulations with homogeneous nucleation only and simulations with homogeneous as well as heterogeneous nucleation with varying initial ice nuclei number densities $n_{IN}(t = 0)$.

Section 2.2.1: It would be very useful to carry out a simulation of the cloud in the Eulerian domain using the COSMO model. The Lagrangian parcel calculations are subject to additional uncertainties (treatment of shear and particle sedimentation) and thus would greatly benefit from the comparison with the cloud simulation in the Eulerian domain.

Response:

The cirrus cloud was also simulated in the Eulerian domain using the COSMO model. One motivation for choosing this particular case was the presence of a cirrus cloud above JFJ in the Eulerian model, which implies that the large-scale temperature and humidity field is well-represented in the driving model. We added some sentence regarding this issue to section 2.2.1..In the figure below we show the lidar raw data of this day. The yellow isolines indicate a cirrus cloud being present in COSMO-2. Clearly, COSMO nicely captures the cirrus cloud observed by the lidar.



Sentences added to the manuscript on lines 206-210 on page 7 of the revised manuscript in blue:

The COSMO-2 simulation predicts an ice-phase cloud above Jungfraujoch in the same time and altitude range at which it was observed by the Lidar (not shown). While this indicates a suitable representation of the thermodynamic conditions in the model, the rather coarse vertical resolution of the model in the upper troposphere with only 3 levels between 10.5 and 11.0 km may hamper the representation of processes with small vertical scales.

Page 7543, lines 11-13: Please state the vertical resolution in the cloud layer. Given the thickness of the cloud (1:5 km), please comment whether such vertical resolution is sufficient.

Response:

This is a good question. The vertical resolution of the COSMO-model in the region of the cloud is about 500 m, which is rather coarse. We added this information to section 2.2.1. However, a cloud is formed within the COSMO-model at the time of the observations, which suggests a rather good representation of the large-scale temperature and humidity field. For the box-model approach, we used a vertical resolution of 100 m. The meteorological data and initial RHice are based on the COSMO-2 model. In the box model, we interpolate vertically the COSMO output to 100 m resolution. Indeed, the sedimentation of ice particles requires high vertical resolution. We tested the effect of different vertical resolutions on simulated cirrus clouds. The 100 m of vertical resolution is chosen here for affordable CPU time and still reasonable small artificial numerical effects.

Sentences added to the manuscript on lines 208-214 on page 7 of the revised manuscript in blue:

While this indicates a suitable representation of the thermodynamic conditions in the model, the rather coarse vertical resolution of the model in the upper troposphere with only 3 levels between 10.5 and 11.0 km may hamper the representation of processes with small vertical scales. The vertical resolution is increased to 100m by vertical interpolation (s. sec. 2.2.2) for the ZOMM simulations. This allows a better representation of cloud microphysical processes, while presumable rather smooth field over the considered height interval as the upstream moisture profile, gravity wave amplitude and phase are not affected by the interpolation.

I suggest referencing Spichtinger and Krämer (2013) and Dinh et al. (2015). These papers have discussed specifically how small-scale, high-frequency temperature fluctuations affect ice nucleation, and thus are particularly relevant here. Also, the high sensitivity of ice number density to the initial water vapour content of air parcels has been studied in Dinh et al. (2015, see their section 5.3).

Response:

These references have been added. We would note here, however, that the paper by Dinh et al. (2015) was submitted after our paper.

References added to the manuscript on line 92 on page 3 as well as lines 105-107 on page 4 of the revised manuscript in blue:

Reference to Spichtinger and Krämer (2013) was added on line 92

Lines 105-107:
As ice nucleation occurs at a certain ice supersaturation humidity errors can lead to significant shifts in the onset of ice nucleation as well as in the number of nucleated ice crystals (Dinh et al., 2015).

The radiative-dynamical effects (see e.g. Dinh et al., 2010; Schmidt and Garrett, 2013), which have not been considered here, could explain why the current model calculation underestimates the cloud extinction, especially at the cloud top in *the active case (figure 14). Indeed, the radiative heating rate could be quite significant in the active case. The radiatively induced updrafts and water vapour flux convergence could help to maintain the cloud, and produce a higher cloud top and cloud thickness (see Dinh et al., 2010, their figure 7). Such features would be consistent with the lidar measurements in figure 14.*

Response:

Thank you for your helpful comment. We have added some sentences about the radiative-dynamical effect, including References, to the Appendix. However, the inclusion of radiative effects is not straightforward in a Lagrangian framework and it is beyond the scope of this study to include this effect.

Sentences added to the manuscript on lines 748-751 on page 30 of the revised manuscript in blue:

One effect that might explain the underestimated extinction in this case are the radiative dynamical effects, that were not considered in this study. Radiatively induced updrafts and water vapor flux convergence could help to maintain the cirrus cloud and produce an optically thicker cloud as well as a higher cloud top (Dinh et al. (2010)).

Answer to Anonymous Referee 2

The authors are grateful for the time and thought that Anonymous Referee 2 put into the review and comments regarding our paper. We incorporate most of those comments into our revised manuscript, which has led to substantial improvements. Detailed responses to all comments follow below. The original comments from Anonymous Referee 2 are in italics and our responses as well as changes in the manuscript in plain text.

