Author’s final response

“Determining stages of cirrus evolution: A cloud classification scheme” by B. Urbanek et al.

Review RC1 by Anonymous Referee #1

We thank Referee #1 for carefully reading our manuscript and for the suggestions that helped us to improve our work. In the following we will answer to his specific comments.

Introduction from Referee

The authors present an attempt to determine the stages of cirrus life-cycle evolution based on in-cloud RHi measurements performed by the airborne Lidar WALES. Though I like the idea and also find the paper well organized and fluently written, I have a major concern with respect to the proposed cirrus life-cycle classification scheme which I explain in the following. To my opinion this point should be cleared before publishing the manuscript in ACP.

Comment 1 from Referee (Major comment)

In the introduction, the authors state:
'*In order to gain more insight into the particular role of different cirrus clouds, great efforts were made to classify cirrus by the meteorological contexts in which they occur (Jackson et al., 2015; Muhlbauer et al., 2014). Categories include “synoptic”, “orographic”, “lee wave” and “anvil” cirrus. Recently Krämer et al. (2016) introduced a more general classification distinguishing the groups of “liquid origin” and “in situ” clouds that describe whether the cirrus formed from a pre-existing liquid cloud or from cloud-free air. Such a classification of recorded data is a prerequisite for statistically investigating the specific properties and influences of different clouds, and to extract the governing mechanisms and parameters from remote sensing and in situ measurements.*'
However, the cirrus life-cycle classification scheme presented in the paper holds only for 'in situ' formed cirrus clouds. In the so-called 'liquid origin' cirrus, the meaning of 'SUB' will be similar, but what about the interpretation of 'DEP', HETin and HOMin in case of pre-existing ice? It is very likely that in case of further lifting of a liquid origin cirrus cloud the supersaturation rises to values of DEP, HETin or HOMin (then, a new, homogeneous nucleation event can occur on top of the liquid origin cirrus), but they are at different stages of cirrus evolution than the in situ cirrus.
In a recent publication of Wernli et al. (2016), GRL, the frequencies of occurrence of in situ and liquid origin cirrus are analyzed from 12 years of ERA-Interim ice clouds in the North Atlantic region. Wernli et al. found that: 'Between 400 and 500 hPa more than 50% are liquid-origin cirrus, whereas this frequency decreases strongly with altitude (<10% at 200hPa).'
Thus, it seems to be important that first of all these two types of cirrus can be identified by a cirrus classification scheme before going in the detail of stages of cirrus life-cycle evolution. So I would highly encourage the authors to continue their work by including an analysis of the cirrus origin prior to the investigation of the stages of evolution. It might be

an idea to first perform a trajectory analysis as done by Wernli et al. (2016) and also Luebke et al. (2016) using ECMWF wind fields and determine whether the back trajectory of an observed air parcel stemmed from temperatures warmer than -38C and carried ice when entering the cirrus temperature range. Then, the classification scheme can be applied to both types separately.
I am aware about that this will be a lot of additional work, but am also convinced that it will be worth the effort to make the study scientifically sound and useful for future investigations.

