Response to the comments of Reviewer #1

We are very much indebted and thankful to the reviewer for the very detailed reading of the manuscript and the very helpful comments and suggestions. Although the comments from the reviewer were rated as "minor", they were very helpful for revising the paper. After consideration of all of them a much-improved paper has resulted. Detailed responses (in italics) follow after each comment.

General comments

- **Reviewer's comment:**

  General comments: overall quality of the discussion paper This study introduces and describes a PMC dataset from MIPAS IR emission observations, shortly presents the retrieval method that was already published in a previous paper, provides evaluation of its quality by comparison of MIPAS ice mass density and cloud altitude to AIM SOFIE observations, and discusses MIPAS cloud properties in relation to previous findings. The important advantages of an IR emission dataset like MIPAS compared to other (UV and/or VIS) remote sensing datasets are: o that observations are available during day and night o but also that retrieved cloud properties are independent of the highly uncertain PMC particle size distribution, which has to be assumed for the retrieval of cloud properties of many other satellite datasets. As such, this paper represent a substantial contribution in the form of new data to scientific progress within the scope of Atmospheric Chemistry and Physics. While the paper would profit from proof-reading by a native English speaker, there are also weaknesses in the discussion of the MIPAS measurement threshold, the discussion of the disagreement with SOFIE ice mass density profiles above 84km (Figure 5), and the discussion of MIPAS diurnal variations. A more thorough evaluation of the dataset could be achieved by additional comparison to another PMC dataset that also offer polar coverage, however, that would probably lengthen this paper too much. On the other hand, the paper can be shortened by emitting results that are not discussed in detail, for example Section 5. The conclusion should be more quantitative when summarizing the agreement with SOFIE. In summary, I think that all the here mentioned weaknesses can be resolved using the existing dataset, so I recommend this paper for publication in ACP with minor revisions.

  Responses:

  We are glad to hear that this work represents a "substantial contribution".

  There was already available a new version revised by a native English speaker where many of the suggested corrections were already done. This was probably caused by the kind of double-review system of ACP.

  Figure 5 has been revised, following the suggestion of the other Reviewer that we should considered the solar local time when comparing MIPAS and SOFIE observations. As a result the agreement is now much better. The text discussing this comparison and the Conclusions section have been revised (see comments below).
  Also, the section on the diurnal variation has been significantly revised including the figures (Figs. 10) (see comments below).

We agree that comparison with other instruments should be done, specifically with the IWC of CIPS. However, as recognized by the reviewer, this would lengthen the paper too much.

About the shortening of Sec. 5, the other reviewer actually suggested to discuss the correlation separately for each hemisphere. This section is already short and reports a finding that we consider important. Hence we have kept the text (actually expanded as suggested by the other reviewer) but it has been merged with the previous section. Figure 9 has also been reduced to just one panel.

We have revised the conclusions about the MIPAS-SOFIE comparison being now more quantitative.

Specific comments: individual scientific questions/issues

- **Reviewer's comment:**
  1. You compare the MIPAS PMC dataset to SOFIE, which observes PMCs at just one latitude each day. This latitude is slowly varying during the PMC season, but basically this restricts your comparison to a narrow latitude range. Have you considered comparing your dataset to other satellite observations, e.g., from CIPS, OSIRIS, SCIAMACHY, ...?

  Response:
  There are two major reasons of why not extending the comparison of MIPAS data to other instruments. First, the difficulty in choosing a common quantity that characterizes the PMCs. As discussed, MIPAS measures the ice volume density, irrespective of their particle size distribution. Most instruments measuring in the UV-VIS are not sensitive to the small ice particles existing in the upper part of the PMC layers; thus they are not the most appropriate instruments for comparison. CIPS might be also useful but provide, to our knowledge, only the integrated column ice (IWC), not profiles. BTW, we already considered the comparison with CIPS a couple of years ago, in conversations with Cora Randall, but comparing cloud coverage is difficult and certainly not very quantitative. Anyway, as you say, that comparison would lengthen the paper too much.

- **Reviewer's comment:**
  2. You retrieve the ice volume density as it is independent of the assumption of the particle size distribution, which is considered uncertain. Have you considered retrieving the particle size and number density, using the same assumption that the SOFIE team uses?

  Response:
  MIPAS does not have information on the particle size. SOFIE extract that information using different channels at different wavelengths in absorption. Unfortunately this is not possible with MIPAS. This is a limitation of the ***IR emission*** *technique. We are sensitive to the volume emission but cannot distinguish the particles' size.*

- **Reviewer's comment:**
  3. Do you have plans for making this dataset publicly available?

  Response:
  Yes, we participate in MesosphEO, a project of ESA, and it is planned that we provide the PMC dataset as part of our duties.

- **Reviewer's comment:**
  4. Your introduction should state clearly which SOFIE version you are using. I have found this information in the figure caption of Figure 5, but it belongs in the introduction.

  Response:
  We agree. We have now included in the introduction that we use version 1.3 of SOFIE data.

- **Reviewer's comment:**
  5. P3 L24-25, also P8 L5: I'm missing a more careful discussion of the MIPAS measurement threshold as done by Hervig et al., Interpretation of SOFIE PMC measurements . . . (2009). Some points regarding the SOFIE detection threshold and how it affects the radius retrieval from that paper: - The SOFIE ice detection threshold corresponds to Mice~0.06 ngm3. - It is important to note that particle size is only determined when the extinction β(1.037) is above the noise. - Although SOFIE can rarely determine particle size for the most tenuous clouds, size is characterized over the dominant range of measurements.

  Response:
  As an IR emission instrument, the detection limit is usually imposed by the instrument's noise mapped into the retrieved quantity, the ice volume density in our case, in the retrieval scheme. We have indicated this value in the single measurements as well as when doing any kind of averaging, which reduces it by the square root of the number of averaged data.
  Since we do not retrieve the particles' size, we have no detection threshold in the sense discussed in SOFIE measurements.

- **Reviewer's comment:**
  6. P3 L30: It also operated with a high sensitivity – How do you define high sensitivity?

  Response:
  The noise equivalent spectral radiance (NESR) of the 5 MIPAS bands are detailed in the given reference of Fischer et al. (2009). In particular, in the spectral region were the measurements analysed were taken (shorter-wavelength end of band A), is about 20 nW/(cm^2 sr cm^{-1}) (it slightly changes from spectrum to spectrum and with wavelength). This was already stated in L1 of page 5. The reference was also given already.

- **Reviewer's comment:**
  7. P6 L8-10: Please comment on how a potential 5-10K cold or warm bias affects your retrieved clouds. Do you believe The MIPAS temperature measurements more/less than those of other instruments?

  Response:
  This point is discussed in more detail and quantitatively in P7, lines 4-7. A 5 K error in temperature induces approximately (Planck function at 145 K and 800 cm^{-1}) an error of about 30%.
  About your second question, it is difficult to answer. The detailed validation carried out by García-Comas et al. (2014) have shown that MIPAS temperatures are in between SABER, MLS and OSIRIS on one side, and ACE and SOFIE on the other. One major point here is the vertical resolution, rather good for SABER and ACE, moderate in the case of MIPAS and rather coarse for MLS. SABER, however, as well as MIPAS, are prone to non-LTE effects and to

uncertainties in the atomic oxygen, while ACE is free of non-LTE. We are very confident in our retrieved MIPAS temperature but certainly cannot discard a systematic error of +/- 5 K near the polar summer mesopause.

- **Reviewer's comment:**
  8. Regarding all figures plotted vs. altitude: shouldn't the vertical axis be tangent altitude, not altitude?

  Response:
  *No, it shouldn't. We normally use tangent height if we plot the measured **radiance** at the limb tangent heights (see, e.g., Fig. 4 in López-Puertas et al., 2009). However, after we perform the retrieval, the retrieved quantities (temperature, H2O vmr and ice volume density) are all expressed in actual vertical heights in the atmosphere. See, for example, how radiances in the mentioned figure, due to the limb geometry are very large even below the PMC layer. Note this is not the case in the quantities shown in this paper.*

- **Reviewer's comment:**
  9. Do you have enough lines of sight through one cloud volume that you could apply a tomographic algorithm? Such an algorithm has the advantage that it solves the problem of clouds in the fore- or back- ground being assigned anomalously low tangent altitudes. You mention this problem on P8/9. Due to this problem SOFIE discards all clouds below a tangent altitude of 79 km. Examples for tomographic algorithms applied to PMC data: Hultgren et al., First simultaneous retrievals of horizontal and vertical structures of Polar Mesospheric Clouds from Odin/OSIRIS tomography, 2013; Hultgren and Gumbel, Tomographic and spectral views on the lifecycle of polar mesospheric clouds from Odin/OSIRIS, 2014.

  Response:
  We did not try but it would worth to do, at least on an orbit-by-orbit basis. However, the current version of our retrieval processor does not have this capability. Extending the processor for including this option would take rather long, certainly beyond the deadline for submitting these responses. This is, however, a very point that we will consider for the future improvements of the retrieval.

- **Reviewer's comment:**
  10. P9 L8-9: Please comment on why in the upper left panel of Figure 2, the clouds fill only a small portion of the region where the temperature is below the frost point temperature, while on the lower left panel (also SH) the cloud coverage seems to agree much better with the frost point temperature boundary.

  Response:
  The fact of the temperature being smaller that the frost temperature for having PMCs is a necessary conditions but not sufficient. Other factors that influence the presence of PMCs are availability of nuclei for condensation, sedimentation, transport, ice growth and sublimation time dependence, and particle size effects on saturation vapor pressure. On the other hand, even assuming thermodynamic equilibrium, T_frost is the temperature below which ice formation is possible but only at 5-10K lower temperatures the ice growth really becomes asymptotic (Hervig et al., 2009). That is, we do not expect having ice clouds everywhere

temperature is below the frost temperature. Finally, we estimated T_frost from a constant mean water vapor profile, whereas water vapor changes. This variability has not been taken into account in the evaluation of our T_frost.

- **Reviewer's comment:**

  11\. P9 L8-9: Please comment about the possibility that you see the effect of 5-day planetary wave activity in Figure 2. You could also comment about the possibility to use your dataset to help track the effect of space shuttle exhaust on PMCs, e.g., Stevens et al., Antarctic mesospheric clouds formed from space shuttle exhaust, 2005; Stevens et al., Bright polar mesospheric clouds formed by main engine exhaust from the space shuttle's final launch, 2012; Stevens et al., Polar mesospheric clouds formed from space shuttle exhaust, 2003.

  Response:

  MIPAS was observing in the middle/upper atmospheric mode during and right after the launch of the space shuttle in July 2011 (see Table 1). We have quickly looked at that and found hints about increasing of the ice density near ALOMAR on 9th July 2011. However, this requires a more careful analysis that is beyond this work.

- **Reviewer's comment:**

  12\. P11 L12-13: reformulate sentence, e.g.: Using the NLC mode data at similar NH latitudes, we derive a mean bottom altitude of ~81 km, slightly lower than that of SOFIE. But I think "similar NH latitudes" is too imprecise. It is not clear how exactly you choose the MIPAS latitude for comparison to SOFIE: do you use one mean latitude value, or a daily changing latitude value based on the changing SOFIE latitudes? Please describe your method better.

  Response:

  We now write that the comparison is done with MIPAS zonal means in a latitudinal band extending ±2 deg around mean latitude of SOFIE's measurements.

- **Reviewer's comment:**

  13\. P11 L13-14: Note, however, that we have not excluded any PMCs here, whereas in SOFIE those found below 79 km were excluded. – You're not comparing apples and apples: what happens when you treat MIPAS observations like SOFIE did? Do you then get a better agreement (as expected)?

  Response:

  When treating MIPAS observations like SOFIE the change is very marginal, only 0.1 km. We have re-written the sentence to:
  "In SOFIE measurements the PMCs with a peak extinction altitude below 79 km were excluded (Hervig et al., 2009b). Applying a similar threshold to MIPAS data, however, does not change significantly the bottom altitude.

- **Reviewer's comment:**

  14\. P11 L28: at those latitudes – please be more precise: what is your coincidence criterion? It may be worth showing a histogram of SOFIE and MIPAS ice mass. This would be helpful in convincing the reader of the nice agreement.

  Response:

The coincidence criterion has now been specified, within 2 degrees of SOFIE latitude measurements.

- **Reviewer's comment:**
  15. P12 L1-3: I don't understand your explanation why MIPAS and SOFIE are expected to observe less ice mass density than the lidar: if MIPAS and SOFIE are able to observe a BIGGER population of the total ice mass by ALSO observing the smaller particles (that the lidar does not observe), shouldn't the resulting ice mass density be BIGGER than the lidar ice mass density?

  Response:
  Our reasoning (see also Hervig et al.) is that if one instrument samples only the larger clouds, it is clear that one would get a mean bias to larger values with respect to another that sample all values, large and small.

- **Reviewer's comment:**
  16. P13 L9-10: ice particles are the smallest and it could be that MIPAS is more sensitive than SOFIE to those particles. – Here you argue that a more sensitive instrument should result in higher values of ice mass density. On the previous page you have argued the opposite: that the larger sensitivity of MIPAS to the smaller ice particles than lidar will lead to lower mean ice mass density values. It makes the impression as if you are contradicting yourself.

  Response:
  We agree that it looks contradictory.
  We have removed that sentence.

- **Reviewer's comment:**
  17. If you haven't done that yet, I would suggest talking to Mark Hervig directly about possible reasons for the disagreement in ice mass density above 84km as seen in Figure 5. Please also discuss possible reasons for this disagreement in more detail, e.g., the role of geophysical differences.

  Response:
  Thank you very much for the suggestion. We did not have the opportunity to talk to Mark Hervig about these differences. The differences in the revised version, however, are much smaller. As suggested by the other reviewer, we have now considered the criterion of having the closest possible solar local time. This has greatly improved the comparison.

- **Reviewer's comment:**
  18. P17 L15-17: The discussion of Figure 9 is very short (2 sentences) and contains only a description of Figure 9. Do you have an overall point you want to get across with Figure 9? Is this a new result or do you show this to relate MIPAS observations to previous studies (which?)? Otherwise, please consider omitting Figure 9 and Section 5.

  Response:
  It is true that the discussion is short and may do not deserve a Section on its own. We have merged it with the previous section.

However, the result is clear, we think. The major point being that when the atmospheric temperature is below the frost point temperatures at lower altitudes, the PMCs are dense (IWC is larger). We think this point is already clear in the text. To our best knowledge, we are not aware of any previous study on this.

- **Reviewer's comment:**
  19. Last paragraph of Section 6: the discussion about column abundance of gas phase H2O around 70◦ is not supported well by Figure 10, which shows the gas-phase H2O vs. altitude and latitude.

  Response:
  That is correct. There are several points here. First, around 70 deg, the distinction between the hydration and dehydration layers in MIPAS data is not so clear as reported by Hervig et al. However it is evident at higher latitudes.
  *Secondly, the quoted values of MIPAS H2O anomalies in both regions should be given as integrated columns and not as the peak values in both regions. When integrating, the column in the hydration region, 6-7 ppmv*km, is about twice larger than in the dehydration region, 3.5-4.5 ppmv*km. On this point MIPAS and SOFIE do not agree well.*
  Third, these anomalies in the gas-phase water are both much smaller than the amount in ice. On this point both SOFIE and MIPAS agree very well.