1 General comments

The objective of the research is to identify and reduce uncertainties in cirrus modelling, which is welcome. The approach is case studies using trajectory box modelling and the uncertainties studied are related to the quality of the thermodynamic fields along the trajectories, the representation of unresolved vertical motions, and the initial values of specific humidity and concentration of ice nuclei. It is no surprise that higher temporal resolution of both the background model and the trajectory interpolation improve the results, and adding small scale temperature fluctuations is an established technique even in Eulerian models. However, unfortunately there seems to be no way how a better initialization of specific (or relative) humidity and IN concentration can be achieved. Unfortunately there is no discussion on these points. Otherwise, the paper is interesting and easy to read. The SAL metric in its current presentation is not of much use, mainly because Fig. 10 is much too small and the symbols cluster together and partly cover each other. The authors should replace the figure with a table giving the respective SAL values.

2 Major comments

1. P 7537, ll 5 ff.: To my opinion, it is too convenient to simply state that "mechanisms are not well understood" and to quote a "low level of scientific understanding". These statements are too general. Please describe what exactly is not well understood. The uncertainties of climate predictions are not necessarily due to cirrus clouds. Sherwood et al. (2014) trace it back mainly to uncertainties related to low clouds and convective mixing.

Response:

We have added additional information to this paragraph and rewritten this section of the introduction. The suggested reference was added.

Rewritten section in manuscript on lines 27 – 49 on page 2 of the revised manuscript in blue:

Cirrus clouds are an important component of the climate system, because they influence the radiative budget by scattering solar radiation back to space and by trapping longwave radiation in the troposphere. The balance between these two mechanisms determines the overall radiative effect of cirrus clouds on the climate. In general it is assumed that cirrus clouds have a warming effect on climate (e.g., Chen et al., 2000), but its magnitude depends strongly the optical thickness and cloud top temperature (e.g., Stephens et al , 1990; Corti and Peter, 2009). The optical thickness of cirrus depends on the nucleation properties of the preexisting aerosols and on the local cooling rates, which both determine the ice crystal number density and crystal size. The optical thickness further depends on the atmospheric relative humidity profile, limiting the geometric thickness of the cloud. Finally, the cloud top temperature determines the cloud emissivity (Platt and Harshvardhan, 1988; Ebert and Curry, 1992; Lin et al., 1998; Chen et al., 2000). In addition, the shape and orientation of the ice crystals influence the radiative properties of cirrus clouds, but both variables are in general not known and hard to determine from measurements (e.g., Stephens et al , 1990). While mid-latitude cirrus have been studied by several authors (e.g., Chen et al., 2000; Fusina et al., 2007; Cziczo and Froyd, 2014), the magnitude of the positive cloud radiative forcing remains uncertain. The microphysical processes leading to cirrus formation are not yet completely understood. Further, the coarse parameterization of cirrus clouds contributes to the uncertainties of radiative forcing predicted by climate models (Dessler and Yang, 2003; Solomon et al., 2007; Myhre et al., 2013). We note here, that the overall radiative forcing effect by cirrus clouds is smaller than the effect of liquid and mixed-phase clouds situated further down in the troposphere (Chen et al., 2000; Sherwood et al., 2014; Kienast-Sjögren et al., 2015). Thus, the uncertainties in the radiative forcing of clouds in climate models can to a large part be attributed to uncertainties considering low clouds and convective mixing (Sherwood et al., 2014).

2. Sect. 2.2.1: Please add information on the vertical coordinate and orography treatment in the COSMO-2 model.

<u>Response:</u>

We added the requested information to section 2.2.1 of the article.

<u>Added section in manuscript on lines 189 – 196 on page 7 of the revised manuscript in blue:</u>

In the vertical we use a Gal-Chen hybrid coordinate system with 60 levels, which provides an average vertical resolution of 388 m. The spacing of levels gradually increases from 13 m close to the model surface to 1190 m at the model top (23 km). For the initial and boundary conditions we used the operational analysis of the Swiss weather service at 6.6 km horizontal resolution. The topography was filtered with a 4th-order low-pass filter based on Raymond (1988), resulting in a cut-off of orographic features at approximately 4Δx. In addition the impact of sub-grid scale orography on the drag and gravity wave generation is parameterized based on Lott and Miller (1997).

3. P 7545, ll 20 ff.: The horizontal spread of the trajectories show that the assumption of a vertical stacking of the boxes that arrive together at Jungfraujoch (JFJ) is not justified at all. While the authors admit that this is a poor assumption there is no discussion on the effect of that assumption. Sedimentation is mentioned to occur before arrival at JFJ and to remove heterogeneously formed ice. This should be no problem for the interpretation. A more important question is whether there are ice crystals falling into a box from above and consuming the excess vapour in that box. Does this occur? Is this effect represented in the model?

<u>Response:</u>

Yes, in the stacked box model, we take the vertical transport of water into account. The total water in the level is increasing due to sedimentation from the level above and decreasing due to sedimentation to the lower level.
The ice particles falling from the level above will grow and decrease the supersaturation, if the air mass is super saturated and vice versa.

This is done for both heterogeneous and homogeneous formed ice particles.
As is also visible in Fig. 6, the nucleation event in connected to the observed cloud is in most simulations not the first nucleation event along the trajectories (trajectories arriving at 11-11.5 km altitude in Fig. 6). These former nucleation events may deplete water vapor and IN (in the runs with heterogeneous nucleation) in the parcels. However, since these processes are just tied to the sedimentation out of the parcel, they should not be affected by the horizontal spread of the trajectories. Accordingly the impact on the conclusions is rather small. We added a few sentences on this issue in section 3.1.