Author's response

We agree with Referee #1 that our classification does not yield any information about earlier temporal development of the observed cirrus clouds. With our method alone, it is not possible to determine whether e.g. a measured freezing event is a primary or a secondary event. Yet we can identify cloud regions where ice nucleation, depositional growth and sublimation occur at the time of the observation. The methods' very strength is to measure the actual atmospheric state with a high spatial resolution that exceeds typical resolutions of GCMs. We added a paragraph that specifies and clarifies this point (Sect. 3).
To prevent possible confusion we decided to avoid the term 'life-cycle stages' and rather use the term 'evolution stages'. We also propose to change the title to 'Determining stages of cirrus evolution: A cloud classification scheme' and to change one phrase in the abstract from 'Thus the whole cirrus life-cycle can be traced' to 'Thus all relevant stages of cirrus evolution can be classified and characterized'.
After specifying the capabilities of our classification, we see no reason why it should not be applicable in "liquid origin" clouds, too.
We share the Referee's opinion that the trajectory based classification of "in situ" and "liquid origin" cirrus, as performed by Krämer et al. and Wernli et al. (see Sect. 1) is very helpful in characterizing the lagrangian history of individual clouds. Combining this method with our classification seems to be a promising approach, for future work (see changes in Sect. 5). However, when comparing ECMWF analyses with observed cirrus clouds, we see that the ice water content is not always in good correlation with the location of observed cirrus clouds which makes the interpretation of a model-based investigation e.g. of trajectory calculations more complex.
While in a more statistical sense the studies based on NWP data may be valid, this might not be the case for a special event. So we want to keep our classification scheme as independent as possible from NWP model input relying on parametrized processes.
The scope of this paper, submitted to "Atmospheric Measurement Techniques", is to outline our classification scheme and to demonstrate a first application. Therefore we do not think that the inclusion of a classification into cloud types is appropriate in this case.

Changes in manuscript

Sect 1:

Recently a more general classification was introduced that distinguishes the groups of ``liquid origin'' and ``in situ'' clouds that describe whether the cirrus formed from a pre-existing liquid cloud or from cloud-free air (Krämer et al., 2016; Wernli et al., 2016)

Sect 3:

During the life-cycle of a cloud, nucleation, growth and sublimation events may occur more than once, e.g. when atmospheric dynamics cause renewed updrafts and a secondary freezing event on top of pre-existing ice takes place.
As described, our method is able to identify nucleation, growth, sublimation regions and pre-stages of cirrus cloud formation. However on its own, it does not yield any information about earlier developments of those regions. Its very strength is to reveal the actual atmospheric state with regards to cirrus evolution at the time of measurement. This is done on a high spatial resolution that exceeds typical resolutions of GCMs, enabling the detailed study of individual cloud parts.

Sect. 5:

The possibility to combine our classification with trajectory based methods promises to reveal details of the temporal succession of evolution stages

Comment 2 from Referee

1) Page 1, line 24 – page 2, line 1:

'*Today many factors are known that determine these properties: the amount and composition of natural and anthropogenic aerosol particles in the troposphere and their ability to nucleate ice crystals (DeMott et al., 2010), ..*'

This statement is much too promising – amount and properties of IN (Ice Nuclei) are not well known until today, in particular in the temperature range of cirrus clouds. Please correct.

Author's response

In accordance with the Referee's wishes, we have now changed this sentence.

Changes in manuscript

Recent studies have investigated factors that affect these properties. The amount and composition of natural and anthropogenic aerosol particles in the troposphere and their ability to nucleate ice crystals are determining details of heterogeneous freezing (DeMott et al., 2010), but aerosol distribution and properties are not well known until today, in particular in the temperature range of cirrus clouds.

Comment 3 from Referee

'*… the exact freezing condition and mechanism (Cziczo et al., 2013), updraft velocity during cloud formation (Kärcher and Lohmann, 2002), …*'

Same here: it is not clear if the work of Cziczo et al. (2013) is globally valid; updraft velocities during cloud formation are theoretically known, but measurements are difficult and rare.

Author's response

Following the Referee's suggestion, we have added clarifying sentences.

Changes in manuscript

Exact freezing conditions and mechanisms were studied by (Cziczo et al., 2013) from in-situ measurements taken during flight campaigns conducted in Middle and North America. They found a dominance of heterogeneous freezing with mineral dust and metallic particles as the main source of residual particles. Although they managed to span a range of geographic regions and seasons, it is not clear, if those results are globally valid.
High water vapor supersaturations inside and outside of cirrus clouds point to several microphysical processes and often occur together with low ice crystal numbers (Krämer et al., 2009).
Sublimation of ice crystals was reported to result in the disappearance of facets and corners, changing the crystal symmetry (Korolev and Isaac, 2006).
The dependence of freezing on the updraft velocity during cloud formation is theoretically known (Kärcher and Lohmann, 2002), but measurements are difficult and rare.