  We should also have in mind that in order to calculate accurately the excess and deficit of water vapour in the lower and upper regions, we should use the H2O gas profile corresponding to the same geolocations but with no ice. Such profile (the background profile of Hervig et al.) was estimated by Hervig et al. from measurements where no ice was present. To determine such profile in the case of MIPAS is very difficult because of the high noise in the single profiles of the retrieved water vapour. Hence, we used as the "no-ice" H2O gas profile the zonal mean profile corresponding to all latitudes. This could partially explain the SOIFE and MIAPS differences.

  The text has been revised along these lines.

- **Reviewer's comment:**
  20. P20 L1: exhibit a very good latitude/longitude spatial correlation – I don't agree: while the dehydrated "hole" in H2O at 90 is neatly centered on the pole, the clouds' center of mass is shifted towards northern Greenland, and at 80km the center of mass of the hydrated region is over the northern Pacific. I wouldn't call this "very good latitude/longitude spatial correlation", but expect a comment on this "rotation".

  Response:
  The comment is very pertinent. We agree that we should not say a "very good ... correlation". It is the first order broad feature what we want to highlight. Also, we do not expect a perfect correlation, as is not expected an immediate response neither the same structure at different altitudes (e.g. propagation of gravity and planetary waves). The text has been changed in this sense.

- **Reviewer's comment:**
  21. P20 L4-5: I don't agree with your statement that the location of the hydration region agrees well with SOFIE observations. From Figure 10 it looks like the MIPAS peak altitude

of the hydration region is at 80km, whereas the bottom of the PMC layer is at 81 km. If anything, then the MIPAS peak in hydration lies BELOW the bottom of the PMC layer. Or do you also count the dark blue shading as PMC? Then I would agree. But for that it would be useful to know if these dark blue PMC observations are above the noise threshold.

Response:
You are fully right. We understood that the peak altitude of the hydration region in SOFIE is 0.3 km BELOW the bottom PMC layer but it is ABOVE.
We have corrected the text stating now that they do not agree.

- **Reviewer's comment:**
  22. P20 L9-10: What do you mean with being "more pronounced"? That the ice layer contains even less H2O than the hydration/dehydration layers? At higher latitudes the dehydration (-0.3 or -0.4 ppmv maybe) looks much less pronounced than the hydration (1.4 ppmv), which does not agree with the SOFIE results that they are roughly equal. But again: my misunderstandings could be solved by showing a plot of the H2O column abundances.

Response:
Sorry for the misunderstanding. We meant that the excess/deficit of of H2O gas phase in MIPAS data are both larger (in absolute values) at latitudes closer to the pole; i.e., they increase from 70ºN towards the pole.
We did not include extra figures but calculate the columns and included the values in the text. See also the response above.

The text has been revised along these lines.

- **Reviewer's comment:**
  23. Section 7 (Diurnal variation of ice volume density, Figure 12) is lacking clarity and not convincing:

Response:
We have re-written the whole section and corrected several typos. We think that the section reads now more easily.

o P20 L26-28: as you write, there is an altitude difference between the morning/evening clouds, and you note that this altitude difference leads to the altitude bipole structure in Figure 12. Is it possible to correct for the altitude difference in order to get rid of the bipole structure?

The alternating negative-positive differences are actually indicative of a change in the mean cloud altitude with the NH pm clouds being on average at lower altitudes at 65-75N. Additionally, the shape of the average Vice is not the same during am and pm. Therefore, a simple vertical displacement of the am clouds would not make the bipole structure to disappear.

o P21 L1-2: These ice volume density differences are remarkably anti-correlated with the 10 am-10 pm differences in the kinetic temperature measured by MIPAS – I don't agree: there is a positive difference in T at 60-70S and 85-90 km, which should result in a negative difference in the clouds in that region, but I see a dipole structure there (possibly only due to clouds being at different altitudes!). In the opposite hemisphere, I don't see any temperature differences, but a big positive signal in the ice volume density and also a (weaker) dipole structure.

We have now zoomed-in Fig. 12 in order to clarify the discussion. We have also refined the discussion. We write now that the good anti-correlation is only found in the NH. That is more clearly seen in the relative V_{ice} differences, that we now include in the manuscript. We also more clearly state that the SH ice differences are not well anti-correlated with temperature.

o P21 L3-4: The negative am-pm difference OF WHAT at 80-85 km at latitudes below (DO YOU MEAN EQUATORWARD?) 80ºN is well anti-correlated to the am-pm ice differences OF WHAT. – Don't understand this sentence.

We re-structured and completed the sentence: 'The positive am-pm ice differences at 80-85 km equatorward of 80N are anti-correlated to negative am-pm temperature differences.

o P21 L4-5: In the NH temperature panel of Figure 12, I see temperature differences around 0K, are they even statistically significant? Also, shouldn't a positive temperature difference lead to a negative ice volume density difference, but the Vice NH plot shows a positive on? Don't understand this sentence.

As written in the previous version, there is a tendency of positive temperature differences that is reflected in negative ice differences. We think that it is more clearly seen in the new zoomed-in Fig. 12.

• **Reviewer's comment:**
24. P22 L3: I wouldn't call Figure 5 showing a "very good agreement" overall

Response:
Even if the new comparison (Fig. 5) is much better that before, we agree, we should not say "very good agreement" overall. Change to "good agreement".

• **Reviewer's comment:**
25. P22 L4: slightly larger – please quantify

Response:
With the new comparison the differences in IWC are small, ~10%.

Technical corrections:

We thank again to the Reviewer for all the technical corrections that resulted in an improved manuscript. They have been all been included except a few exceptions as explained below. We also response below to the questions risen in this Section.

2. You mostly use both terms PMCs and NLCs, while I think it would be more consistent to stick to one term throughout the paper.

We mainly used the term PMC. We only use "NLC" once in the introduction, to say that PMC and NLC are the same phenomena. To avoid misunderstanding, we have deleted 'as seen from the ground'. We use NLC in many cases when referring to the MIPAS "NLC-mode" measurements. This "NLC-mode" was defined in the MIPAS mission plan as a particular observation mode and hence we have kept its name.

P8 L6: Noise errors in these plots are about 0.3 × 10−14 cm3/cm3. – How do you calculate this noise error?

By the standard error of the mean, i.e., by dividing the single noise error by the square root of the number of averaged profiles.
We state this now explicitly in all figure captions and in the text.

Please comment on the low latitude clouds detected outside regions colder than the frost point temperature: why there?

We include the following text: "Weak PMCs located at latitudes equatorwards of about 60 degrees and outside of the frost point temperature contour are likely false detections caused by instrumental (most likely offset) errors."

62. Figure 4: It seems you have forgotten to put the SH results as in Fig. 3. Also the ordering is wrong (the two NH plots should be below each other, not next to each other).

Correct. The caption was wrong. It has been corrected in the revised version.

Figure 5: why do you only show results from the MA and UA modes (MUA), and not the NLC mode?

Because we did not want to mix up measurements with different vertical resolution and those of MUA have a better statistics.

93. P13 L5: (except in 2011) - I don't agree: also in NH2011, the MIPAS ice mass density is higher than the SOFIE ice mass density above 85 km.

This has changed in the new figures (using only MIPAS pm data). The agreement is better now.

P13 L25: since, to our knowledge, the water ice content has not been measured at latitudes higher than ←−75. – I don't agree: AIM CIPS measures the IWC at latitudes higher than 75, see e.g., http://lasp.colorado.edu/aim/browse-images.php.

Thank you. The paragraph has been removed. Has this been reported in published papers?

P17 L29 – P19 L3: This text interrupts the discussion of Figure 11 and should be moved to the introduction (Section 1).

We agree that, as it is written, the H2O retrieval description interrupts the discussion. However, it is too short and would also be isolated if moved to the "MIPAS measurements" section, which is mainly devoted to ice volume density retrieval. We have re-arranged the text in Section 6 so it does not interrupt the discussion that much now.

Response to the comments of Reviewer #2

We are very much grateful to the reviewer for the very helpful comments and suggestions. After consideration of all of them a much-improved paper has resulted. Detailed responses to the Reviewer (in italics) follow after each comment.

- **Reviewer's comment:**
  Major Comments:
  Given the limited amount of data used from MIPAS, it would be useful to better quantify the observed variability in PMC properties throughout the paper. For example, what is the range of "top altitudes" from MIPAS? If there is a high degree of variability, the mean calculated from 12 or 19 days is likely insufficient to converge on the "true" mean.

  Response:
  We agree with the referee on this point. We stated already in several instances of the manuscript the large variability of PMCs in MIPAS measurements, caused not only by their natural variability but also for the large single measurement noise (already included in the text). The variability is also evident in the daily zonal mean examples shown in Fig. 1. It is true, however, that we did not provide a quantification of the variability in some cases (note that in most of the zonal mean figures and maps we already stated the estimated noise error). We have quantified the variability of the "top altitude" and found that it is rather large (1 sigma values changing from 1.6 to 2.7 km, depending on the mode of measurement and latitude).

  The next couple of sentences have been added in Sec. 3.1:
  "The highest altitude of PMCs derived from MIPAS NLC mode measurements is highly variable, as can be seen in the typical examples shown in Fig. 1. At 70N, it is about 88.5 km (Fig. 3b). Its variability depends on latitude and takes 1-sigma values from 2.7 km near 70º to 1.6 km near the pole."

  We have also estimated the variability of the bottom altitude and of the mean altitude layers (see responses below).

- **Reviewer's comment:**
  I would check Figure 5, as I would expect better agreement with SOFIE based on the rest of your analysis. In 2009, for example, the average of 175 MIPAS profiles at 87 km is ~15ng/m^2, compared to ~2ng/m^2 from 165 profiles from SOFIE. If this figure is correct, then I think the large differences and variability compared with SOFIE call into question the entire analysis. It also looks like you may even be seeing ice above 90 km in Figure 5 and are simply setting these values to 0. Also, Figure 4 and Figure 5 do not seem to be in agreement. 2009 and 2010 show a peak in mass density above 87 km that is not represented at all in Figure 4.

  Response:
  This is a very good point. We have revised the comparison following the reviewer's comment below suggesting that we should compare MIPAS measurements with a similar local time as those taken by SOFIE. Thus, we have re-done Fig. 5 including ONLY 10 pm measurements, which are closer to SOFIE's local time of observations in the NH. The agreement is much

better now (see new Fig. 5 as Fig. 1 below) because of the smaller ice concentration at 10 pm, particularly at altitudes of 85-87 km (see Fig. 12). The agreement is better now for all years in the region above 85 km. Still we obtain a significantly larger ice amount above around 85 km for 2009 and 2011, although, they are of similar magnitude than the peak below. It is also worth noting that MIPAS does not have a vertical resolution as good as SOFIE. However, the column amount is a more comparable quantity. We see that even for these years, the agreement in the column amount is very good 46 µg/m2 (SOFIE) vs. 41 (MIPAS) for 2009, and 60 µg/m2 vs. 56 for 2011. Thus, although the noise in MIPAS measurements is rather large and the vertical resolution is not as good as in SOFIE, we do think that our measurements are very valid and the analysis is trustworthy.

Action: Fig. 5 has been revised and the text has been accordingly revised.

- **Reviewer's comment:**

  It also looks like you may even be seeing ice above 90 km in Figure 5 and are simply setting these values to 0. Also, Figure 4 and Figure 5 do not seem to be in agreement. 2009 and 2010 show a peak in mass density above 87 km that is not represented at all in Figure 4.

  Response:

  That is correct. In some days there appear some small radiances at tangent heights above 90 km which appear as ice in the retrieval. We think this is not real but caused by the large variability in the offset of MIPAS spectra, which, when integrating over the large spectral range of 770–920 cm^{-1} (see Lopez-Puertas et al., 2009) results in some significant radiance-integrated offset. This offset changes significantly with latitude and season and also with altitude. We have improved significantly the offset correction from Lopez-Puertas et al. (2009) (see the text) but there are still some scans that show some signal above 90 km. Since we think there is no physical reason for attributing this signal to PMC's we did not show it.

  About the possible disagreement between Figs. 4 and 5, it is apparent. Fig. 4b shows the mean of all the years, not only 2009 and 2010 but also 2008 and 2011. The latter show also a peak (more pronounced in 2011) at lower altitudes. As a result, when averaging over all years, it results in a kind of broad peak near 70º N extending from 83 km up to 87 km, as shown in Fig. 4b. Actually, we do see a very small increase in this broad peak at about 85-87 km (follow the "10" contour line in Fig. 4b).

- **Reviewer's comment:**

  Comments:
  General: make sure you define each acronym once, the first time it appears.

  Response:

  We have revised the acronyms and have deleted a few double definitions. We have retained, however, the duplicity between the abstract and the rest of the text and also when they appear in the figure caption (in order to facilitate the reading). Also, we have duplicated the definition of uncommon terms like MA and UA, when they appear in the text far away from where they were defined. Again, we think the addition of these few extra words justify the much easier reading of the paper.

- **Reviewer's comment:**

Line 25: can't temperatures be lower that 150K?

Response:
Yes, they can. We have replaced "as low as " by "about".

- **Reviewer's comment:**
  The paragraph beginning at line 35 provides little information except to say that PMCs have been studied. What did these papers show?

  Response:
  The idea with this sentence was to express that PMCs have been measured by many instruments using different techniques and also from the modeling point of view. This is a kind of summary of major observations and modeling efforts. The particular aspects derived from some of these instruments are detailed in the following paragraphs.

- **Reviewer's comment:**
  Line 55: This paragraph could be reduced to say that similar results were found by Stevens and Hervig [2014] using SBUV.

  Response:
  The paragraph actually contains two pieces of information, one about the temporal evolution of PMCs and another one about the SBUV and SOFIE data comparison. We have re-written the paragraph to:

  Similar results were found by Hervig and Stevens [2014] by using SBUV data and a different method for calculating the ice water content (IWC). These authors also compared SBUV and SOFIE data and found good agreement in average IWC if an appropriate threshold was applied to the SOFIE data set and consistent day-to-day and year-to-year variations between both data sets were used.

- **Reviewer's comment:**
  Line 70: What do you mean by "the responses"? Are you saying that the 27-day solar cycle somehow accounts for long term PMC trends?

  Response:
  No, we meant to say that the 27-day solar cycle variations were not induced directly by the 27-day solar cycle variations in the solar flux but by 27-day variations in the vertical winds. The paragraph has been written to:

  Thomas (2015) have studied the solar-induced 27-day variations in polar mesospheric clouds using 15 seasons of SOFIE data and suggested that the 27-day variations in the PMCs are due to 27-day variations of vertical winds.

- **Reviewer's comment:**
  Titles of Figure 4 are not consistent with figure caption. It looks like the figure caption is wrong.

  Response:
  Correct. Sorry about that. It was a leftover of a previous figure.

- **Reviewer's comment:**
  In Figure 5, put the red line on top of the shading.

  Response:
  Done.

- **Reviewer's comment:**
  What is the reasoning for showing a single day in Figures 10 and 11? Wouldn't it make more sense to do this analysis using all the data, so you could more easily compare with previous work?

  Response:
  There are several reasons. First, not all the H2O middle and upper atmosphere data have been processed but only the period of the NLC season in 2005. Secondly, it was not the main aim of this paper to present a detailed study of the analysis of the PMCs (ice) and gas phase H2O data. This is beyond the scope of the paper. However, we thought it is useful to illustrate this as an example since very few (if any) instruments are able to measure global-latitude fields of temperature, ice, and water vapour simultaneously. A more quantitative and extended study is planned for the future.