Added section in manuscript on lines 315 – 329 on pages 10 and 11 of the revised manuscript in blue:

In general parcels arriving at altitudes between 8 km and 12 km above Jungfraujoch are located just north of the Massif Central 10 h earlier and impinge from a north-westerly direction on the Alps. A significant spread of the trajectories in the horizontal is observed. In addition, there are significant differences in travel speeds between online- and offline-trajectories. The spread and the different travel speed on the air parcels can be problematic for column microphysical models, because these models do not take horizontal or vertical shear into account. This may lead to significant errors as sedimenting ice crystals may enter lower trajectories at unrealistic times. If only trajectories relevant for the observed cirrus cloud are considered, i.e., those arriving between 10.5 km and 11.5 km a.s.l., the spread is somewhat reduced (yellow to orange colors in Fig. 2). More importantly, the simulation results show that the air parcels most crucial for the formation of the observed cirrus cloud are not affected by ice crystals falling out of higher level parcels (Fig. 6 later). Accordingly, these parcels can be considered as decoupled from the trajectory stack and therefore as unaffected by any assumptions on horizontal and temporal alignment for the sedimentation treatment. The evaporation of the ice crystals in lower parcels may, however, be affected by the treatment of sedimentation, as crystals from earlier nucleation events modify the specific moisture content in these parcels (Fig. 6 later).

4. P 7556, ll 1–4: It is questionable whether the PSD of T is the appropriate quantity for describing an influence of T–fluctuations on the resulting cloud, since it is the cooling rate at the nucleation threshold rather than the temperature that matters. I wonder why you do not look at the pdf of the cooling rates. Can you please discuss this?

Response:

We agree with the referee that the cooling rate during the nucleation rate is probably more important than the temperature amplitude of the gravity wave itself. However, the box model takes the temperature time series as input and therefore we think it is worthwhile to show the PSD of temperature. The PSD of temperature is coupled with the PSD of cooling via the relationship $F(k)_T^2 = \frac{1}{k^2} F(k)_{dT/dt}^2$.

In addition, we would like to highlight that we show in addition also the PSD for the vertical velocity, which is directly linked to the cooling rate by the adiabatic constant in Fig. 4. The major points we conclude in the paper based on Fig. 3 (cut-off frequency, lower energy of long-wavelength waves compared to MACPEX and SUCCESS) are equally supported by this figure.

Changes in manuscript:

No changes were done in the manuscript

3 Minor comments

1. P 7539, l 4: It should be noted that cirrus cloud modelling mostly is done in the Eulerian framework, e.g. in NWP and climate models. The question of the quality of trajectories does not apply to such models and this should explain why not much attention has been paid so far to this question.

Response:

We have added some sentences concerning this issue.

Added section in manuscript on lines 120 – 127 on page 4 of the revised manuscript in blue:

In general, the uncertainties discussed above pertain also to the modelling of cirrus clouds with Eulerian models, except for the uncertainty in the trajectory path (a). Several studies have adressed these uncertainties in individual case studies in Lagrangian and Eulerian modeling frameworks (e.g., Jensen et al., 1994b; Hoyle et al., 2005; Jensen et al., 2013; Cirisan et al., 2014; Muhlbauer et al., 2014). Most studies focused on the role of different representations of ice nucleation and small-scale temperature fluctuations, while the impact of the temporal resolution of the trajectory data (not relevant for Eulerian studies) and forecast errors in the initial moisture content has so far received less attention.

2. P 7542, l 10: Please rewrite this sentence. Measurement uncertainties never affect the vertical position of any cloud.

Response:

The sentence has been rewritten.

Added section in manuscript on lines 167 – 170 on page 6 of the revised manuscript in blue:

The measurement uncertainties pertain only the absolute extinction value. However, the vertical position of the cloud, which is most important for the comparison with the model results, is not subject to measurement uncertainties (e.g., Fig. 8 below).

3. Fig. 2: Please explain thin and thick contours in the plot. (Thick is evident, but could be mentioned for completeness).

Response:

This information has been added.

Added sentence to caption of Fig. 2 on page 12 of the revised manuscript in blue:

Offline (left) and online (right) trajectories arriving above Jungfraujoch at 09 UTC on 22 November 2011. Offline trajectories: based on 5-minute wind field data. Trajectory lengths: plotted for 10 h or until they leave the domain. Color coding: trajectory altitude upon their arrival above Jungfraujoch. Thick contours: Swiss border as well as coast of the Mediterranean Sea. Grey contour lines: topography from COSMO-2.

4. P 7549, l 25: change "mediates" into "mitigates".

Response:

Done

Changes on line 378-380 on page 13 of the revised manuscript in blue:

By means of the online trajectories
with 20 s time steps a new trajectory calculation tool is available, which mitigates the problems introduced by temporal interpolation of wind field data (Miltenberger et al., 2013).

5. Fig. 3: Colored vertical lines are too thin. Check calculation for fmax (currently the units are 1=(s m)).

Response:

We corrected this.

Modified Fig. 3 and caption on page 14 of the revised manuscript:

(fmax = 17.4 m/s /(4 x 2.2 km)≈ 2 · 10^{-3} s^{-1})

6. PP 7751: please explain why w2 is the velocity variance and not simply the velocity squared. These quantities are the same only if the mean w is zero. Is this assumed? Or is it meteorological parlance?