Comment 4 from Referee

2) Page 2, line 13-14:
'...*a cloud is expected to show different properties at the time of formation and break up.*'
Better 'dissipation' instead of 'break up'

Author's response

We have changed that sentence according to the suggestion.

Changes in manuscript

Likewise, detailed knowledge of cloud properties at different stages of evolution is yet to be gained, as a cloud is expected to show different properties at the time of formation and dissipation.

Comment 5 from Referee

3) Page 3, lines 3-5:
'*Once ice particles are present, remaining supersaturation is depleted by deposition of water vapor onto existing crystals. Depending on the particle number and average radius, it may take a few minutes to a few hours for the equilibrium of 100 % to be reached (Korolev and Mazin, 2003).*'
Korolev and Mazin (2003) show relaxation times to reach the 'dynamical equilibrium' (steady state), which is -in dependence on the updraft- higher than 100%. Saturation in

cirrus is quickly reached as soon as the cooling stops, i.e. when the updraft is zero. Please correct.

Author's response

We thank Referee #1 for correcting us here and changed the paragraph accordingly.

Changes in manuscript

Once ice particles are present and no cooling, e.g. from updraft motion takes place, remaining supersaturation is quickly depleted by deposition of water vapor onto existing crystals. In updraft regions of ice clouds however, it may take a few minutes to a few hours until the air reaches the quasi-steady supersaturation which is a function of vertical velocity and ice particle size distribution and higher than 100 % in updraft regions (Korolev and Mazin, 2003).

Comment 6 from Referee

4) Page 4, line 32:
'*It should be noted that ice is forming as soon as conditions for homogeneous freezing get reached, …*'
Please correct:
… ice is forming **latest** as soon as conditions for homogeneous freezing get reached,...
since heterogeneous freezing starts earlier at lower RHi → higher tempeartures.

Author's response

We changed the sentence as proposed.

Changes in manuscript

It should be noted that ice is forming latest, as soon as conditions for homogeneous freezing get reached, as there is always a sufficient amount of solution droplets in the atmosphere.

Comment 7 from Referee

5) Page 4, line 32 – page 5, line 3:
' *Therefore, a cloud classification should not feature considerable regions of HOMout. This fact should be kept in mind when choosing a BSR threshold value for the cloud border detection, making sure that HOM regions lie inside the cloud. HETout regions, however, may exist in cases with no sufficient amount of aerosol ice nuclei.* '
Have you chosen the threshold BSR? So that no HOMout occured?

Author's response

We aimed for the lowest threshold value possible to include also optically very thin parts of the cloud. Yet lowering the value further would lead to misclassification of cloud-free, aerosol polluted air as cloud (mentioned in the beginning of Sect. 3). Therefore in many cases it might not be possible to classify all HOM regions completely as HOMin. We added a sentence, clarifying this point. In our case study HOM regions lie on the cloud border, thus also HOMout occurs.

Changes in manuscript

However, this might not always be completely achievable without misclassifying aerosol layers (see above)

Comment 8 from Referee

Also, HETout can occur in case RHi is higher than the chosen threshold RHi_HET, not only due to a lack of IN.

Author's response

In response to the Referee's comment we mention HETout and the possibility of misclassification one paragraph later where the RHi_HET parametrization and its limitations are discussed.

Changes in manuscript

In contrast to HOMout, HETout regions may exist in cases with no sufficient amount of aerosol ice nuclei, or due to simplifications in the utilized RHi_HET threshold.

Comment 9 from Referee

6) Page 5, line12:
'*To this end, we use an aerosol classification suggested by Groß et al. (2013). Then we employ simplified onset parameterizations RH^(MD)_i,HET(T) and RH^(CS)i,HET (T) (see Table 1 and Krämer et al. (2016, their Fig. 4)).* '
Please briefly explain the aerosol classifiaction.