- **Reviewer's comment:**
  Why do you show latitudes equatorward of 50◦ in Figure 12? Also, the temperature anomalies do not seem to correspond to the anomalies in ice volume density. Maybe this is because you are comparing January and July differences in temperature to full season differences in ice volume density.

  Response:
  The main reason for showing latitudes equatorward of 50º was to illustrate global tidal features and that the temperatures differences at mid-lat. and near the polar region are due to tides. We agree that it is much easier for looking at correlation between ice concentration and temperature to show the same altitude/latitude coverage in both figures. Thus, this figure has been re-plotted along this line. Note also that the temperature differences have been plotted for the same days of measurements of the PMCs so they are directly comparable now. We have also included new panels with the relative am-pm ice volume densities differences and removed a few outliers (with V_{ice}>4-sigma).
  In the revised version of the text we have also refined the discussion on the temperature and the ice anti-correlation and state that it is not clear in the SH.

- **Reviewer's comment:**
  Also, how do your results in Figures 12a and 12b affect your comparison to SOFIE in Figure 5? Would it make sense to only compare am or pm to SOFIE? SOFIE observes sunrise in the NH summer and sunset in the SH summer.

  Response:
  This is a very good point. As described above we have now compared MIPAS pm with SOFIE NH measurements, taken around 23pm on average, (revised Fig. 5) and the agreement is much better. Thank you very much for pointing this to us.

- **Reviewer's comment:**
  Figure 9 seems to show two distinct populations for the NH and SH. I don't think it makes sense to do a regression analysis of both hemispheres. Looking at the left panel, it seems that there is a strong linear trend in the NH, but in the SH, ice water content seems independent of frost point altitude. Maybe expand your analysis to discuss hemispheric differences and compute the correlation in each hemisphere separately.

  Response:
  If it is a physical reason for such a correlation it is not clear why it should happen in one hemisphere and not in the other. For that reason we presented the analysis together. It is true that for the NLC mode (left panel) there is a stronger correlation in the SH than in the NH (note that this is contrary to what you state). However, the correlations for NH (black) and SH (red) are similar for the MA+UA modes (right panel).
  We have now repeated the analysis for each hemisphere separately and found the same conclusion (see figures 2 and 3 below). We find overall a rather good correlation except in the case of the NLC mode in the NH. This could be caused by the smaller statistics we have for this case.
  Thus, because we have found the same behavior separately in each hemisphere, and the other reviewer suggested to shorten/remove this section, we have replaced the previous 2-panel figure by one panel showing the analysis for all modes + the two hemispheres together.

- **Reviewer's comment:**
  Line 217: There is no 70◦N in the bottom-left panel of Figure 1

  Response:
  Correct. It refers to a previous figure showing the zonal mean distribution for the 5th July 2009 in the NLC mode. We have removed this reference in the revised manuscript.

- **Reviewer's comment:**
  Figure 2: Any thoughts on what drives the zonal variability observed here (i.e., planetary waves such as the 2-day or 5-day wave)? See Siskind, Nielsen, and Merkel

  Response:
  Yes, it could be driven by PW activity. However, MIPAS was operating in the middle/upper atmospheric modes only occasionally (see Table 1) and unfortunately the time sampling does not allow for unambiguous determination of individual periods of zonal oscillations. Effects of the 2-day and 5-day waves are aliased with stationary waves and tides and cannot be isolated. Nevertheless, we now mention the possibility of the wavenumber-1 longitudinal variations in the plot being due to planetary waves, but mainly based on findings from other authors.

- **Reviewer's comment:**
  Line 261: What is the standard deviation for MIPAS?

  Response:
  The standard deviation of the bottom altitude of PMCs in MIPAS varies with the mode of observation from +/-1.2 km for the NLC mode to +/-1.8 km for the MUA mode. Thus, the bottom altitude in MIPAS is 80.9+/-1.2 km for the NLC mode and 80.0+/-1.8 km for the MUA mode. These data have been included in the text.

- **Reviewer's comment:**
  You talk about Figure 4 like it is a 4 panel plot, but it only has 2 panels

  Response:
  Correct. Sorry about that, it is a leftover of a previous version of the figure. The text has been changed: "Fig. 4b and 4d" to "Fig. 4a and 4b", and the legend of the figure appropriately corrected.

- **Reviewer's comment:**
  Line 295: Bardeen et al. [2010] has done this exact analysis.

  Response:
  I think this is a misunderstanding. We refer to a detailed comparison between CARMA and ***MIPAS data****, covering high latitudes, not with SOFIE data. We have clarified this in the text: "A thorough comparison with the CARMA model and MIPAS data, including higher latitude regions, would be very useful but is beyond the scope of this paper."*

- **Reviewer's comment:**
  Line 355: What lidar measurements, and at what latitude?

  Response:
  With ALOMAR lidar measurements in Norway (69ºN). This has been added to the text.

Reviewer's comment:
Line 390: I don't understand how this result is consistent with Figures 7 and 8, which have nothing to do with the bottom altitude.

Response:
We wanted to say that the denser PMCs, which, as Fig. 8 shows, are closer to the poles, are located at lower mean altitudes, as shown in Fig. 7.
We have clarified this in the revised version: "This is consistent with the behaviour shown in Figs. 7 and 8 where the denser layers are usually found near the poles and at lower mean altitudes."

- **Reviewer's comment:**
  Line 460: This anti-correlation doesn't seem apparent to me.

  Response:
  We now clearly state that the anti-correlation is generally good only in the NH but not in the SH. As mentioned above, we have re-written Section 9.

- **Reviewer's comment:**
  Line 513: Didn't you show this in Figure 1 and 3?

  Response:
  Not really in Figs. 1 because it shows some examples which might be or not a general behavior. About Fig. 3, yes, it shows the inter-hemispheric differences qualitatively although

not quantitatively. In any case, we are recapping the major results in the Conclusions' section and find it useful mentioning this again.

- **Reviewer's comment:**

  Minor Changes:

  All the minor changes have been included. Thank you very much.

  FIgures:

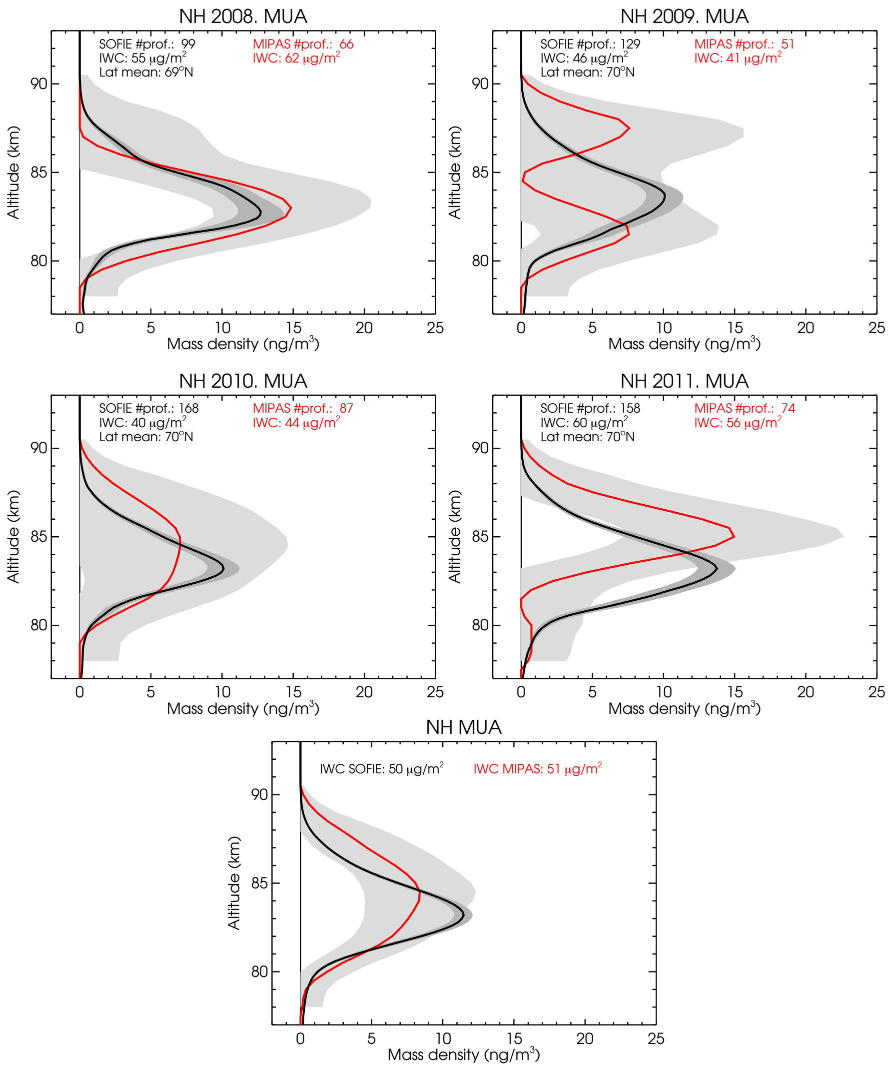

Figure 5. Comparison of the ice mass density of MIPAS MUA modes of measurements (see Table 1) with SOFIE v1.3 L2 data for the 2008 to 2011 period and the mean of the four years in the NH. The solid lines show the mean profiles, SOFIE in black and MIPAS in red. The shaded areas are the standard deviations divided by the square root of the number of profiles. The means of the IWC are also shown.

13

Fig. 1. New Fig. 5.

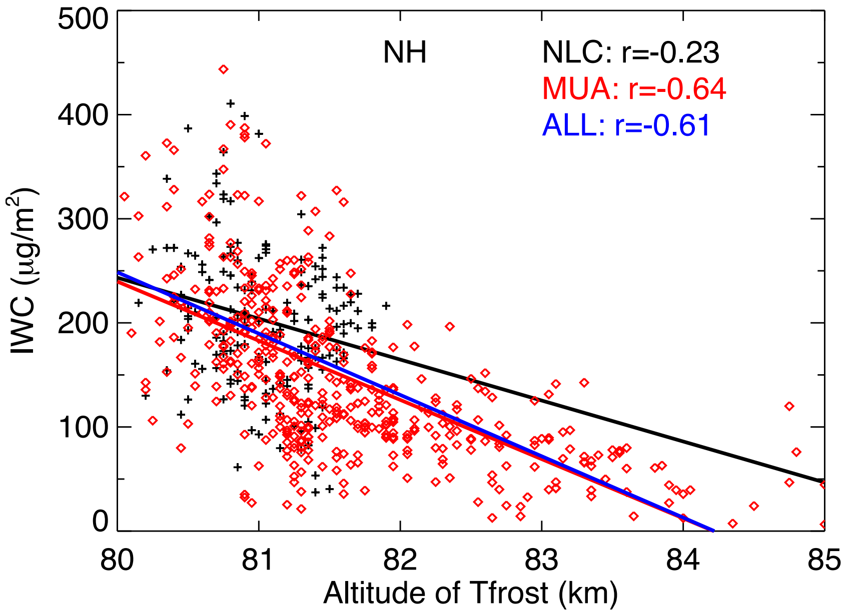

Fig. 2. Correlation between IWC and the altitude of the lower branch of the frost point temperature contour for the data taken in the NLC (black '+') and MUA (red diamonds) in the NH.

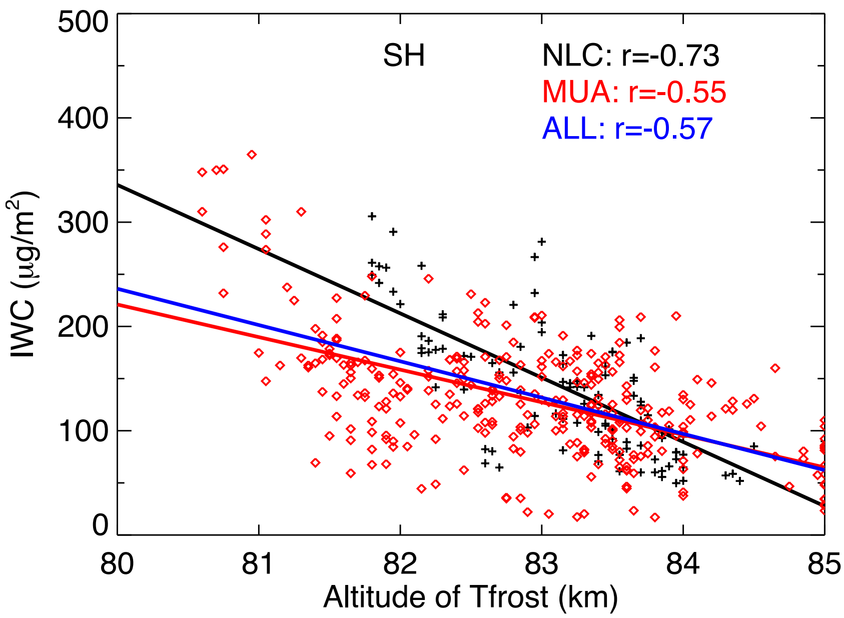

Fig. 3. As Fig. 2 but for the SH.

Measurements of Global Distributions of Polar Mesospheric Clouds during 2005-2012 by MIPAS/Envisat

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Abstract. We have analysed ~~the~~ MIPAS IR measurements of PMCs for the summer seasons in the Northern ~~and Southern~~ (NH) and Southern (SH) Hemispheres from 2005 to 2012. Measurements of PMCs using this technique are very useful because they are sensitive to the total ice volume and independent of particle size. For the first time, MIPAS has provided coverage of the ~~PMCs~~ PMC total ice volume from mid-latitudes to the poles. MIPAS measurements indicate the existence of a continuous layer of mesospheric ice, extending from about $\sim$81 km up to about 88-89 km on average and from the poles to about 50–60° in each hemisphere, increasing in concentration with proximity to the poles. We have found that the ice concentration is larger in the Northern Hemisphere than in the Southern Hemisphere. The ratio between the ice water content (IWC) in both hemispheres is also latitude-dependent, varying from a NH/SH ratio of 1.4 close to the poles to a factor of 2.1 around 60°. This also implies that PMCs extend to lower latitudes in the NH. A very clear feature of the MIPAS observations is that PMCs tend to be at higher altitudes with increasing distance from the polar region (in both hemispheres), particularly equator-wards of 70°, and that they are about 1 km higher in the SH than in the NH. The difference between the mean altitude of the PMC layer and the mesopause altitude increases towards the poles and is larger in the NH than in the SH. The PMC layers are denser and wider when the frost point temperature occurs at lower altitudes. The layered water vapour structure caused by sequestration and ~~by~~ sublimation of PMCs is ~~more pronounced at latitudes northernmost~~ present at latitudes northward of 70~~degrees~~°N and more pronounced towards the pole. Finally, MIPAS observations have also shown a clear impact of the migrating diurnal tide on the diurnal variation of the ~~PMCs ice concentration~~PMC volume ice density.

1 Introduction

Polar mesospheric clouds (PMCs), ~~usually~~ also called noctilucent clouds (NLCs)~~when observed from the ground, occur at~~, occur in the coldest regions of the atmosphere near the summer ~~high latitude~~ polar mesopause. PMCs normally form a layer extending vertically for several kilometres, peaking near 83 km, located at latitudes poleward of 50°. In this region the temperature frequently drops below the frost point which, for mesospheric pressures and humidities, is ~~as low as~~ about 150 K. They mainly consist of water ice particles with radii ranging from a few nm to about 100 nm (Rusch et al., 1991; Gumbel and Witt, 1998; Hervig et al., 2001; von Savigny et al., 2005).