Response:

We appreciate the reviewer for this critical comment. Indeed we should use simply w^2.
In the case of COSMO2 data, we found that
$\acute{w} \approx 0.05\sqrt{w^2}$.
w^2 is then practically equal to the variance $w^2 - \acute{w}^2$.

We changed the variance to w^2 in the manuscript, when it is applicable.

Modified text in manuscript in blue:

l. 7-9, p. 1:
Variations of the temporal resolution of the wind field data (COSMO-model at 2.2 km resolution) between 20 s and 1 h have only a marginal impact on the trajectory path, while the representation of the vertical velocity variability and therefore the cooling rate distribution are significantly affected.

l. 98-101, p. 4:
As an alternative NWP model data becomes available at successively higher spatial resolution, but here it remains unclear, which fraction of the vertical velocity variability is actually explicitly resolved by the NWP model and in the derived trajectory data.

l. 437-445, p. 16:
Rather, for comparison we constructed a COSMO-2-based climatology of the squared vertical velocity amplitudes w^2 over the Alpine region for the years 2010-2014. For this we used hourly domain-averaged (COSMO-2, i.e., Alpine region) values of w^2 at altitudes between approximately 7 and 9 km. Both data sets are depicted together with the SUCCESS and the MACPEX campaign data in Fig. 5. w^2 derived from the COSMO-2 analysis and the balloon sounding agree very well, showing w^2 in the range 10^{-3} m^2 s^{-2} to 2 m^2 s^{-2}. This range corresponds very well to previous observational data reporting w^2 between 0.005 m^2 s^{-2} to 0.4 m^2 s^{-2} (Ecklund et al., 1986; Gage et al., 1986). In contrast, only w^2 larger than about 0.02 m^2 s^{-2} were observed during the SUCCESS- and the MACPEX campaigns.

7. Fig. 5: should be larger. I can hardly read the insert text.

Response:

We are not sure to what the referee is referring since the text insert in Fig. 5 is fairly large already.

Changes in manuscript:

No changes were done in the manuscript

8. Figs. 8–10 are too small.

Response:

We enlarged those figures as requested.

Changes in manuscript:

See enlarged figures on pages 23 – 25 of the revised manuscript.

Answer to Anonymous Referee 3

The authors are grateful for the time and thought that Anonymous Referee 3 put into the review and comments regarding our paper. We incorporate most of those comments into our revised manuscript, which has led to substantial improvements. Detailed responses to all comments follow below. The original comments from Anonymous Referee 3 are in italics and our responses as well as changes in the manuscript in plain text.

In this study the authors investigated the influence of input data uncertainties on the simulated cirrus cloud properties over Jungfraujoch using a microphysical trajectory box model. They looked at the impact of trajectory resolution, unresolved updraft velocities, and the assumed IN number concentration on the simulated accuracy. Not surprisingly, they found higher trajectory resolution and the addition of small scale temperature fluctuations helped to improve the agreement between model and observation. On the other hand, the higher sensitivity to the specified initial humidity than to the unsolved temperature fluctuation is interesting. My major comment is that the observational data (lidar retrievals) used to the evaluate the model result are too limited in time (20min). This made the case study too specific and perhaps not applicable to other conditions. In general, the paper is well written and easy to read. However, I agree with reviewer 2 that the information presented in figure 10 is not very clear and should be improved. Some of the figure indices are mismatched and need to be carefully checked before final publication.

<u>Response</u>:

The representativity was addressed by Reviewer 1 as well. In the manuscript we emphasize that our results may not be representative for all atmospheric conditions. To examine further atmospheric conditions, the more active case in the Appendix was added. We have additionally performed simulations for different times during 2011-11-22, with similar results as those presented in the manuscript. Therefore we presented only the results of the chosen time slot. A discussion on this issue was added in the Conclusions.

<u>Added section in manuscript on lines 689-709 on page 28 of the revised manuscript in blue</u>:

Lagrangian cirrus cloud modeling shows large sensitivities to all investigated factors. However, the order of their importance can vary from case to case. The presented case study of an isolated temporally persistent cirrus cloud with rather small horizontal extent may only be representative for cirrus cloud formation under some specific conditions. In addition, the wave activity on the investigated day is clearly below the climatological average. Therefore we present a case with dynamically more active conditions in the appendix. For the active day, the modelled cirrus clouds shows different responses to modifications of the initial humidity and the assumed ice nuclei number density: variations of both parameters lead in general to a variation of the optical thickness of the cloud, while they affected also the vertical location of the cloud on the quiet day. Similar to the quiet day, simulations with ice nuclei number density in excess of 20 L^{-1} are found to be inconsistent with the observations. The best match with the observed extinction profile is obtained for an increased initial moisture content. A high sensitivity of Lagrangian cirrus cloud modeling to initial humidity was also found by Dinh et al. (2015) in simulations for cirrus clouds in the tropical tropopause layer.

While the use of high resolution trajectory data is shown to be mandatory for cirrus cloud modeling, there are significant uncertainties tied to the specific humidity and ice nuclei number density, turning cirrus cloud modeling into a challenging task with many non-linearly linked uncertainties. The representation of small-scale temperature fluctuations remains an issue for cirrus cloud modeling, particularly due to the large day-to-day variations in the wave activity, but the results presented here indicate that high-resolution numerical weather prediction models are capable to capture these variations.

Specific Comments:

P7536L18: Typo "bysignificantly"

Response:

Thanks for the comment.