Author's response

We added a sentence briefly explaining the aerosol classification.

Changes in manuscript

Together with a synergistic analysis, WALES Lidar data can be used to identify the relevant aerosol type in the measurement area. To this end, we apply an aerosol classification suggested by Groß et al., 2013. It uses the fact that aerosol types can be distinguished by three intensive optical properties, aerosol Lidar ratio, aerosol linear depolarization ratio, and color ratio. Mineral dust shows linear depolarization values of more than 20 %, coated soot less than 20 %.

Comment 10 from Referee

In addition, why not define two classes of supersaturation,
HET^(MD)_in/out and HET^(CS)_in/out ? This would provide even more detail!

Author's response

We think, the distinction between HET_MD and HET_CS is a question of finding the right threshold parameterization for heterogeneous freezing, depending on the dominant aerosol type. They should not be regarded as two evolution classes. Therefore we prefer to keep only one class for heterogeneous freezing.

Comment 11 from Referee

7) Page 6 line15:
'…; *low clouds are depicted in yellow.*' green *??*

Author's response

For clarification, we added a description of how the false color image was constructed and also mention that green corresponds to cloud-free areas over land.

Changes in manuscript

Fig. 2 b shows a false color image of the Pyrenees area derived from SEVIRI ("Spinning Enhanced Visible and InfraRed Imager") data at 14:30 UTC. The red, green and blue color channels of the image take SEVIRI's 635 nm, 850 nm and inverted 10.8 µm channel data. This way, the high and therefore cool cirrus clouds stand out by a bluish color. Low clouds get depicted in yellow and the surface of the Earth has a green tone.

Comment 12 from Referee: (Technical)

- Fig. 1: BSR < 2 would be better BSR <> 2 in the scheme

general:	DEP	why not	ISSR_in	sounds more clear
general:	ISSR		ISSR_out	sounds more clear

Author's response

For the sake of uniformity we prefer to keep the Yes/No scheme and thus BSR<2.
Following the Referees' suggestion, we changed the label ISSR to ISSR_out
However, as DEP describes the actual microphysical process of "depositional growth" in this class, we regard it to be an appropriate label.

Comment 13 from Referee: (Technical)

- Fig. 2 b: explain also the green color

Author's response

We added an explanation of green areas to the caption of Fig. 2.

Changes in manuscript

High ice clouds have a blue color, lower liquid clouds are yellow, cloud-free ground has green color.

Comment 14 from Referee: (Technical)

- Fig. 3 - 7: insert an arrow to show the wind direction

Author's response

We added an arrow of main wind direction to Figures 3 to 7.

Comment 15 from Referee: (Technical)
- Fig. 4: insert a panel with the ECMWF temperature!

Author's response

Following the Referees suggestion, we added contour lines of ECMWF temperatures to Fig. 4 a).

Changes in manuscript

Water vapor volume mixing ratio r_w measured by WALES is plotted in Fig. 4 a, together with red isolines of ECMWF temperature.

Review RC2 by Anonymous Referee #3

We thank Referee #3 for the detailed review of our manuscript. In the following we comment on the remarks. For the two main concerns see Comments #4 and #9.

Introduction from Referee

This manuscript describes the use of airborne lidar measurements of water vapor to demonstrate a cirrus classification scheme that is able to identify the evolution stages of the cirrus life-cycle using primarily relativity humidity with respect ice thresholds deemed from the literature. This is a interesting idea that would be useful in the analysis of airborne and remotely sensed cirrus clouds and would put measurements of cirrus microphysical properties in context with cirrus lifecycle. Overall the manuscript is well written and well organized, but I have some concerns about the data as presented.
First, the uncertainty in the computed relative humidity measurement is only loosely mentioned and should be considered in the context of the classification scheme. Second, I have some concerns about the generating mechanism described in this case.
I maybe misinterpreting the data as it is represented in the figures. This may influence the lifecycle, formulation, and interpretation of the classification scheme. These can likely be easily addressed by clarifications from the authors. I recommend this manuscript to be published after these concerns are addressed.