~~NLCs are only the optically visible (and lower) part of the layer of icy particles covering the entire polar mesopause region (Berger and Zahn, 2002; Rapp and Thomas, 2006). However, the whole layer modifies the~~ PMCs modify the ambient plasma of the D-region and gives rise to intense radar echoes, the so-called PMSE (Polar Mesospheric Summer Echoes) (Rapp and Lübken, 2004). It is now generally accepted that ~~the larger~~ larger ice particles are located near the bottom of the layer, while ~~the~~ smaller ones are more likely to be near the top of the layer (Berger and Zahn, 2002; von Savigny et al., 2005; Baumgarten and Fiedler, 2008).

PMCs have been intensively studied using ground, rocket, and space observations (SNOE/UVS, SBUV, ODIN/OSIRIS, SCIAMACHY, GOMOS, AIM~~) (Baumgarten and Fiedler, 2008; Fiedler et al., 2009; Gumbel and Witt, 1998; Bailey et al., 2005; DeLand~~ AIM/CIPS) (e.g., Baumgarten and Fiedler, 2008; Fiedler et al., 2009; Gumbel and Witt, 1998; Bailey et al., 2005; DeLand et al., 2003; Pe as well as sophisticated models ~~(Berger and Zahn, 2002; Berger and von Zahn, 2007)~~(e.g., Berger and Zahn, 2002; Berger and von Zahn, 2 A good review on our knowledge about PMCs up until 2006 was compiled by Rapp and Thomas (2006). A more recent review, including a comparison with mesospheric clouds on Mars, was conducted by Määttänen et al. (2013).

PMCs are being discussed as potential early indicators of global climate change in the middle atmosphere (Thomas et al., 1989; von Zahn, 2003) because they are very sensitive to temperature and water vapour concentration. Since enhanced CO_2 amounts (see, e.g., Yue et al., 2015) ~~would~~ are expected to lead to an eventual cooler upper mesosphere/lower thermosphere, and higher CH_4 amounts ~~may lead~~ to enhanced H_2O near the mesopause (Roble and Dickinson, 1989; Nedoluha et al., 2009; Garcia et al., 2015), they ~~could~~ may both lead to an increase of PMC occurrence, which might be interpreted as an effect of climate change in the ~~upper~~ middle atmosphere. There is not, however, a consensus in the scientific community about this aspect (von Zahn, 2003; Thomas, 2003). The recent study of SBUV (Solar Backscatter Ultraviolet) data from 1979 through 2013 by DeLand and Thomas (2015) has shown, in addition to the clear solar cycle signal, a good correlation with stratospheric ozone variations. Also, they have found that PMC ice water content in bright clouds increased rapidly from 1979 through the late 1990s and has been approximately constant from the late 1990s through 2013.

~~Hervig and Stevens (2014) calculated SBUV~~ Similar results were found by Hervig and Stevens (2014) by using SBUV data and a different method for calculating the ice water content (IWC)~~values using a different method to DeLand and Thomas (2015) and compared their results with SOFIE data . They~~. These authors also compared SBUV and SOFIE data and found good agreement in average IWC if an appropriate threshold was applied to the SOFIE data set ~~,~~ and consistent day-to-day and year-to-year variations between both data sets were used.

Russell et al. (2014) looked at trends in the northern mid-latitude noctilucent cloud occurrences using satellite data and model simulations and found a significant increase in the PMC occurrences at mid-latitudes from 2002 to 2011. This result differs somewhat from the insignificant trend found by DeLand and Thomas (2015) for a similar period but at higher latitudes.

Berger and Lübken (2015) analysed trends in mesospheric ice layers in the high latitude Northern Hemisphere for the 1961–2013 period with model simulations. They reported a generally good agreement between long-term PMC variations from the MIMAS model and the SBUV satellite observations. They found that the modelled trends in ice water content are latitudinally dependent with no clear trend at mid-latitudes (50°-60°N) but with a clear positive trend at high latitudes (74°-82°N) and also in extreme PMC events.

Thomas et al. (2015) have studied the solar-induced 27-day variations in polar mesospheric clouds using 15 seasons of ~~data taken by the SOFIE instrument~~ SOFIE data and suggested that the ~~changes~~ 27-day variations in the PMCs are due to 27-day variations of vertical winds.

As described above, a large fraction of the observations taken so far were performed by measuring the scattered light, in the visible or UV, of the solar radiation (in the case of instruments from space) or of the lidar light (in case of ground instruments). This technique usually observes the ice particles with radii larger than about 20 nm but lacks sensitivity for smaller particles (see, e.g., Rapp and Thomas, 2006). A different technique, however, has been ~~used~~ developed recently by the AIM ~~/SOFIE~~ (Aeronomy of Ice in the Mesosphere)~~/Solar Occultation for Ice Experiment)~~SOFIE instrument. These measurements have provided key characteristics of PMC's such as their frequency, mass density, particle shape, and size distribution, as well as their seasonal evolution and altitude dependence (see, e.g. Hervig et al., 2009a, b, 2011, 2013). Furthermore these satellite data have supplied critical information about the relationship of the ice density distribution with mesopause temperature and water vapour concentration (see, e.g. Hervig et al., 2009c; Russell et al., 2010; Hervig et al., 2015).

While PMCs emit thermal radiation, their infrared emissions are very difficult to observe due to the low ice particle volume density and the very cold polar summer mesopause temperatures. In fact, only three IR emission observations have been reported to date: that taken by CRISTA (Grossmann et al., 2006), by ~~the~~ SPIRIT (O'Neil et al., 2008) and those taken by ~~MIPAS~~ by the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) (López-Puertas et al., 2009). This technique has the advantages of being able to measure PMCs in dark conditions~~–thus~~ , thus providing a better spatial ~~coverage–~~ and temporal coverage, and of being sensitive to the total ice volume density, regardless of particle size, and hence ~~including~~ include the very small particles.

In ~~this previous paper (López-Puertas et al., 2009) we~~ a previous paper López-Puertas et al. (2009) reported the detection of infrared emissions from PMCs taken by the ~~Michelson Interferometer for Passive Atmospheric Sounding (MIPAS)~~ MIPAS instrument on board ENVISAT (Environmental Satellite), and provided further evidence of the water ice nature of the PMC particles. We also described the retrieval of the ice particle volume density and reported the analysis of the retrieved densities for 19-21 July 2005. In this paper we present the global ~~distributions~~ distribution (altitude, latitude and longitude) of ~~the~~ ice volume density measured by MIPAS for several days in each of the Northern (NH) and Southern Hemisphere (SH) seasons from 2005 until early 2012. We also analyse several aspects of the PMCs such as: (i) the mean altitude of the layer, the ice water content and ~~their~~ its hemispheric dependence; (ii) the correlation of ~~the~~ ice volume density with the frost point temperature and ~~with~~ the water vapour concentration; and (iii) the diurnal variation of the ice volume density. MIPAS, as well as SOFIE, has the advantage of measuring the whole content of ice particles (all sizes) in the mesosphere. Hence, a comparison with SOFIE observations, version 1.3, is also shown.

2 MIPAS Measurements and Ice Density Retrieval

MIPAS is a high-resolution limb sounder on board the ENVISAT satellite, launched on March 1, 2002. It took measurements until 8 April 2012, when the Envisat satellite failed. MIPAS measurements covered a wide spectral range with a high spectral

Table 1. Days of MIPAS observations of PMCs in the different modes.

Mode	Days
NLC	20050719 20050720 20050721 20070704 20070705 20070714 20070715 20080705 20080706
	20080707 20090105 20090106 20090107 20090705 20090706 20090707 20100104 20100105
	20100106 20100703 20100704 20100705 20110109 20110110 20110111 20110708 20110709
	20110710 20120104 20120105 20120106
MA	20050110 20050111 20050112 20050113 20051229 20051230 20060621 20060622 20061219
	20061220 20061221 20070622 20070725 20070804 20071219 20071229 20080108 20080116
	20080126 20080205 20080616 20080625 20080715 20080725 20080804 20081222 20090101
	20090111 20090205 20090615 20090625 20090715 20090725 20090801 20090811 20091215
	20091225 20100114 20100122 20100613 20100623 20100713 20100723 20100802 20100812
	20110119 20110618 20110628 20110719 20110801 20110807 20111225 20120114
UA	20050121 20050122 20050722 20051231 20060623 20061222 20070620 20070621 20071220
	20071230 20080109 20080117 20080127 20080206 20080622 20080716 20080726 20080805
	20081223 20090102 20090112 20090119 20090120 20090206 20090616 20090626 20090716
	20090726 20090802 20090812 20091220 20091230 20100109 20100117 20100618 20100628
	20100718 20100728 20100807 20100817 20101225 20110104 20110114 20110124 20110130
	20110131 20110201 20110623 20110703 20110714 20110727 20110804 20110812 20111220
	20111230 20120109 20120124

resolution, operating at 0.025 cm^{-1} from 2002-2004 and 0.0625 cm^{-1} from 2005 until the end of the mission. It also operated with a high sensitivity, allowing ~~measurement~~ measurements of most of the atmospheric emissions in the mid-infrared over a large altitude range (Fischer et al., 2008). MIPAS operated with a global latitude coverage (pole-to-pole) and performed measurements irrespective of day- or night-time. The instrument spent most of the time observing in the ~~6-68~~ 6–68 km altitude range (the nominal mode) but it also regularly observed at higher altitudes in its middle atmosphere (MA), noctilucent (NLC), and upper atmosphere (UA) modes (De Laurentis, 2005; Oelhaf, 2008).

In the MA mode, the spectra are available at limb tangent heights from about 20 km up to 102 km with a vertical sampling of 3 km. The UA mode ranges from about 42 km to 172 km, and has a vertical sampling of 3 km up to 102 km, and 5 km above this altitude. The NLC mode is a variant of the middle atmosphere mode specifically tailored for measuring the PMCs during the ~~summers~~ summer seasons (De Laurentis, 2005; Oelhaf, 2008). In this mode the spectra cover tangent heights from 39 km up to 78 km at 3-km steps; then from 78 km up to 87 km at 1.5 km steps, and from 87 km up to 102 km again in 3-km steps. ~~MIPAS~~ The horizontal field of view (FOV) of MIPAS is approximately 30 km. The days of PMC measurements in the different observation modes are listed in Table 1, and a summary of the distribution of these days ~~along~~ within the different seasons is shown in Table 2.

Table 2. Distribution of MIPAS days of observation of PMCs per season* .

	NLC		MA		UA		Total	
Year	NH	SH	NH	SH	NH	SH	NH	SH
2005	3	-	-	4	1	2	4	6
2006	-	-	2	2	1	1	3	3
2007	4	-	3	3	2	1	9	4
2008	3	-	5	6	4	6	12	12
2009	3	3	6	4	6	6	15	13
2010	3	3	6	4	6	4	15	11
2011	3	3	5	1	6	7	14	11
2012	-	3	-	2	-	4	-	9
Total	19	12	27	26	26	31	72	69

* For the NH season the days correspond to June-August of the listed year. For SH season the days correspond to December of the preceding year and January-February of the listed year.

The method used for the ~~inversion~~ retieval of PMC ice volume density from the MIPAS spectra has been described ~~in~~ by López-Puertas et al. (2009). A brief excerpt is included here. The spectra analysed in this work were all taken with the optimized spectral resolution of 0.0625 cm^{-1}. The ice volume density was retrieved from the radiance profiles obtained by integrating the spectra from ~~730 to 950~~770 to 920 cm^{-1}. The profiles were corrected for an offset variable in altitude, latitude and time. The noise equivalent spectral radiance in this spectral region is about 20 nW/(cm^2 sr cm^{-1}), and the corresponding noise in the integrated radiances of a single scan is $\sim$60 nW/(cm^2 sr).

The ice volume density was retrieved from the spectrally-integrated radiance profiles using a linearly constrained least squares fitting, where the Jacobians were calculated using the KOPRA radiative transfer algorithm (Stiller et al., 2002). The inversion was constrained by a Tikhonov-type scheme (Tikhonov, 1963) using a squared first-order differences matrix to obtain a reasonably smoothed vertical profile of volume densities. The ice refractive indices were taken from Toon et al. (1994).

In this analysis we have included the following improvements and updates with respect to López-Puertas et al. (2009): (i) The more recent version 5 (5.02/5.06) of MIPAS L1b spectra has been used (Perron et al., 2010; Raspollini et al., 2010); (ii) an updated version of the temperature is used for the retrieval of ice density (see below); (iii) the altitude registration of the L1b spectra has been improved by using the information from the retrieved temperature and LOS (line of sight) instead of the engineering information included in the L1b files (von Clarmann et al., 2003; García-Comas et al., 2012); (iv) the offset correction of the integrated radiance profiles was improved by taking into account its altitude and latitudinal variations; (v) the ice density profiles were retrieved only for ~~the~~ scans with converged pressure-temperature profiles (no latitude/longitude interpolation was done); and (vi) due to a mistake in the calculation of the volume of the particles distribution, the volume densities presented here are nearly double those previously reported ~~in~~ by López-Puertas et al. (2009).

The temperature and LOS required to retrieve the ice density have been ~~inverted~~ retrieved from the CO_2 emission near 15 μm, recorded in the same MIPAS band A as the PMC emission. Non-local thermodynamic equilibrium (non-LTE) emission was taken into account. The detailed description of the method and the characterization of the inverted temperature profiles are described ~~in~~ by García-Comas et al. (2012). The upgrades in the retrieval of the temperature used here (version vM21) and a validation of the results are reported by García-Comas et al. (2014). Briefly, these authors include an updated version of the calibrated L1b spectra in the 15 μm region (versions 5.02/5.06); the HITRAN 2008 database for CO_2 spectroscopic data; the use of a different climatology of atomic oxygen and carbon dioxide concentrations; the improvement of several aspects of the retrieval set-up (temperature gradient along the line of sight, offset regularization, and the spectral apodization); and some minor corrections to the CO_2 non-LTE modelling as detailed by Funke et al. (2012). This version of MIPAS temperatures ~~correct~~ corrects the main systematic errors of the previous version and ~~have~~show, in general, a remarkable agreement with the measurements taken by ACE-FTS (Atmospheric Chemistry Experiment), MLS, OSIRIS, SABER, SOFIE and the Rayleigh lidars at Mauna Loa and Table Mountain (García-Comas et al., 2014). In the region of interest here, however, there are still significant differences, with MIPAS polar summer mesopause temperatures differing by 5-10 K from the other instruments, being warmer than SABER, MLS and OSIRIS and colder than ACE-FTS and SOFIE.