Changes in the manuscript on lines 7-9 on page 1 of the revised manuscript in blue (new formulation of sentence):

Variations of the temporal resolution of the wind field data (COSMO-model at 2.2 km resolution) between 20 s and 1 h have only a marginal impact on the trajectory path, while the representation of the vertical velocity variability and therefore the cooling rate distribution are significantly affected.

P7537L11: Remove "in turn"

Response:

Thanks for the comment.

Changes in the manuscript on lines 32 on page 2 of the revised manuscript:

"in turn" was removed

P7540L3: Would be better to note that the reported IN concentration in DeMott et al. (2010) is in per standard liter, not per liter under the ambient state. What's the unit (L-1 STP or L-1 under ambient state) used in the IN sensitivity simulations?

Response:

Our unit used in the simulations is in 1 per volume of ambient air.

Changes in the manuscript on lines 110-113 on page 4 as well as on lines 256-257 on page 9 of the revised manuscript in blue:

Lines 110-113:
Ice nuclei, whose number densities are typically between 10 and 100 L^{-1} (per standard liter) (DeMott et al., 2010), lead to heterogeneous nucleation on solid particles such as for instance dust and ash (Pruppacher and Klett, 1997; Kärcher and Lohmann, 2003; Wiacek et al., 2010; Cziczo et al., 2013; Cziczo and Froyd, 2014).

Lines 256-257:
For simulations including heterogeneous nucleation we used ice nuclei concentrations of 10 L^{-1}, 20 L^{-1}, 50 L^{-1}, and 100 L^{-1} (in unit 1 per volume of ambient air).

P7541L22: How does ZOMM represent the size distribution of ice particles?

Response:

ZOMM uses a log-normal size distribution. It is initialized with 100 logarithmically spaced size bins. The number and radius of each size bin is allowed to change during the model run. We added this information to section 2.3. For further details we refer to the work of A. Cirisan, 2014 (cited in the manuscript).

Added sentences in the manuscript on lines 266-268 on page 9 of the revised manuscript in blue:

ZOMM uses a log-normal size distribution. It is initialized with 100 logarithmically spaced size bins. The number and radius of each size bin is allowed to change during the model run.

P7542L16: Why only 20min's data were used? Why not using more lidar data and including more trajectories in the analysis?

Response:

We chose this time window because we manage to hit Jungfraujoch with a sufficient number of online trajectories at this time and because the underlying NWP-model produced a cirrus cloud at this time. We therefore assume that the NWP-model correctly models the larger scale temperature and moisture field at that particular time, so that we can rely on the *p* and *T*-fields that we need to force the microphysical box model. We have analyzed different time windows on this day. Since the results did not differ significantly for other time windows, we decided for brevity to only show the results for this particular time. In addition, it has to be considered, that for each trajectory type (20 s, 1 min, 5 min), we performed 25*21=525 different simulations, adding up to a total of 1575 boxmodel runs. To improve the robustness of the analysis, we analyzed also a more active day and present the results in the Appendix.

Changes in the manuscript on lines 204-208 on page 7 as well as 689-701 on page 28 of the revised manuscript in blue:

Line 204-208:
In order to obtain the best possible representation of the real atmospheric conditions observational data routinely used for the COSMO analysis by MeteoSwiss was used for nudging of the simulation (based on the method of Schraff, 1996, 1997). The COSMO-2 simulation predicts an ice-phase cloud above Jungfraujoch in the same time and altitude range at which it was observed by the Lidar (not shown).

Line 689-701:
Lagrangian cirrus cloud modeling shows large sensitivities to all investigated factors. However, the order of their importance can vary from case to case. The presented case study of an isolated temporally persistent cirrus cloud with rather small horizontal extent may only be representative for cirrus cloud formation under some specific conditions. In addition, the wave activity on the investigated day is clearly below the climatological average. Therefore we present a case with dynamically more active conditions in the appendix. For the active day, the modelled cirrus clouds shows different responses to modifications of the initial humidity and the assumed ice nuclei number density: variations of both parameters lead in general to a variation of the optical thickness of the cloud, while they affected also the vertical location of the cloud on the quiet day. Similar to the quiet day, simulations with ice nuclei number density in excess of 20 L^{-1} are found to be inconsistent with the observations. The best match with the observed extinction profile is obtained for an increased initial moisture content. A high sensitivity of Lagrangian cirrus cloud modeling to initial humidity was also found by Dinh et al. (2015) in simulations for cirrus clouds in the tropical tropopause layer.

P7544L24: If more trajectories were included, do you expect the result would change?

Response:

If including more trajectories for the same case, we would not expect to see major changes in the results as to the sensitivity of the simulations to initial moisture, cooling rate statistics or IN number density. The major reason is the fairly homogeneous large-scale situation during this period. If the same analysis would be conducted for other case studies, we expect somewhat different results, particularly in the relative importance of uncertainties in the small-scale temperature fluctuations and other variables. However, we anticipate that the simulations will be still sensitive to all of the parameters. This is seen in the more active case presented in the Appendix.
We would like to highlight again that a more general assessment of the relative uncertainty for a variety of different large-scale situations is beyond the scope of the current study, as the number of required box-model simulations is quite significant and the calculation of online-trajectories – ensuring a suitable coverage- is quite demanding.