Comment 1 from Referee

p. 2 L19-25: Heymsfield 1975 was the first to illustrate and document the vertical and dynamical structure of cirrus uncinus clouds and should be stated as such in this paragraph.

> **Author's response**
>
> Following the Referees' suggestion we rewrote the paragraph to specify the contribution of Heymsfield et al. (1975).
>
> > **Changes in manuscript**
> >
> > Heymsfield et al. (1975) first illustrated and documented the vertical and dynamical structure of ice generating cirrus uncinus clouds. This early work and following in-situ measurements (Heymsfield and Miloshevich, 1995) indicate that there is a vertical order of cirrus evolution stages with ice nucleation near cloud top level, deposition of water vapor onto ice crystals and thus particle growth in the middle, and sublimation and sedimentation at cloud base level.

Comment 2 from Referee

I am not sure I would agree with the statement '... where individual clouds may show strongly different distributions.' It is the cloud type or generating mechanism that will influence this distribution (i.e. anvil, synoptic, in situ generated, orographic). There have been a number of studies (Sassen, Mace, Protat) that have looked at these differences.

Author’s response

To our knowledge, Comstock et al. (2004) were the first that used an extensive dataset of atmospheric cross sections to identify evolution stages with regards to relative humidity over ice. In accordance with earlier work (Heymsfield et al. 1975), their statistical approach revealed the dominance of a vertical order with nucleation at cloud top, crystal growth in the middle and sublimation and sedimentation near the cloud base. However they also present one cirrus case (15. November 2000) that does not feature this order. Another case lacking this “standard” order can be found in (Groß et al. 2014).

We agree with Referee #3 that cloud type and generation mechanism amongst others may influence the spatial distribution of evolution stages, but do not know of other studies investigating such dependencies.

We rewrote the paragraph to emphasize these points.

Changes in manuscript

A more recent, statistical study by Comstock et al. (2004) evaluates an extensive data set of ground-based Lidar measurements taken at the ARM Southern Great Plains site (Oklahoma, USA) over a time period of one year. Vertical profiles of determined relative humidity with respect to ice (RHi) inside of cirrus clouds get divided into the upper most 25 %, the middle 50 % and the lower 25 % of total cloud depth. The frequency distribution of RHi of the upper 25 % show a considerable amount of supersaturated regions with high RHi values up to 160 %, associated with ice nucleation. The distribution of the lower 25 % is shifted towards subsaturation with a maximum between 70 % and 80 % and values down to 10 %, clearly dominated by crystal sedimentation and sublimation. Therefore they showed that the generally accepted vertical order of evolution stages dominated the majority of measured clouds while individual clouds, depending on cloud type, generation mechanism, cloud age, and atmospheric dynamics, may show strongly differing distributions (Groß et al., 2014; Comstock et al. 2004). The classification scheme that we present is based on atmospheric Lidar cross-sections and therefore facilitates the detailed investigation of evolution stages, their vertical and horizontal order and the impact of atmospheric dynamics.

Comment 3 from Referee

p. 2 L19 and p. 7, L27: The Comstock et al. 2004 study was for data over Oklahoma, U.S.A., not France.

Author’s response

We corrected this point.

Changes in manuscript

A more recent statistical study by Comstock et al. (2004) evaluated an extensive data set of ground-based Lidar measurements taken at the ARM Southern Great Plains site (Oklahoma, USA) over a time period of one year.