Since MIPAS measures PMCs in IR emission, knowledge of the temperature of the ice particles is crucial. There is still disagreement about the temperature of the particles, particularly ~~if~~ about whether they are warmer or colder than the ambient atmosphere. Using SOFIE measurements, Hervig and Gordley (2010) have found that the ice particles are about 5-20 K cooler than the ambient ~~temperature~~atmosphere. They suggested, however, that the V1.022 SOFIE CO_2 temperatures they used might have a warm bias of 5-10 K near the polar summer mesopause. Petelina and Zasetsky (2009), using infrared solar occultation measurements from the ~~Atmospheric Chemistry Experiment (ACE)~~ ACE instrument, also found that the ice particles are cooler than the ambient temperature. They argue that this might be caused by inhomogeneities in the temperature along the instrument field of view, with the ice particles sensing only the cold(er) parcels, where they are present, while the gas temperature is representative of the whole (warmer) air mass along the FOV. Physical considerations, however, would suggest that the particles are warmer than the surrounding gas because they will be heated ~~up~~ by absorption of radiation (Rapp and Thomas, 2006; Espy and Jutt, 2002). For example, for a particle distribution with a mean radius between 30 and 50 nm and an accommodation coefficient of 0.5, Rapp and Thomas (2006) found that the ice particles are warmer than the ambient gas ~~in~~ by about 1 K at 80 km and 2 K at 90 km. Analogously, the model calculation of Espy and Jutt (2002), when applied to a normal distribution of ice particle size with a mean radius varying from 40 nm at 80 km to 15 nm at 90 km, gives a temperature increase of 0.7 K at 80 km and 2.7 K at 90 km. As suggested by these models, we applied a temperature correction of the emitting particles that varies linearly from 1 K at 80 km to 2 K at 90 km. In principle, MIPAS measurements should also be affected by the problem pointed out by Petelina and Zasetsky (2009). However, our observations do not support that finding. If we assume that ~~the~~ ice particles are cooler than the retrieved gas temperature we ~~would~~ obtain very high (and unreasonable) concentrations of ice particles (see ~~See.~~Section 3).

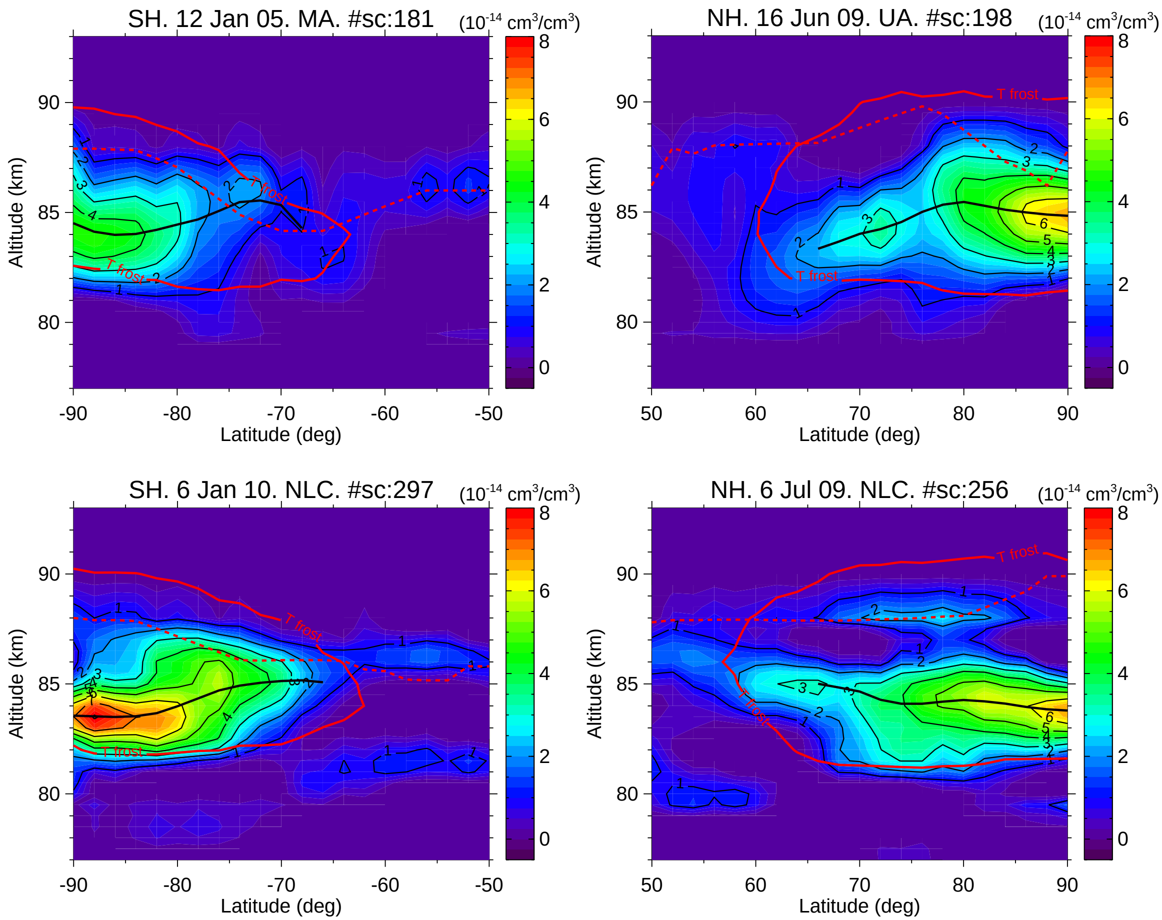

Figure 1. Zonal mean ~~of~~ ice volume density ~~for~~ during four days, two in the ~~Southern Hemisphere~~ SH and two in the ~~Northern Hemisphere~~ NH as measured by MIPAS in different observation modes (MA, UA and NLC, see labels). The solid red lines indicate the frost point temperature~~(thick line) and frost point temperature plus 3 K (thinner line)~~. The red dashed line is the mesopause as ~~measured by~~ derived from MIPAS. The black solid line is an estimated mean altitude (weighted with the ice density to power of 4) of the PMC layer. The ~~estimated~~ number of measured profiles, '#sc', is also shown. The noise error of the mean volume density plotted here, estimated by the standard error of the mean, is about 0.3×10^{-14} cm^3/cm^3.

The vertical resolution of the ice density ~~vertical~~ profiles, in terms of the half-width of the columns of the averaging kernel matrix, depends on the observational mode. For the over-sampled NLC mode, it varies from ∼2.5 km at 81–82 km to ∼3 km at 86 km, and to 3.5–4 km at 90 km. For the middle and upper atmosphere modes (MA and UA~~),~~, or together MUA) it is coarser, with values ranging from 3.5 to 4 km. The error in the absolute pointing is about 200 m.

The averaging kernels shown in López-Puertas et al. (2009) are for the NLC mode measurements that have a sampling step (i.e. tangent altitude increment) of 1.5 km. For the MA and UA modes the averaging kernels are wider because of the coarser sampling of 3 km.

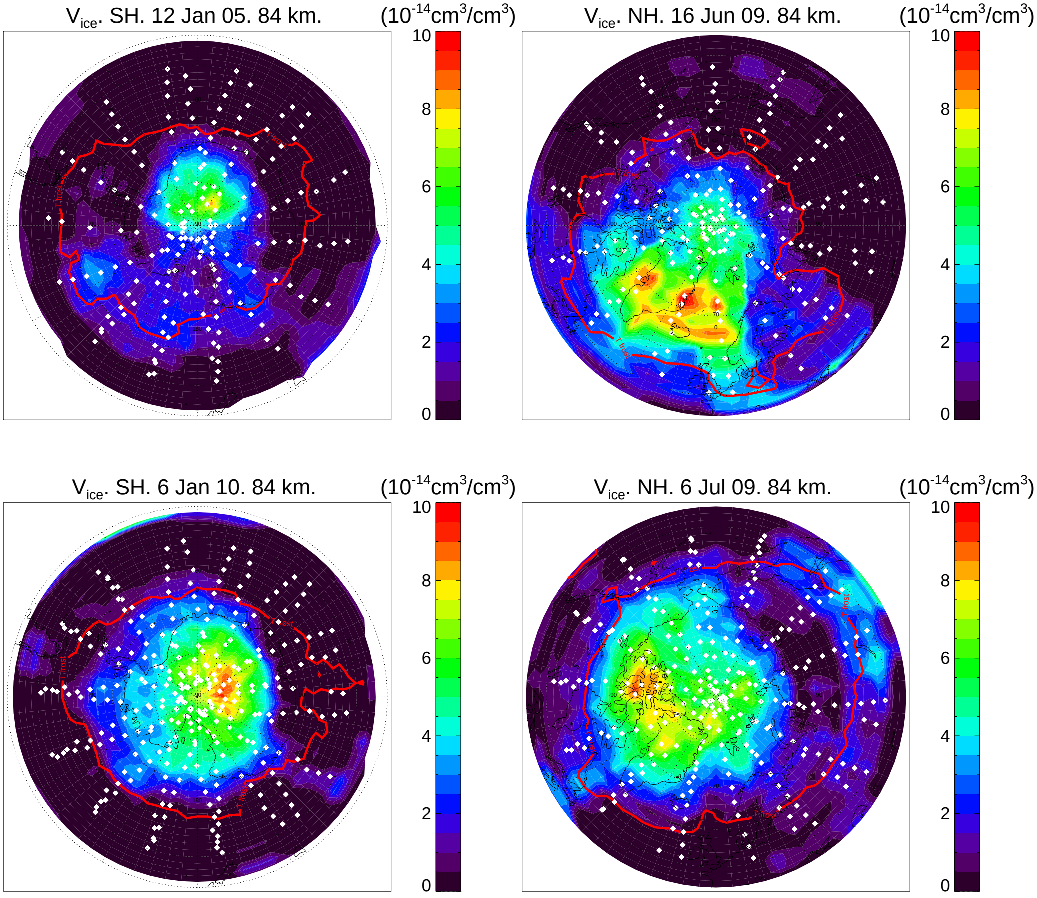

Figure 2. ~~Latitude/longitude distribution~~ Polar maps of ice volume density at 84 km for the same days as in Fig. 1. The solid red lines indicate the frost point temperature. The diamonds represent the geolocations of the MIPAS measurements.

The random single profile error of the retrieved ice volume density is about 60%, including both the instrumental noise and the temperature noise error. The systematic error is about 25-30% and is mainly due to the temperature error in the summer mesopause region (García-Comas et al., 2014). More details of the retrieval of the ice volume density can be found ~~in~~ by López-Puertas et al. (2009).

3 Ice volume density distributions

Figure 1 shows typical daily zonal means of ice volume density retrieved from MIPAS for four days in SH and NH summer seasons in different observation modes. The thick solid red line is the frost point temperature contour, and the red ~~dash~~ dashed line is the mesopause altitude. The solid black line is an estimated altitude of the PMC layer (i.e., the altitude weighted with the 4th power of the density). Note that MIPAS ~~measurements are~~ is sensitive to all ice particles, including those with small radius. Noise errors in these plots, estimated by the standard error of the mean, are about 0.3×10^{-14} cm^3/cm^3. The PMCs are generally located at regions colder than the frost point temperature for almost all conditions. Note also the large variability in latitude and altitude of the ice density, particularly on 6 July 2009 (bottom right panel) where the PMCs reach latitudes as low as 60°N. Weak PMCs located at latitudes equatorward of about 60° and outside of the frost point temperature contour are likely false detections caused by instrumental (most likely offset) errors.

Anomalous low-altitude detection of weak PMCs (i.e., below ∼80 km and outside of the T_{frost} region) could be due to the limb nature of the measurements. Emission from isolated clouds located in the LOS far away from the tangent point ~~, and hence at higher altitudes, can be measured and thus attributed to these lower tangent heights~~ is reported at abnormally low tangent altitudes (see, e.g., Hervig et al. (2009b), their Fig. 11). Also, the FOV can affect the height of the lower and upper boundaries of the layer. Hervig et al. (2009b) have shown that the bottom and top altitudes as measured by SOFIE, which has a FOV of 1.5 km, can be smeared out in about 1-1.5 km. These two effects, along with the temperature error, can explain why MIPAS observes occasional ice volume concentration at the bottom of the layer at temperatures warmer than the frost point temperature~~, see bottom-left panel of Fig. 1 around 70°N.~~ .

The latitude/longitude distributions of ice volume density at 84 km for corresponding days are shown in Figure 2. As shown before for the zonal means, the PMC layer is almost always confined to regions with temperature below the frost point temperature. The variability of the latitude/longitude spread is also large. Although the PMCs are generally ~~centred~~ around the pole, they are sometimes far away (see top right panel in Fig. 2) ~~.~~ and their distribution could be controlled by 2-day and/or 5-day planetary waves (Merkel et al., 2003; Merkel et al., 2009; Nielsen et al., 2010). In particular the distributions of days 12 Jan 2005 (top/left), 16 Jan 2009 (top/right), and 6 Jul 2009 (bottom/right) seems to be affected by wavenumber-1 planetary waves.

Figure 3 shows the zonal mean ~~distributions of~~ ice volume density averaged for all measured days in the Southern (left) and Northern (right) hemispheres for the NLC (top panels) and for the MA+UA (MUA) (lower panels) MIPAS modes (see Table 2). These distributions are analysed in detail later, but we describe the main features briefly here: 1) PMCs are confined to altitudes between around 81 km and 89 km with maximum concentrations around 84 km; 2) PMCs are confined to latitudes poleward of about 60°, with increasing concentration towards the poles; 3) From these figures it is evident that the ice particles occur in higher concentrations in the NH, and that the ice layer is located at slightly lower altitudes in the ~~Northern Hemisphere~~NH. These figures also show an apparent higher concentration for the measurements taken in the NLC mode than in the MUA mode. The NLC mode has a better vertical resolution, which leads to sharper temperature profiles (see García-Comas et al., 2014) and hence to sharper ice particle profiles and larger ice particle densities. However, not all the differences between the NLC and the MUA modes can be attributed to the better vertical resolution of the former because ~~they were taken in the summer~~ observations in different modes occurred on different days, with ~~those of~~ observations in the NLC mode ~~closer~~ generally occurring closer in time to the peak of the ~~PMCs season~~ PMC season than observations in the other modes.

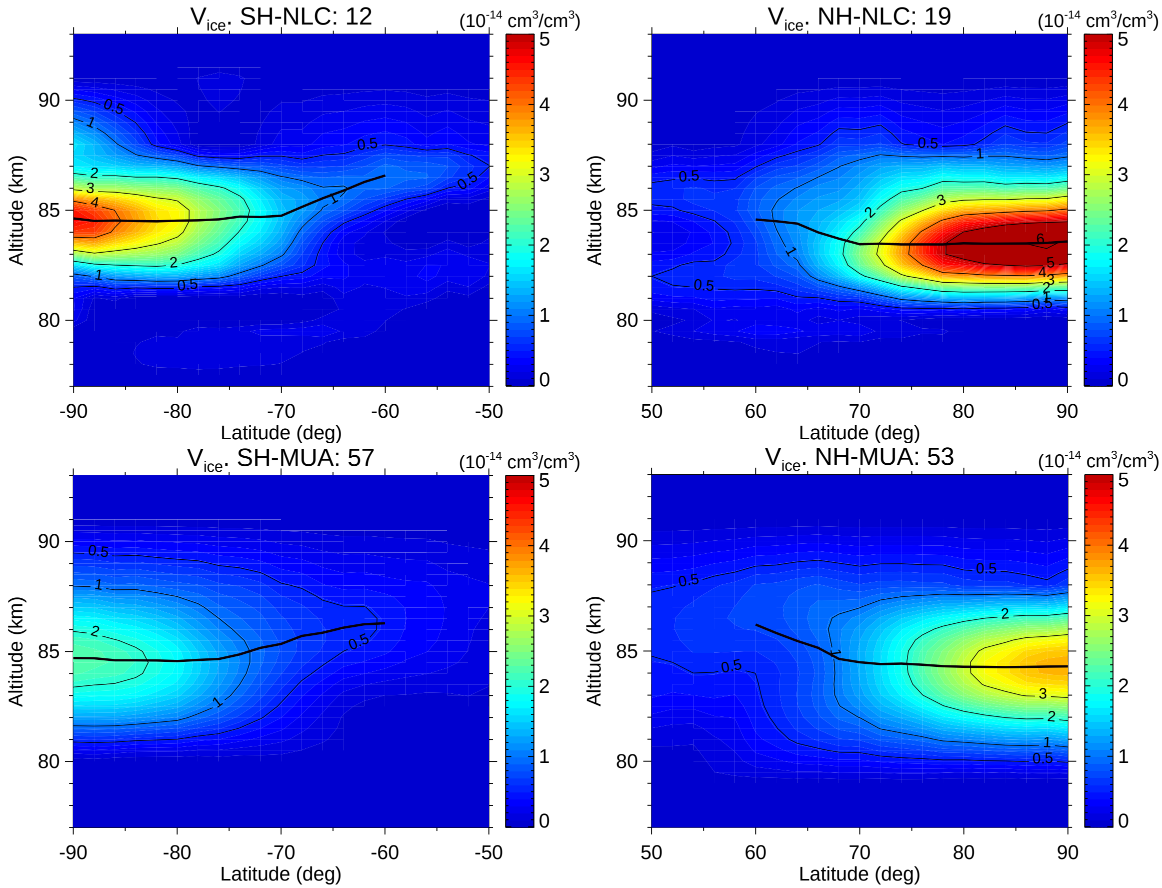

Figure 3. Zonal mean ~~distributions of~~ ice volume density for all measured days in the Southern (left panels) and Northern (right panels) hemispheres for the NLC (top panels) and ~~for~~ the ~~MA+UA (~~MUA ~~)~~ (lower panels) MIPAS modes (see Table 2). The solid black line is an estimated mean altitude (weighted with the ice volume density to power of 4) of the PMC layer. The ~~estimated~~ noise error of the volume density plotted here, estimated by the standard error of the mean, is about 0.08×10^{-14} cm^3/cm^3 and 0.04×10^{-14} cm^3/cm^3 for the NLC and MUA measurements, respectively.