Changes in the manuscript on lines 689-701 on page 28 of the revised manuscript in blue:

Lagrangian cirrus cloud modeling shows large sensitivities to all investigated factors. However, the order of their importance can vary from case to case. The presented case study of an isolated temporally persistent cirrus cloud with rather small horizontal extent may only be representative for cirrus cloud formation under some specific conditions. In addition, the wave activity on the investigated day is clearly below the climatological average. Therefore we present a case with dynamically more active conditions in the appendix. For the active day, the modelled cirrus clouds shows different responses to modifications of the initial humidity and the assumed ice nuclei number density: variations of both parameters lead in general to a variation of the optical thickness of the cloud, while they affected also the vertical location of the cloud on the quiet day. Similar to the quiet day, simulations with ice nuclei number density in excess of 20 L^{-1} are found to be inconsistent with the observations. The best match with the observed extinction profile is obtained for an increased initial moisture content. A high sensitivity of Lagrangian cirrus cloud modeling to initial humidity was also found by Dinh et al. (2015) in simulations for cirrus clouds in the tropical tropopause layer.

P7544L11: What is the number of solution droplets assumed in the model?

Response:

We assume 250 sulfate particles per cm^3. Their sizes are distributed log-normally with a mode radius of 0.05 micrometers and a sigma of 1.4.

Added sentences in the manuscript on lines 268-270 on page 9 of the revised manuscript in blue:

We assume 250 sulfate particles per cm^3. Their sizes are distributed log-normally with a mode radius of 0.05 micrometers and a sigma of 1.4.

P7545L13: "according to the formulation of : : :" this part is a bit misleading.

Response:

We reformulated this sentence.

Changes in the manuscript on lines 255 on page 9 of the revised manuscript in blue:

…for example dust or ash as suggested by Marcolli et al. (2007) for Arizona test dust.

P7545 section 2.3: more details of the ZOMM model are needed. For example, apart from the nucleation process, which other processes are considered in the model? How these processes are coupled? And what is the microphysical time step?

Response:

ZOMM takes uptake and release of water vapour by ice crystals as well as solution droplets into account. In addition, sedimentation of ice crystals is treated. For more details on the of the ZOMM model we refer to section 3.4 in the paper of A. Cirisan from 2014.

Sentences added in the manuscript on lines 264-271 on page 9 of the revised manuscript in blue:

The total water in the level is increasing due to sedimentation from the level above and decreasing due to sedimentation to the lower level. The ice particles falling from the level above will grow and decrease the supersaturation, if the air mass is super saturated and vice versa. ZOMM uses a log-normal size distribution. It is initialized with 100 logarithmically spaced size bins. The number and radius of each size bin is allowed to change during the model run. We assume 250 sulfate particles per cm^3. Their sizes are distributed log-normally with a mode radius of 0.05 micrometers and a sigma of 1.4. In the model, we apply a dynamic time step. The composition of liquid solution will change maximal 0.1 % in the nucleation regions and 1% for other regions during one time step.

P7545L18: Offline trajectories are based BACKWARD calculation, while the online trajectories are based on FORWARD calculations. Will this make a difference in the box model simulations?

Response:

No this will make no difference at all. If only the grid-scale wind field is used (as in the present study) and turbulent motions are not explicitly taken into account, trajectories calculated forward or backward in time will have an identical path, if the forward trajectories are started from the location at which the backward trajectories end (or vice-versa). Therefore also the evolution of temperature and pressure along the trajectories will be identical and hence the information that will be used by the boxmodel. The microphysical box model is run forward in time for all trajectory data-sets. We included the later information in section 2.3 of the paper.

Sentence added in the manuscript on lines 262-263 on page 9 of the revised manuscript in blue:

The microphysical box model is run forward in time for all trajectory data-sets.

P7545L19: Could you elaborate more about the sedimentation treatment? The current statement is not clear to me. Do you take the sedimentation flux from the host COSMO model? If so, do you consider the same ice particle size distribution in COSMO and in ZOMM?

Response:

No, we do not use the sedimentation flux from COSMO. Sedimentational fluxes to lower parcels are based on ZOMM simulations along higher level trajectories. We reformulated the respective sentences in section 2.3.

Sentences added in the manuscript on lines 264-266 on page 9 of the revised manuscript in blue:

The total water in the level is increasing due to sedimentation from the level above and decreasing due to sedimentation to the lower level. The ice particles falling from the level above will grow and decrease the supersaturation, if the air mass is super saturated and vice versa.

P7555L7: Do you mean Fig.8 here?

Response:

Thanks for the hint. We mean Fig. 9 but the correct color on line 6 should be blue.

Changes in the manuscript on lines 518-519 on page 21 of the revised manuscript in blue:

SAL metric. The extinction profiles from the three simulations are shown by the blue lines in Fig. 9.

P7555L12: Doesn't the green curve in fig8a indicate a cloud?

Response:

It indeed does. In lines 10 and 13 it should be Figure 9 instead of 8. Please excuse for the confusion.

Changes in the manuscript on lines 519-524 on page 21 of the revised manuscript in blue:

The model extinction profiles compare well with the extinction profile retrieved from the Lidar measurement (black lines) in terms of the amplitude as well as in the vertical positioning of the cloud for trajectory data at a temporal resolution of 20 s and 1 min (Fig. 9 (b) and (c)). Accordingly the location, amplitude and structure error in the SAL metric are small for all simulations (see orange upward-pointing triangles in Fig. 10 below). In contrast, no cloud forms above Jungfraujoch in simulations with trajectories with 5 min temporal resolution (Fig. 9 (a)).

P7556L1: Do you mean Fig.8c?