The detailed distribution of these major stages of cirrus evolution features a horizontal order instead of a general vertical structure found in cirrus clouds over the Southern Great Planes (Comstock et al., 2004)

Comment 4 from Referee

p. 4 L20: The stated uncertainty in the relative humidity with respect to ice (RHI) is 10-15%, which is quite large. Your proposed classification scheme relies on thresholds for RHI (Fig. 1, Table 1). There is currently no discussion of how this uncertainty impacts the classification scheme. Clearly a 10-15% uncertainty would have quite an impact on this thresholding approach. This is a major issue that needs addressing.

Author's response

We thank the Referee for pointing us to that important topic. We are convinced that the thresholding approach is well suited for our classification scheme, but for more detailed, future investigations of optical and microphysical properties of classified evolution stages, RHi uncertainties and their impact on the classification must be discussed. In Sect. 2, we emphasize that 15 % uncertainty determined by Groß et. al. (2014) can be seen as an upper border. We also mention the possibility to improve the uncertainty of RHi by incorporating independent temperature measurements from e.g. drop sondes that are not assimilated in the ECMWF model.
Furthermore, we added a paragraph discussing the influence of RHi uncertainties on the result of our case study classification in Sect. 4.2.
Also we would like to mention that unresolved small scale fluctuations and their impact on the classification are discussed in Sect. 4.3 of the original manuscript.

Changes in manuscript

Section 2
The applicability of ECMWF temperature in this calculation was investigated by Groß et al. (2014). They showed that during ascent and descent of a similar research flight in 2010 the mean temperature difference between ECMWF and on-board temperature sensors was 0.8 K and estimated a resulting maximum relative uncertainty of 10 to 15 % as an upper boundary for the calculated RHi at typical cirrus temperatures.
In cases where collocated radiosonde or dropsonde measurements are available, their temperature profiles can be used to calibrate ECMWF temperature fields, eliminating possible offsets. As modern sondes feature measurement uncertainties of down to 0.2 K, the total relative uncertainty of RHi therefore potentially can be reduced to values as low as 6 %.

Section 4.2.
Unfortunately, no dropsonde temperature measurements were conducted in this cirrus case. Thus we must assume a relative uncertainty of RHi between 10 % and 15 % at cirrus level (see Sect. 2). This directly translates into an uncertainty in locating the exact border between evolution stages. However, we found that the horizontal distribution order and the existence of SUB regions at the cloud top continue to exist even after offsetting the temperature field by ±0.8 K. Therefore we are confident that ECMWF temperature data is suitable for this kind of analysis.

Comment 5 from Referee

Vertical velocity plays a key role in the initiation and evolution of cirrus clouds. Did you consider including the in situ vertical velocity measurements from the HALO in your classification scheme? This could help compensate for the errors in the RHI data.

Author's response

We did not consider including in-situ data of vertical velocity in out classification scheme. As described in our answer to Comment #4, we are confident that the uncertainty of RHi is sufficiently small for analyzing the spatial distribution inside cirrus clouds, already without independent temperature measurements from dropsondes or radiosondes. Furthermore, incorporating such temperature measurements could potentially reduce uncertainties to values as low as 6 %.
Keeping our method independent from in-situ data also retains many benefits: A bigger data set can be evaluated, including purely remote sensed cases and the method can readily be adapted to ground-based and spaceborne Lidar data.
Nevertheless, we plan to compare in-situ data to the results from our method in future work, e.g. to investigate microphysical properties in the context of evolution stages.

Comment 6 from Referee

p. 5 L32: It is stated that high dust concentrations were expected. What is the evidence for this statement? Did you look at the lidar ratios or the in situ aerosol data? Please provide some quantitative justification for this statement.

Author's response

Here we are referring to dust forecasts done as part of the flight preparation and planning procedure two days before the research flight. Those forecasts proofed to be valid as we later measured aerosol layers (Fig. 3), exhibiting typical values of aerosol linear depolarization ratio (>20 %) and Lidar ratio (> 35 sr) for Saharan dust. We added clarifying passages.