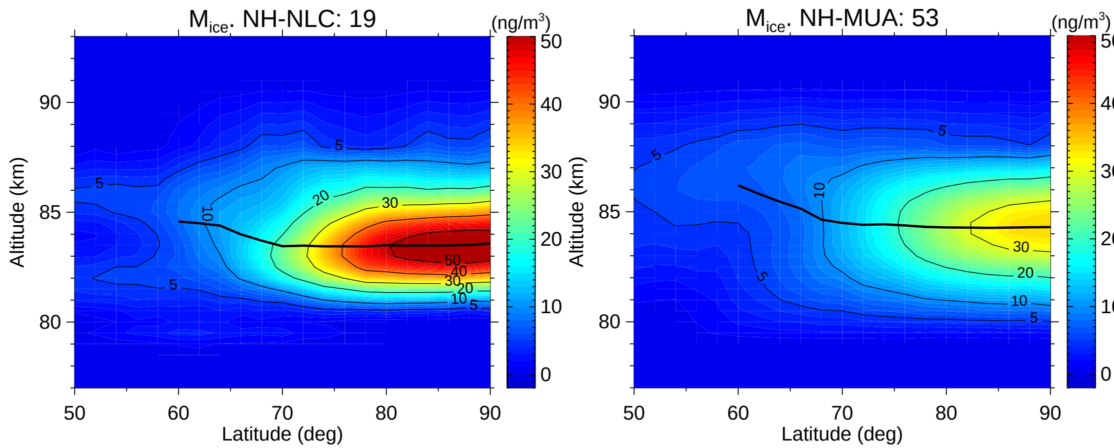

Figure 4. Zonal ~~distribution of~~ mean ice mass density for ~~all measurements (see Table 2) in~~ the ~~Southern~~ NLC (left panel) and ~~Northern~~ for the MA+UA (MUA) (right panel) ~~hemispheres~~MIPAS modes (see Table 2) for the Northern Hemisphere. The solid black line is an estimated mean altitude (weighted with the ice volume density to the 4th power) of the PMC layer. The ~~estimated~~ noise error of the mass density plotted here, estimated by the standard error of the mean, is about 0.8 ng/m^3 and 0.4 ng/m^3 for the NLC and MUA measurements, respectively.

3.1 Top altitude

Figure 3 shows that MIPAS observes significant abundances of ice up to about 88-89 km. A similar behaviour has been found in the SOFIE ~~IR extinction~~ measurements (Hervig et al., 2009b). This altitude is about 3-4 km higher than the average maximum altitude of 84.4 km measured by the lidars ~~. Hervig et al. (2009b) have shown for SOFIE that~~ (Hervig et al., 2009b). These authors have shown that, for SOFIE measurements, the vertical smoothing ~~of the~~ due to limb view geometry can cause an extension of the uppermost altitude of about 2/3 of the vertical resolution, i.e., 1.5-2 km for the MIPAS NLC observation mode. This, however, cannot fully explain that difference. The detection of PMCs by SOFIE and MIPAS at altitudes higher than the lidars is most likely due to the different sensitivities of the two techniques. While the lidar signal varies with r^6, the MIPAS (in IR emission) and SOFIE (in IR extinction) signals change with the total ice volume density. As the ice particle size decreases towards higher altitudes (Baumgarten and Fiedler, 2008; Hervig et al., 2009b; Pérot et al., 2010), MIPAS and SOFIE are then more sensitive than ~~the lidars to higher altitude PMCs.~~ lidars to clouds at higher altitudes. The highest altitude of PMCs derived from MIPAS NLC mode measurements is ~~about 89 km for the NH near~~ largely variable, as can be seen in the typical examples shown in Fig. 1. At 70°~~-~~N, it is about 88.5 km (Fig. 3b). ~~This~~ Its variability depends on latitude and takes 1-σ values from 2.7 km near 70°N to 1.6 km near the pole. The uppermost altitude derived here is slightly higher than that obtained by SOFIE of 86.8±2.1 km but agrees very well with the CARMA model prediction of 88.5±0.5 km (Hervig et al., 2009b, 2013). Thus, as pointed out by López-Puertas et al. (2009) and Hervig et al. (2009b), MIPAS and SOFIE results are consistent with the current understanding of temperatures and water vapour distributions at these altitudes (Lübken, 1999), and the associated ice particles at high altitudes are likely to be related to polar mesosphere summer echoes (e.g., Rapp and Lübken, 2004). This has also been evidenced more recently by the concurrent observations from the ALOMAR wind (ALWIN) radar and ~~measurements from SOFIE~~ SOFIE measurements (Hervig et al., 2011).

3.2 Bottom altitude

The bottom altitude of the PMC layers measured by the lidar measurements ~~in the Northern Hemisphere (at a latitude close to 70°)~~ at 69° N was found at 82.2 km. SOFIE obtained a slightly lower altitude of 81.6 ± 1.6 km, which is within ~~their mutual~~ the lidar and SOFIE combined standard deviations (Hervig et al., 2009b). For the NH and similar latitudes MIPAS in its NLC mode (see Fig. 3b) ~~gave~~ measured an altitude of ~~$\sim$81~~80.9 ± 1.2 km, slightly lower than SOFIE. ~~Note, however, that we have not excluded any PMCs here, whereas in SOFIE those found~~ In SOFIE measurements the PMCs with a peak extinction altitude below 79 km were excluded ~~.~~ (Hervig et al., 2009b). Applying a similar threshold to MIPAS data, however, does not change significantly the bottom altitude.

The bottom altitude also changes rapidly with latitude from 65 to 75° (Fig. 3b); hence a difference of a few degrees in latitude might ~~also~~ induce a significant change in ~~the~~ bottom altitude. Thus, in summary, we can conclude that they are in good agreement. It is also worth noting that the bottom altitude derived from the MUA modes, which have a coarser vertical sampling (3 km), is lower by about 1 km (80.0 ± 1.8 km) than that derived from the NLC mode (Fig. 3d). This is very likely due to the limb sounding geometry, as discussed above. The bottom altitude in the Southern Hemisphere is found to be located at about 1 km higher than in the NH (see Figs. 3a and 3c).

3.3 ~~Concentration~~Ice mass density

As discussed above, MIPAS and SOFIE/AIM are the only two instruments whose ice concentration data are comparable because they both measure the total ice volume density, irrespective of the ice crystal size. Although it is not the aim of this paper to carry out a detailed comparison or validation, we include some comparisons here. First, we compare the maximum (peak) values of the PMC layer, and then we compare mean profiles for several seasons.

SOFIE measured ice mass densities at the altitude of maximum concentration, z_{max}, for the 2007 NH season that range from 0.1 to 80 ng m^{-3}, with a mean value of 14.2 ng m^{-3} (Fig. 14a and Table 5 in Hervig et al., 2009b). These SOFIE measurements ~~were taken~~ occurred at latitudes between $\sim$66°N ~~,~~ in the early season, to ~~74°N ,~~ $\sim$68°N at mid-summer, and at $\sim$74°N towards the end of the season. MIPAS measurements for the 2005-2012 period at ~~those latitudes~~ latitudes of $\pm$2 degrees of SOFIE latitudes have mean values of just above 20 ng m^{-3} for the NLC mode and of $\sim$12 ng m^{-3} (with a broader peak) for the MUA modes (see Figs. 4~~b and 4d~~a and 4b, respectively), which agree well with SOFIE data for the 2007 NH season. As a result, the conclusion drawn by Hervig et al. (2009b) from SOFIE applies to the comparison of MIPAS with other measurements and models. That is, MIPAS ice mass densities are also significantly smaller than the lidar measurements taken at ALOMAR (69°N), that ~~present~~ show an average value of 47.4 ng m^{-3}, and the lidar results reported by von Cossart et al. (1999) ~~, with ice mass~~ that show ice mass densities ranging from 36 to 102 ng m^{-3}. ~~MIPAS, as well as SOFIE, also measure thinner ice clouds than other IR instruments measuring the PMCs from space, e.g., HALOE (Hervig et al., 2003). Those~~ These differences can be explained, at least partially, by the larger sensitivity of MIPAS (and SOFIE) to the smaller particles (i.e., being sensitive to smaller amounts leads to lower mean concentrations). Another reason causing the differences could be, at least for the lidar observations, the averaging over the relatively larger atmospheric volumes sampled by MIPAS (and SOFIE). Furthermore, MIPAS, as well as SOFIE, is also able to detect thinner ice clouds than other IR instruments measuring the PMCs from space, e.g., HALOE (Hervig et al., 2003).

Although a detailed comparison ~~with~~ between MIPAS data and the Community Aerosol and Radiation Model for Atmospheres (CARMA) (Rapp and Thomas, 2006) has not been performed, the results reported ~~in~~ by Hervig et al. (2009b) suggest that MIPAS and CARMA are in agreement, at least for the 65-75° ~~latitudes~~latitude range. A thorough comparison with the CARMA model and MIPAS data, including higher latitude regions, ~~is necessary~~ would be very useful but is beyond the scope of this paper.

Figure 5 shows a more detailed comparison between MIPAS and SOFIE ice mass densities, M_{ice}, for the coincident days and latitudes (within ±2 degrees of SOFIE mean latitude) in the NH season for the years with more coincident data: 2008-2011. The variation of ice mass density with local time is important (see, e.g. Stevens et al., 2010, and Section 6 below). Since most of SOFIE measurements were taken at local times between 23 and 24 hours in the NH, we have taken only the MIPAS measurements taken at 10 pm. The comparison is based on the mean profiles for all days of measurements for each season/year for each instrument because of the large variability of ~~the ice concentration~~ MIPAS ice mass density (see, e.g., Fig. 1~~in the case of MIPAS~~). The solid black lines represent the mean of ~~the~~ SOFIE measurements and the solid red line the ~~MIPAS ice mean~~ mean MIPAS ice mass density. ~~As discussed before, these figures also show that, in general, there is a very~~ These figures show a quite good agreement between the two instruments ~~in~~ for 2008 and 2010. For 2009 and 2011, the peak values ~~of the layer (the 2009 NH season is an exception).However,~~ are also in good agreement but the vertical distributions are rather different. The average over the four years (bottom panel in Fig. 1) reflects that above about 85 km, MIPAS values are ~~nearly double~~ generally larger than those measured by SOFIE~~(except in 2011). This MIPAS data feature, of large ice densities at high altitudes, can also be seen in the zonal mean distributions (Fig. 4, bottom right panel): the high values above 84 km extend from the North pole to fairly low latitudes, near 70°N or even lower. The same behaviour is~~ , and smaller below that altitude. A similar behaviour is also seen in the ~~MIPAS data for the SH (see left panels in Fig. 3~~SH (not shown). This seems to be a clear characteristic of MIPAS measurements but absent in SOFIE. We do not have a plausible explanation for this difference. ~~In this region the ice particles are the smallest and it could be that MIPAS is more sensitive than SOFIE to those particles. Another~~ A possible reason could be a negative bias of MIPAS temperature at those altitudes/latitudes which would result in a higher ice mass density, but such a bias present only in ~~those~~ these localized regions seems unlikely. Another reason could be that the averaging kernels are wider in the PMC upper region (see Fig. 5 in López-Puertas et al., 2009). Note also that this vertical zonal distribution of the ice density in MIPAS is consistent with the water vapour (gas phase) latitudinal distribution measured by MIPAS (see Fig. 10), since the depletion of water vapour near 60-70°N occurs at higher altitudes than near the North pole.

The ~~integrated water column, which is written for both instruments~~IWC of both instruments, which are reported in Fig. 5, ~~is generally larger in~~ are in very good agreement. In the case of MIPAS ~~, which essentially reflects the higher values in~~ the ~~ice mass densities of MIPAS at altitudes above ∼84~~values are only slightly larger. The mean IWC of the coincident days for the 2008-2011 period in the NH is 50 ~~km discussed above.~~ μg m^{-2} for SOFIE and 51 μg m^{-2} for MIPAS pm measurements (see bottom panel in Fig. 1). It is noteworthy, ~~however, that~~ that the NH MIPAS observations are in slightly better agreement than SOFIE with model calculations carried out by Hervig et al. (2009c) (see their Fig. 5d). The mean IWC values for the 2008-2011 period for the SH are 24 $\mu\mathrm{g\,m^{-2}}$ for SOFIE and 27 $\mu\mathrm{g\,m^{-2}}$ for MIPAS measurements including both, 10 am and 10 pm data (SOFIE measures between 1 am and 3 am in the SH).

3.4 Q_{ice}

We also show in Fig. 6 the zonal mean of ice volume density (similar to Fig. 3) but in units of ppmv, Q_{ice}; i.e., the partial concentration of water vapour if all the ice were to sublimate. For that conversion we used the pressure and temperature measured by MIPAS (García-Comas et al., 2014). As expected ~~they show~~ Fig. 6 shows the same general behaviour as discussed above for the volume density ~~. We note in general~~ (Fig. 3). In NLC mode, which contains observations during the mid-season period, we note that the amount of water vapour in the form of ice ranges from 1 to 3 ppmv ~~, although close to the North pole during the high season period (NLC) it can be as much as 6 ppmv . We think this is an important result since, to our knowledge, the water ice content has not been measured at latitudes higher than ∼75°.~~ at latitudes equatorward of 70-75°, and reaches values up to 5–6 ppmv close to the poles. Again these values are in good agreement with SOFIE measurements. Hervig et al. (2015) have shown time series of SOFIE Q_{ice} at the altitude of peak extinction for the 2007-2013 period for the Northern and Southern hemispheres ~~.~~ (their Fig. 2). The NH mid-summer values range from 2 to 3.3 ppmv, which compare well with those shown in the right panels of Figure 6 at the latitudes of SOFIE measurements, ∼66°-74°N. Similarly, for the SH they show values spanning from 1.5 to 2.5 ppmv, also in good agreement with those of MIPAS shown in the left ~~panel~~ panels of Figure 6. This point is discussed further in ~~Sec.~~ Section 5.