Response:

No, 9c

Changes in the manuscript on lines 536-538 on page 22 of the revised manuscript in blue:

For online trajectories the superimposed temperature fluctuations have, however, no significant influence on the modeled extinction profile (Fig. 9c).

P7556L24: Do you mean Fig.8a?

Response:

Yes

Changes in the manuscript on lines 560-561 on page 22 of the revised manuscript in blue:

For the offline trajectories with a temporal resolution of 5 min, the variation of the initial humidity leads in almost all cases to a disappearance of the cloud (Fig. 8a).

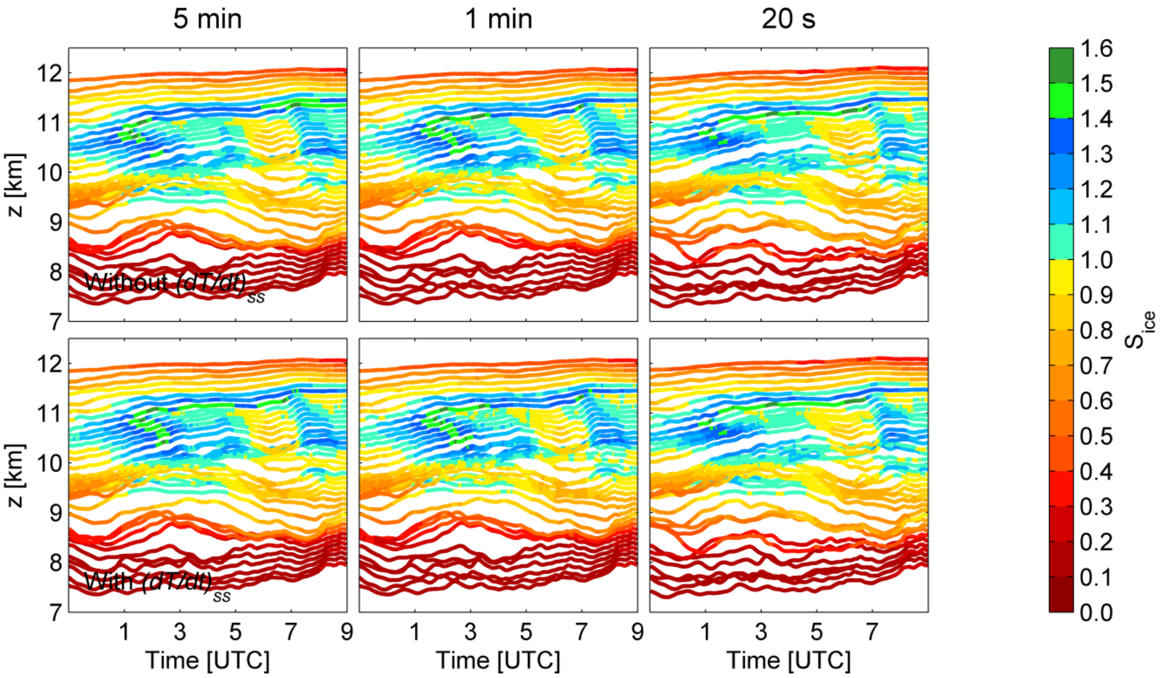
P7557L21-228: The discussion here is a bit hand-waving. Would be nice to plot the supersaturation (as figure 6 and 7) before and after the microphysical calculation and the ice crystal size to facilitate the discussion.

Response:

We provide the supersaturation figures below. We do not think that there is a need to include those figures in the paper. However, we reformulated this paragraph in the article to be more precise.

Changes in the manuscript on lines 587-595 on pages 24 and 25 of the revised manuscript in blue:

The evaporation timescale strongly depends on the relative humidity, which is likely not very robust in our simulations due to the effect of previous nucleation events on the moisture content on lower level parcels. As discussed in section 3.1 these modifications of the moisture content depend on the treatment of sedimentation and assumptions on temporal and horizontal alignment of the parcels. These assumptions may not hold for the present case due to the comparable large horizontal spread of trajectories. For the 1-min and 5-min offline trajectories the evaporation is much slower leading to larger extinction values between 9.5 and 10 km altitude (red lines in Fig. 9a, b). Slight differences in the vertical paths between the trajectory data sets contribute additionally to the variation of the evaporation timescale, as these also impact the relative humidity.



5 min
1 min
20 s
z [km]
Without $(dT/dt)_{ss}$
With $(dT/dt)_{ss}$
Time [UTC]
S_{ice}

Answer to Anonymous Referee 4

The authors are grateful for the time and thought that Anonymous Referee 4 put into the review and comments regarding our paper. We incorporate most of those comments into our revised manuscript, which has led to substantial improvements. Detailed responses to all comments follow below. The original comments from Anonymous Referee 4 are in italics and our responses as well as changes in the manuscript in plain text.

This manuscript presents a research study to investigate the influence of uncertainties in input data on the simulated cirrus cloud properties. The study is interesting, and the paper is well written. I suggest publication of the manuscript after consideration of some mostly minor comments.

General comment:
Considering the evaluation of the model with lidar measurements I agree with reviewer #3 that one case study with observational data of 20 min may be too specific and the results may not be comparable to other conditions.