Changes in manuscript

Two days before the research flight, model forecasts indicated the existence of cirrus forming from high updrafts over the Pyrenees, as well as cirrus influenced by lee waves north of the mountain ridge. Additionally highly dust loaded air masses over Southern France, originating from Saharan dust events over Algeria were expected.

Comment 7 from Referee

Later, depolarization ratio is used (P. 6, L25) but still there is no reference, nor are typical values of dust mentioned.

Author's response

Following the Referee's suggestion we added typical values for Saharan mineral dust, backed with reference literature, and explicitly state our measured depolarization ratio values.

Changes in manuscript

Even lower, at a height of 4 km a thick aerosol layer is discernible. An analysis of ADEP shows values between 20 % and 30 %, typical for Saharan mineral dust (Groß et al., 2013) which is consistent with the origin of the air masses in North Africa, as forecasted by dust models.

Comment 8 from Referee

Fig. 2b - SEVIRI image: Can you provide the time at the northern most point on the white flight track line and also the southern most point? This will help put the lidar profiles in context with the satellite data (I assume the northern most point is roughly 14:20 UTC).

Author's response

The white flight track covers exactly the area depicted in Fig. 3 (14:16 – 14:58 UTC). We added a corresponding remark in the caption of Fig 2.

Changes in manuscript

The path of the research flight is plotted in red and the flight leg used in the case study (14:16 - 14:58 UTC) is marked white.

Comment 9 from Referee

Also, I am wondering what type of cloud the green color is associated with? Are these convective clouds? The reason I ask is that the lidar profiles in Fig. 3, 4, and 5 suggest that the clouds are thicker (3-4 km deep) than what I would expect in orographic lee clouds (~1-2 km deep) and the cloud looks to be more stratiform in its morphology. This suggests to me the cloud is a cirrostratus or anvil, that may have some gravity wave influences from the mountains. This would influence your discussion and conclusions about the formation and evolution of the cloud since anvil cirrus is formed in a much different environment than synoptic or in situ/orographic cirrus. Please consider the possibility if I am interpreting the figure appropriately. Adding a brightness temperature scale to the SEVIRI image would be helpful.

Author's response

We would like to mention that we specified the construction of SEVIRI false color image in Fig 2b) according to a suggestion from Referee #1 and also describe the green color. In Fig. 2b green color is cloud free area over land. In Fig 3 it is region of backscatter ratio ~5. There is a prominent aerosol layer with BSR~5 at about 4000 m

height, visible in front of and behind the Pyrenees Mountains in cloud free air (14:34-14:42 UTC and 14:51-14:58 UTC).
We agree with Referee #3 that the cloud regime is not a pure orographic lee wave cloud but the southern part of the cross-section investigated in this work is primarily dominated by gravity lee waves. From our analysis of satellite pictures, ECMWF data and preliminary MTP-temperature data, we found no sign, indicating an anvil cirrus. We included our findings in the manuscript.

Changes in manuscript

Earlier satellite pictures and ECMWF data (not shown) indicate that the cirrus cloud regime formed under the influence of a highly humid air mass stemming from Southern Spain that also shows the tendency to produce lower liquid clouds. As the air mass is transported to the North, it is impacted by gravity waves generated when crossing the Pyrenees. The analysis of preliminary temperature data (not shown) provided by the onboard, passive "Microwave Temperature Profiler" (Xu et al. 2016) shows that temperature oscillations, caused by gravity waves, continue to exist inside the cirrus cloud intersected by the flight path.

Comment 10 from Referee

P. 7 L25: '... probably caused by large-scale descent.' The ECMWF vertical velocity data could provide some clues to the large-scale dynamics.

Author's response

Indeed, the ECMWF data shows vertical downward motion over the middle and northern parts of France.

Comment 11 from Referee

Editorial: p. 2 L16: loose -> lose p. 2 L30: ascends -> ascent p. 5 L14: 'a uncertainty' -> 'an uncertainty' p. 5 L18: represent -> represents

Author's response

Thank you. We corrected those typos.