4 Altitude and column density of the PMCs

Figure 7 shows the mean altitude of the PMC layer for the SH (left) and the NH (right) seasons for all measurements. The altitude of the PMC layer has been calculated as the altitude weighted with the 4th power of the volume ice density. We observe that the mean altitude in the NH for the NLC mode is located around 83.5-84 km, while in the SH it is about 1 km higher (84.5-85 km). The fact that the mean altitude is higher (in ∼1 km) for the MA+UA modes is attributed to the coarser sampling and to the broader vertical resolution in the retrieved temperature from these modes. The different temporal sampling of the NLC and MUA modes might also have an effect though. Hervig et al. (2013) have shown that PMCs are located higher at the beginning and the end of the season, and lower in the middle of the season. This coincides with our results since the ~~NLC~~ NLC-mode measurements are usually taken in the middle of the PMC season while MUA are taken earlier and later in the season. We should also note from Fig. 7 that PMCs tend to be located at lower altitudes near the poles, and at higher altitudes towards mid-latitudes (both in NH and SH but more clearly in the latter).

Hervig et al. (2009b, 2013) reported an average value for the mean altitude of the PMC layer of 83.5 km for NH and 84.7 km for SH in SOFIE measurements, and of 83.3 km for the NH from ~~the lidar measurements~~concurrent lidar ALOMAR measurements in northern Norway (69°N). The MIPAS mean ~~value~~ values for the mean altitude obtained here for the NH is very close to both measurements. Also, it is very much in line with SOFIE, locating the maximum of the layer about 1 km higher in the SH than in the NH.

Russell et al. (2010) carried out a multi-year analysis of the ~~OSIRIS/Odin, SNOE, AIM, and~~ Odin/OSIRIS, SNOE/UVS, AIM/SOFIE, and TIMED/SABER ~~/TIMED~~data sets in the polar regions north (south) of 65°N (°S) and found that the mean PMC height is located 3.5 km±0.5 km below the mean mesopause height. In the case of SOFIE measurements, however, this difference is significantly smaller, ~~in~~ by ∼1 km, for most of the season, except around the middle of the season (Russell et al., 2010). We also looked at the difference between the mean PMC height and the mean mesopause height in the MIPAS PMC measurements (see Fig. 7). In general MIPAS observations are more in line with SOFIE observations than with the other instruments. For the case of NLC and MUA MIPAS observation modes in the NH near 70°N, the difference is about 2.5 km, smaller than the mean value of 3.5 km obtained for all instruments and closer to the SOFIE value obtained by Russell et al. (2010). It is worth noting that this altitude difference increases towards the North pole, more clearly in the case of the NLC mode (taken around the middle of the season) and reaching about 4 km. In the Southern Hemisphere the difference between the mesopause and mean ice layer altitudes is even smaller than for NH, with values ranging between 2 and 2.8 km; again in better agreement with SOFIE than with the other instruments.

Figure 8 shows the latitudinal variation of the ice water content of the PMC layer for the SH (left) and the NH (right) seasons for all measurements. The figure shows clearly that PMCs are more abundant in the NH than in the SH, extending to lower latitudes in the NH. The main reason for this is the warmer polar upper mesosphere in the SH than in the NH, about a 10 K difference as measured by MIPAS (García-Comas et al., 2014). ~~As shown in the zonal fields (Figs. 1 and 3), the ice column volume increases toward~~ Figure 8 is consistent with the zonal mean ice volume density shown in Figure 3, which shows that ice mass density increases towards the poles. ~~The large variability~~ Large variability from season to season is also clearly visible ~~, which~~which, in the case of MIPAS, is attributable not only to the yearly changes but also to the daily variation because of the infrequent temporal sampling of MIPAS. The ice column is large for the NLC mode (not shown), in ~~consonance~~ correspondence with the zonal mean fields shown in Fig. 3. As mentioned before, this is probably due to the fact that the NLC measurements are taken around the middle of the season (see Table 1). The NH/SH ratio of the ice water content varies with latitude (not shown), ranging from about a factor of 2 near 60° to 1.4 near the poles, with a value of 1.7 near 70°, which is din very good agreement with the factor of 65% reported by Hervig et al. (2013) from SOFIE measurements.

5 ~~Correlation of ice volume density with the frost point temperature~~

Figure 9 shows the correlation between the ice water content and the altitude of the lower branch of the frost point temperature contour (see Fig. 1) for the data taken in the ~~different~~ NLC and MUA observation modes in the SH and NH PMCs seasons. The correlation is significant and shows that the PMC layers ~~are denser and wider~~ contain more ice when the frost point temperature occurs at lower altitudes. ~~Furthermore, the~~ We have done the analysis for each hemisphere and mode separately (not shown) and found a very similar correlation for all cases except for the NLC mode in the NH. The reason for this exception could be the smaller sample size of this case or that the altitude range of the frost temperature in NH for this mode is very small and hardly reach altitudes higher than 82 km.

We have also found that the ice volume density is also ~~anticorrelated~~ anti-correlated with the mean altitude of the PMC layer (not shown), that is, that the denser PMC layers are located at lower altitudes and the thinner ones at higher altitudes~~, which~~. This is consistent with the behaviours shown in Figs. 7 and 8 where the denser layers are usually found near the poles and at lower mean altitudes.

5 Correlation of ice volume density with H_2O concentration

Hervig et al. (2015) suggest that, as opposed to ~~other satellite instruments' like~~ HALOE and MLS water vapour measurements, the ~~vertical resolutions from SOFIE are~~ SOFIE vertical resolution is well suited for the study of correlations between water ice and water vapour. This is also the case for MIPAS. Given the good latitude coverage of MIPAS (covering the whole polar region) and the fact that the instrument is able to measure the ice water content and the water vapour concentration simultaneously, we have looked at the zonal mean and latitudinal/longitudinal distribution of both quantities in the polar summer region. ~~Fig. 10 shows a typical case (21 July 2005) of the zonal mean cross sections of the ice volume density (left) and the concentration anomaly (right). Also Fig. 11 shows the latitude/longitude distributions for the vmr at 90 km (top) and 80 km (bottom), and for the ice volume density at 83 km (middle).~~

The water vapour concentrations used here have been derived from MIPAS high resolution spectra in the region around 6.3 μm. We used version v5r_h2o_M22 retrievals. The retrieval baseline is an extension to the lower mesosphere of the set-up described by Milz et al. (2005) with the updates described ~~in~~ by von Clarmann et al. (2009). The main difference of this extension is the inclusion of non-LTE emission from the H_2O vibrational levels, which are important above around 50 km (Stiller et al., 2012). Additional microwindows, covering stronger H_2O v_2 spectral lines, are also included in order to increase the sensitivity in the upper mesosphere (García-Comas et al., 2012).

Figure 10 shows a typical case (21 July 2005) of the zonal mean cross sections of the ice volume density (left) and the H_2O concentration anomaly (right). We can clearly distinguish three distinct altitude zones near the polar region~~. The~~: region centred near the peak of the PMC layer (~83 km), where the ice volume density is largest; a few kilometers below, a hydrated region where H_2O presents a relative maximum at latitudes northward of 70°N, more markedly seen in the bottom panel of Fig. 11; and a dehydrated region above the ice layer, around ~ 90 km, where H_2O exhibits a clear relative minimum (see top panel of Fig. 11). This global behaviour fits very well with the current picture we have about the PMCs, where sequestration of H_2O in the gas phase to form ice leads to a drier atmosphere just above the ice layer, and where the sedimentation of ice and its subsequent sublimation enhances the H_2O gas phase abundance at ~80 km. The MIPAS water vapor layered structure gets sharper towards the pole. That is in contrast to findings from von Zahn and Berger (2003), who located the maximum at about 70°N.

These features are more clearly observed in the latitude/longitude maps (Fig. 11), where the dry region at 90 km (top), the water ice layer at 83 km (middle) and the wetter H_2O region at 80 km (bottom) ~~exhibit a very good latitude/longitude~~

~~spatial correlation~~are all well confined in the polar region. This topic has been recently studied quantitatively by Hervig et al. (2015) ~~by~~ using SOFIE observation of ice content, water vapour and temperature at latitudes near 70°. They found that, in both hemispheres, the altitude of the peak of the dehydration regions is $\sim$1.8 km above the height of peak ice mass density, and the altitude of the peak of the hydration region is $\sim$0.3 km above the observed bottom ~~altitude~~ of the ice layer. Although no general conclusion can be drawn from the single day of MIPAS data shown here, ~~the location~~ we have found different results. In MIPAS the peak altitude of the hydration region ~~agrees well with SOFIE observations. The dehydration region , however, is found in MIPAS~~ is about 1 km below the bottom altitude of the PMC layer, and the dehydration region is found to be significantly (about 2-3 km) higher than in SOFIE (see right panel in Fig. 10).

Hervig et al. (2015) also found that the column abundance of H_2O in the gas phase is roughly equal in the dehydration and hydration ~~layers~~regions, but less than that contained in the ice layer. ~~MIPAS data also shows a similar feature, being more pronounced at latitudeshigher than those sounded by SOFIE. The right panel of Fig.~~ From the day of MIPAS data analyzed here we have obtained that the excess of H_2O gas-phase column in the hydration region ranges from 5.5 to 9 ppmv×km for 70°N-90°N, while the column of the upper drier region is significantly smaller, ranging from –1 to –4.5 ppmv×km. We should note however that we use as the 'background' H_2O gas profile the mean profile averaged over all latitudes, which could probably partially explain the differences with SOFIE. MIPAS and SOFIE, however, agree very well in that the excess and deficit H_2O gas-phase concentrations are significantly much smaller than that contained in the ice cloud. Figure 10 shows MIPAS enhanced values of about 1.5 ppmv in the hydration layer and ~~decreased by~~ a decrease of 0.5 ppmv in the dehydration region, while the $Q_{\rm ice}$ peak is about 6 ppmv. A more comprehensive study ~~,~~ using all MIPAS data ~~, shouldhowever~~ should, however, be performed to confirm these findings. ~~A further insight provided by MIPAS observations, with respect to SOFIE, is that this layer's structure is more pronounced at latitudes northernmost of 70°.~~

6 Diurnal variation of ~~the~~ ice volume density

The diurnal variation of ~~the~~ PMCs is an important factor to be taken into account when comparing ~~the datasets for different PMCs~~datasets with different temporal sampling. Several studies have shown that the IWC may have a ~~very large~~ significant diurnal variation at latitudes close to and ~~equator-wards~~ equatorward of 70°, mainly driven by tidal effects in ~~the~~ temperature and in ~~the~~ meridional advection at sub-polar latitudes (Stevens et al., 2010; Gerding et al., 2013). MIPAS measures PMCs at two local times, 10 am and 10 pm, and hence ~~allows us to look at~~ easily allows for the inspection of variations due to the diurnal migrating ~~variation (see García-Comas et al., 2016). Fig.~~tide (see García-Comas et al., 2016). Figure 12 shows the ~~diurnal~~ absolute (upper panels) and relative (middle panels) zonal mean differences (am-pm) of MIPAS ice volume density averaged over all measurements in the SH (left ~~panel~~panels) and NH (right ~~panel). The~~ panels).

The am–pm absolute differences are larger in the NH, ~~which are correlated with~~ partially due to the larger concentrations in this hemisphere. The ~~am-pm~~ relative differences in the NH are larger at 60-80~~º~~°N, and reach a maximum value ~~close to~~ of 0.75$\cdot10^{-14}$ cm^3/cm^3. ~~This am~~ The morning enhancement is in line with the predictions of Stevens et al. (2010) but ~~it is~~ not as large as their ~~calculations of a factor of 4.5~~ calculated factor of 4-5 in the IWC at 69~~º~~°N. At this latitude, we find a maximum ~~daytime~~ enhancement of about ~~60~~80% in the volume density and ~~36~~40-50% in the IWC (not shown). Note however that ~~the IWC am-pm differences are also influenced by the slightly negative volume density difference at altitudes above 86 km.The vertically alternating increase at 84 km and decrease at 88 km in the am ice volume density indicates am clouds of lower altitude~~simulations by Stevens et al. (2010) correspond only to June 2007. The changes in the ice volume density at 65-75°N shown in Fig. 12 result in the MIPAS NH pm clouds being on average at slightly lower altitudes, also in agreement with Stevens et al. (2010).

The am-pm difference of ice volume density at 50-60°N is 0.25-0.5$\cdot 10^{-14}$ cm^3/cm^3 at 81-87 km~~(Fig. 12).That corresponds to an~~, i.e., am/pm ~~ratio~~ ratios lying between 1.5 at 86 km and 7 at 82 km ~~. That indicates a significantly~~ (Fig. 12). These changes result in narrower and thinner pm ~~cloud,~~ clouds, on average, that mainly disappear below 84 km, in agreement with findings at sub-polar latitudes from Stevens et al. (2010) and Gerding et al. (2013)~~, which mainly disappears below 84 km. The corresponding~~. The IWC am/pm ratio increases rapidly towards these lower latitudes and varies in the range of 1.5 to 2.8 at 50-60°N (not shown).

~~These ice volume density differences are remarkably anti-correlated with the~~ The bottom panels of Fig. 12 correspond to 10 am-10 pm differences in the kinetic temperature measured by MIPAS ~~(bottom panels in Fig. 12) which~~ simultaneously with the ice volume densities. These are a good measure of the temperature perturbations due to the diurnal migrating tide ~~. The negative~~ (García-Comas et al., 2016). The am-pm ~~difference~~ ice volume density differences in the NH (right panels in Fig. 12) are generally anti-correlated with the corresponding am-pm kinetic temperature differences. For example, the positive am-pm ice differences at 80-85 km ~~at latitudes below~~ equatorward of 80°N ~~is well anti-correlated to the~~ correspond to negative am-pm ~~ice differences. Also, the~~ temperature differences. The temperature differences tend to be positive ~~at higher altitudes~~ above 87 km northward of 65~~°~~°N, which is ~~well~~ reflected in the ice volume ~~densities~~density differences. Nevertheless, it is not possible to infer from ~~this correlation alone , and without looking at wind fields,~~ these anti-correlations alone the extent to which ~~these~~ diurnal temperature perturbations affect the ice ~~. Influence~~ volume density. Direct influence from other factors, like tidal ~~effects on meridional advection (Gerding et al., 2013, see, e.g.)~~ variation of meridional advection (see, e.g. Gerding et al., 2013) or non-linear behavior of phase transitions, cannot be ruled out.

~~The~~

Indeed, the anti-correlation between ~~the~~ diurnal variation of the ice density ~~in the SH (upper left panel~~ (upper and middle left panels in Fig. 12) and that of temperature (lower left panel) ~~is not ubiquitous~~in the SH is not so clear. In this hemisphere, the negative am-pm temperature difference at 50-60°S and 80-84 km is weaker and located at lower altitudes than in the NH. The ~~diurnal positive~~ corresponding absolute diurnal ice change is ~~correspondingly small but~~ small but also the ice volume density at these latitudes is ~~also very low~~ very small (less than 5×10^{-15} cm^3/cm^3). The ~~positive temperature difference above 85 km does anti-correlate with the negative am-pm~~ negative ice concentration difference at ~~65-80~~84-88 km corresponds to a positive temperature difference but only at 60-80°S. ~~However, in contrast to the northern hemisphere, the~~ And most strikingly, the am-pm temperature perturbation around 80-84 km at 65-80°S is positive ~~also at 80-85 km~~ but so is the ice variation. This indicates that ~~another factor~~ a diurnally varying driver other than temperature more significantly affects the diurnal ice variation ~~more significantly than temperature~~ at those latitudes, at least below 84 km. ~~Its effect~~ The overall effect on ice density results in vertically alternating positive and negative changes that ~~may lead to larger am-pm cloud altitudedifferences than in the northern hemisphere.~~ lead to lower SH am mean cloud altitude. The impact of that driver most likely depends on altitude and latitude. A deeper analysis ~~of this behaviour~~ involving also wind fields is beyond the scope of this paper and will be ~~analysed in the future~~ focus of a future study.