Response:

This issue has already been addressed in the answers to Reviewer 3 and was copied to here:

"We chose this time window because we manage to hit Jungfraujoch with a sufficient number of online trajectories at this time and because the underlying NWP-model produced a cirrus cloud at this time. We therefore assume that the NWP-model correctly models the larger scale temperature and moisture field at that particular time, so that we can rely on the *p* and *T*-fields that we need to force the microphysical box model. We have analyzed different time windows on this day. Since the results did not differ significantly for other time windows, we decided for brevity to only show the results for this particular time. In addition, it has to be considered, that for each trajectory type (20 s, 1 min, 5 min), we performed 25*21=525 different simulations, adding up to a total of 1575 boxmodel runs. To improve the robustness of the analysis, we analyzed also a more active day and present the results in the Appendix. "

Changes in the manuscript on lines 204-208 on page 7 as well as 689-701 on page 28 of the revised manuscript in blue:

Line 204-208, page 7:
In order to obtain the best possible representation of the real atmospheric conditions observational data routinely used for the COSMO analysis by MeteoSwiss was used for nudging of the simulation (based on the method of Schraff, 1996, 1997). The COSMO-2 simulation predicts an ice-phase cloud above Jungfraujoch in the same time and altitude range at which it was observed by the Lidar (not shown).

Line 689-701, page 28:
Lagrangian cirrus cloud modeling shows large sensitivities to all investigated factors. However, the order of their importance can vary from case to case. The presented case study of an isolated temporally persistent cirrus cloud with rather small horizontal extent may only be representative for cirrus cloud formation under some specific conditions. In addition, the wave activity on the investigated day is clearly below the climatological average. Therefore we present a case with dynamically more active conditions in the appendix. For the active day, the modelled cirrus clouds shows different responses to modifications of the initial humidity and the assumed ice nuclei number density: variations of both parameters lead in general to a variation of the optical thickness of the

cloud, while they affected also the vertical location of the cloud on the quiet day. Similar to the quiet day, simulations with ice nuclei number density in excess of 20 L^{-1} are found to be inconsistent with the observations. The best match with the observed extinction profile is obtained for an increased initial moisture content. A high sensitivity of Lagrangian cirrus cloud modeling to initial humidity was also found by Dinh et al. (2015) in simulations for cirrus clouds in the tropical tropopause layer.

Specific comments:
p. 7536, l. 15: Typo – 'bysignificantly : : :'

Response:

Thanks for the comment.

Changes in the manuscript on lines 7-9 on page 1 of the revised manuscript in blue (new formulation of sentence):

Variations of the temporal resolution of the wind field data (COSMO-model at 2.2 km resolution) between 20 s and 1 h have only a marginal impact on the trajectory path, while the representation of the vertical velocity variability and therefore the cooling rate distribution are significantly affected.

p. 7546, l. 9: What about the extinction calculated from lidar measurements? Is this property sensitive to the retrieval and input parameters?

Response:

In Fig. 8 & 9 as well as Fig. 14 the uncertainties in the lidar evaluation (uncertainty in lidar ratio, in the signal itself as well as the molecular properties, see p. 6 line 165-170 in the revised manuscript) is shown.

Changes in manuscript:

No changes were done in the manuscript.

P. 7546, l. 18: Typo – 'compares compares : : :'

Response:

Done.

Changes in manuscript:

Corrected on l. 292 p. 10 of the revised manuscript.

p. 7547, l. 19: Do you mean differences in the on- and offline trajectories?

Response:

Yes, we added this to the sentence.

Revised sentence in line 317-318 on page 10 of the revised manuscript:

In addition, there are significant differences in travel speeds between online- and offline-trajectories.

p. 7551, l. 6: Can you explain these differences?

Response:

The differences at long-wave length are very likely related to differences in the large-scale meteorological situation, i.e., smaller or larger gravity wave activity. There is a number of potential sources for this variability as for instance: differences in the stability of the lower atmosphere changing the vertical propagation of gravity waves induced in the lower atmosphere (e.g.,), differences in the wind direction and strength modifying the generation of terrain-induced gravity waves, the presence or absence of deep convection or fronts, which may induce gravity waves.

Added section in line 417-427 on page 15 of the revised manuscript in blue:

To understand the differences in the mesoscale range it is important that the model simulations and the SUCCESS and MACPEX measurements took place a different geographic locations and under different meteorological conditions. Mesoscale gravity waves may be excited by a number of different phenomena, including flow over topography, fronts, convection, large wind shear and jet streams (e.g., Nastrom et al., 1992; Fritts et al., 1992), and their vertical propagation depends on the state of the atmosphere, particularly the low-level stability (e.g., Nastrom et al., 1992). The spread between the power spectral densities observed during SUCCESS and MACPEX and those simulated for the cirrus case study corresponds to the variation of the PSD observed by Ecklund et al. (1985) for different meteorological situations during ALPEX. The PSDs observed during ALPEX for active and quite days are shown by the blue lines in Fig. 4.

p. 7551, l. 27: Do you mean 'ascent data'?

Response:

Yes

Corrected on line 441 on page 16 of the revised manuscript in blue:

…original ascent data of the sounding balloons by subtracting a 500 s running mean…

Figures 6 and 7: labeling/time scale is inconsistent (upper and lower panel) for 1m and 20s cases.

Response:

Thanks, this has been corrected.

Corrections in revised manuscript:

See Figures 6 and 7 on page 19 and 20 of the revised manuscript.

Figures 11-14: Maybe the order of the figures should be adapted following the argumentation in the text.

Response:

We are not sure what the referee means, since the order of the figures is identical to the sequence they are mentioned in the text.

Changes in manuscript:

No changes were made in the manuscript.