7 Conclusions

We have ~~analysed the~~ analyzed MIPAS IR measurements of PMCs for the ~~summer seasons in the Northern and Southern Hemispheres~~ NH and SH summer seasons from 2005 to 2012.

PMCs were measured in the middle IR in emission where, due to the small particle size, the signal is only affected by absorption and not by scattering. ~~It~~ MIPAS is therefore sensitive to the total ice volume, including the very small ice particles ~~, not generally sounded by the~~ that UV-VIS scattering ~~instruments.~~

observations are generally not sensitive to. The measurements cover only a few days of the PMC season (varying from 3 to 15) but ~~, on the contrary, have a global latitudinal~~ have global pole-to-pole coverage. In this way, MIPAS measurements show, for the first time, global latitudinal coverage (from 50° to the pole) of the total ice volume density.

MIPAS measurements indicate mesospheric ice existing as a continuous layer extending from about ∼81 km up to about 88-89 km on average and from the poles to about 55-60° in each hemisphere. These altitudes are in very good agreement with SOFIE measurements, with the lowest altitude being slightly lower (~~0.5~~∼0.7 km) in MIPAS, and the uppermost altitude slightly higher (~~1-2~~1.7 km), probably caused by the wider MIPAS field of view. This bottom altitude is also slightly lower than that derived from ~~lidars~~ lidar measurements but the uppermost altitude is significantly higher (4-5 km on average) than that obtained from lidar measurements. This indicates that both MIPAS and SOFIE instruments are sensing the small ice particles ~~at~~ in the upper part of the PMC layer~~which are usually related to polar mesosphere summer echoes.~~. This has also been proved recently by the concurrent observations from the ALOMAR wind (ALWIN) radar and measurements from SOFIE (Hervig et al., 2011).

~~The~~ PMCs are very variable, both in space and time. On average, MIPAS measurements show that ~~PMCs are confined to latitudes poleward of about 50–60°, with increasing concentration~~ ice mass density increases towards the poles. ~~The water ice content in the PMCs~~ The IWC measured by MIPAS at ~~the latitudes of the measurements of SOFIE~~ latitudes where SOFIE measurements are available show, overall, a ~~very good agreement , particularly at the peak of the layer. The water ice content observed by MIPAS is,~~ good agreement being, in general, slightly larger (∼10%), and also ~~exhibits~~ exhibiting a larger variability, probably caused by ~~its~~ MIPAS smaller sensitivity. A distinctive feature, however, is that, in general, MIPAS shows ~~significantly larger values~~ larger ice volume densities than SOFIE in the region above ∼85 km, ~~which can be twice those measured by SOFIE. In terms of ice water content, IWC, MIPAS are also generally larger than SOFIE values, principally caused by the larger concentrations above ∼ 85 km.~~ and smaller below.

The ice concentration is larger in the Northern Hemisphere than in the Southern Hemisphere. The ratio between the IWC in both hemispheres is also latitude-dependent, varying from a NH/SH ratio of 1.4 close to the poles to a factor of 2.1 around 60°. This also implies that PMCs extend to lower latitudes in the NH.

We have found that the mean altitude of the PMC layer in the NH for the NLC mode of MIPAS observations is located around 83.5-84 km, while in the SH it is about 1 km higher (84.5-85 km). This hemispheric asymmetry is in very good agreement with SOFIE observations (Hervig et al., 2013). For those MIPAS observations taken in the middle and upper atmosphere modes~~(MA and UA)~~, the mean altitude is higher (~~in~~ by ∼1 km). This difference is attributed to the coarser sampling and to the broader vertical resolution (particularly in the retrieved temperature) and also to ~~their~~ the different temporal sampling ~~since the NLC~~ of the modes since the NLC-mode measurements are usually taken in the middle of the PMC season while ~~MUA~~ MUA-mode observations are taken earlier and later in the season. A very clear feature in MIPAS observations is that PMCs tend to be at higher ~~altitudes as we move away from the polar region~~ mean altitudes towards lower latitudes (in both hemispheres), particularly ~~equator-wards~~ equatorwards of 70°.

MIPAS observations show that the difference between the mean PMC height and the mean mesopause height is about 2.5 km in the NH near 70°N. This is smaller than the mean value of 3.5 km obtained ~~for several~~ from several satellite instruments by Russell et al. (2010) and closer to the SOFIE value (Hervig et al., 2013). MIPAS also shows that this altitude difference increases towards the North pole, reaching a value close to 4 km. In the Southern Hemisphere this difference is smaller than for the NH, with values ranging between 2 and 2.8 km; again ~~in better~~ the agreement with SOFIE ~~than with the~~ is better than that with other instruments.

The anti-correlation between the ice water content and the altitude of the lower branch of the frost point temperature contour is significant in MIPAS observations and shows that the PMC layers ~~are denser and wider~~ have larger ice mass densities when the frost point temperature occurs at lower altitudes.

The simultaneous observations of MIPAS PMCs and water vapour ~~of MIPAS have shown that the~~ have confirmed that PMC layers are surrounded by a hydrated region below and a dehydrated region above. These regions are more pronounced towards the poles, particularly at latitudes ~~northernmost~~ poleward of 70°N. This global behaviour fits very well with the current picture we have about the PMCs where sequestration of H_2O in the gas phase to form ice leads to a drier atmosphere just above the ice layer, and where the sedimentation of ice and its subsequent sublimation enhances the H_2O gas phase abundance at ∼80 km. The analysis of a single day of water vapour and PMCs measurements ~~have shown that the location~~ of MIPAS has shown different results than in SOFIE. The peak altitude of the hydration region ~~agrees well with SOFIE observations (Hervig et al., 2015). The dehydration region , however,~~ is about 1 km below the bottom altitude of the PMC layer in MIPAS while in SOFIE it is ∼0.3 km above (Hervig et al., 2015)), and the dehydration region is found to be ~~significantly higher in MIPAS than~~ at ∼2-3 km above the height of peak ice mass density in MIPAS but ∼1.8 km in SOFIE. ~~Further, as for SOFIE, measured near 70°,~~ Further, MIPAS shows that the column abundance of ~~in the gas phase is roughly equal~~ water vapour excess in the hydration layer is about twice than the deficit in the dehydration ~~and hydration layers, but less than that contained in the ice layer. MIPAS observations at latitudes north of~~ layer near 70~~° show that this layering structure is more pronounced.~~ °N, while they are very similar in SOFIE. However, they both agree that both quantities they are much smaller than the water content in the form of ice.

Finally, MIPAS observations, which are taken at 10 am and 10 pm, also show a diurnal variation in the ice volume density~~,~~ ~~with larger concentration, and slightly lower altitudes, at~~ . The IWC is larger at 10 am than at ~~pm~~10 pm in the NH, in line with the model predictions of Stevens et al. (2010). This diurnal variation is anti-correlated with corresponding differences in temperature in the ~~northern hemisphere~~NH, suggesting that it is driven by the temperature migrating diurnal tide, but effects from other factors cannot be ruled out. In the ~~Southern Hemisphere~~SH, the lack of a clear anti-correlation with temperature ~~suggests the~~ points to a significant impact of an additional ~~factor below 84 km~~driver.

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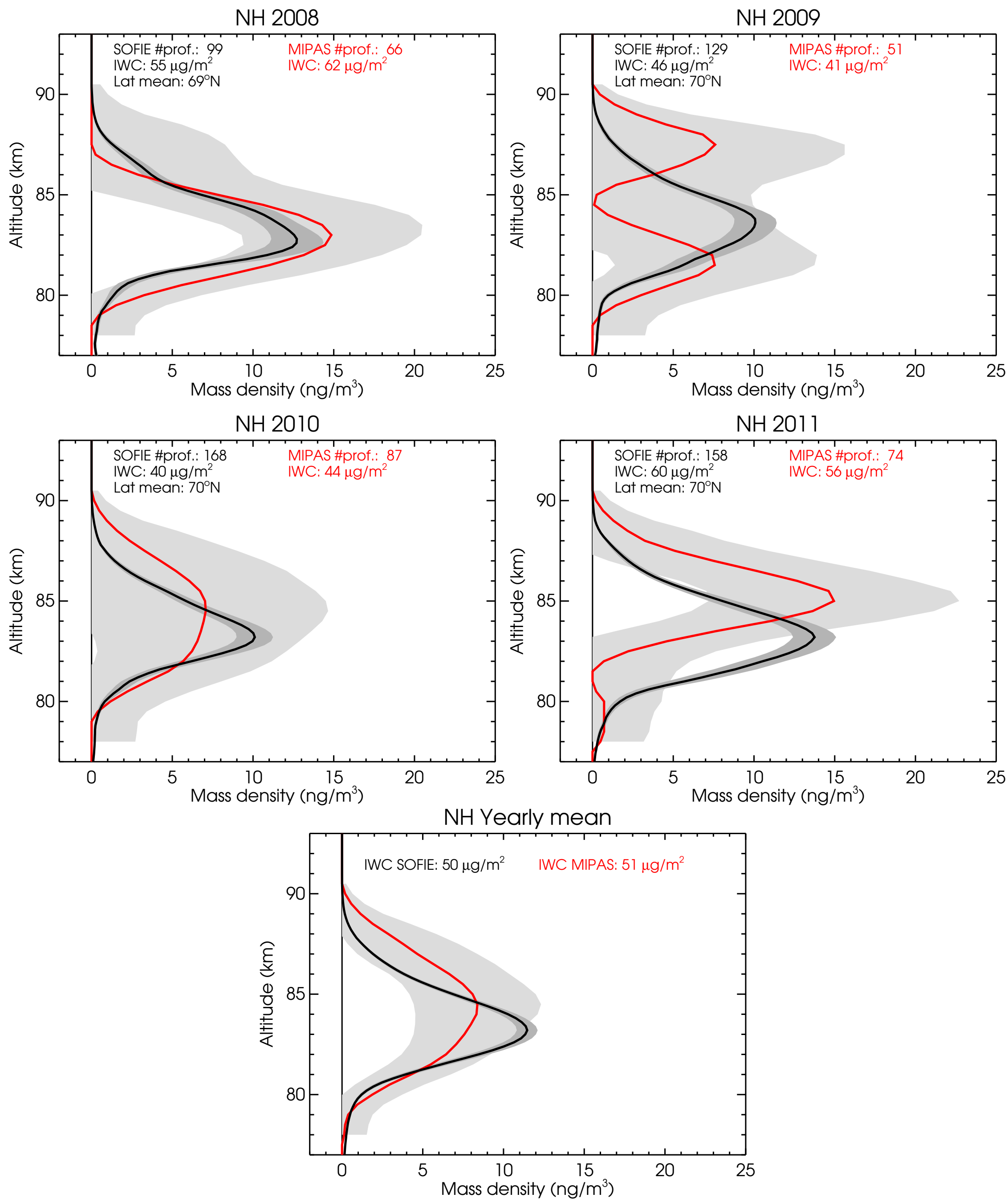

Figure 5. Comparison of the ice mass density of MIPAS ~~MA and UA~~ MUA modes of measurements (see Table 1) with SOFIE v1.3 L2 data for the 2008 to 2011 period and the yearly mean (lower panel) in the NH. The solid lines show the mean profiles, SOFIE in black and MIPAS in red. The shaded areas are the standard deviations divided by the square root of the number of profiles. The means of the ~~integrated water column (~~IWC ~~)~~ are also shown.

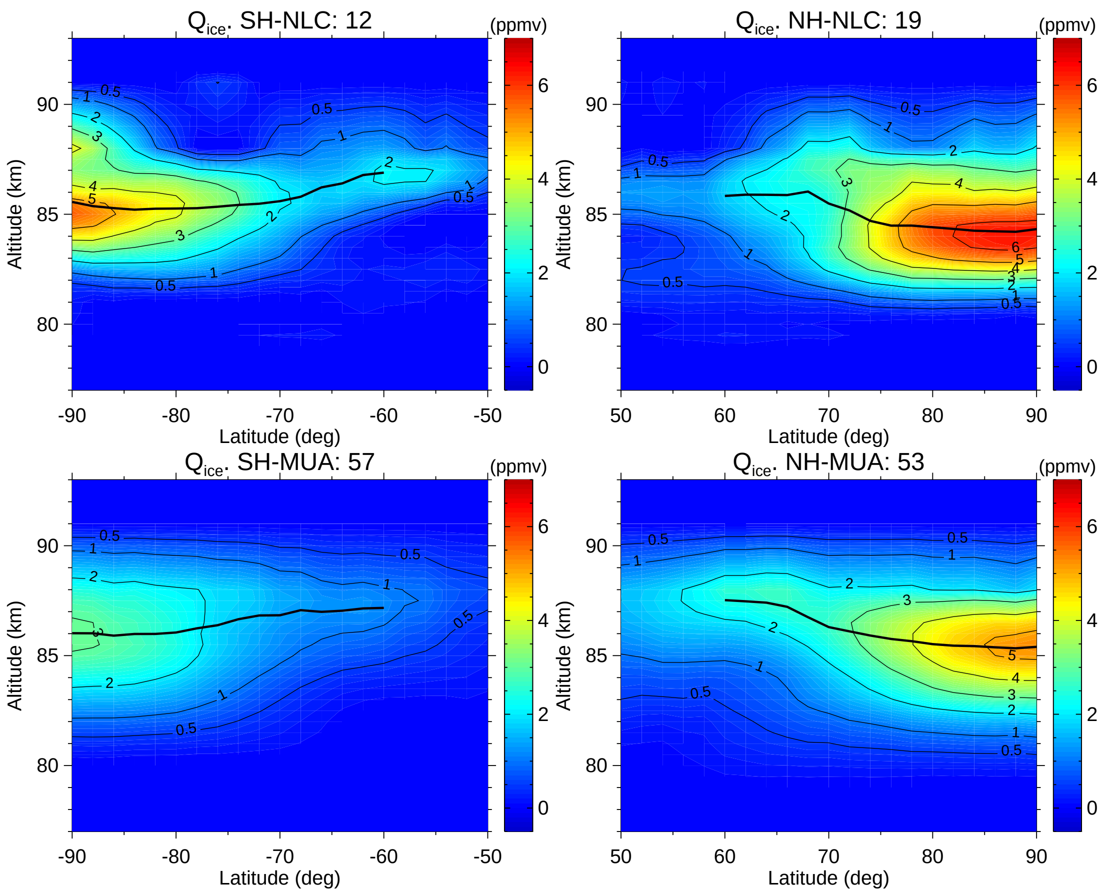

Figure 6. Same as Fig. 3 but in units of ppmv. The ~~estimated~~ noise error of the H_2O ice concentration plotted here, estimated by the standard error of the mean, is about 0.08 ppmv and 0.04 ppmv for the NLC and MUA measurements, respectively.

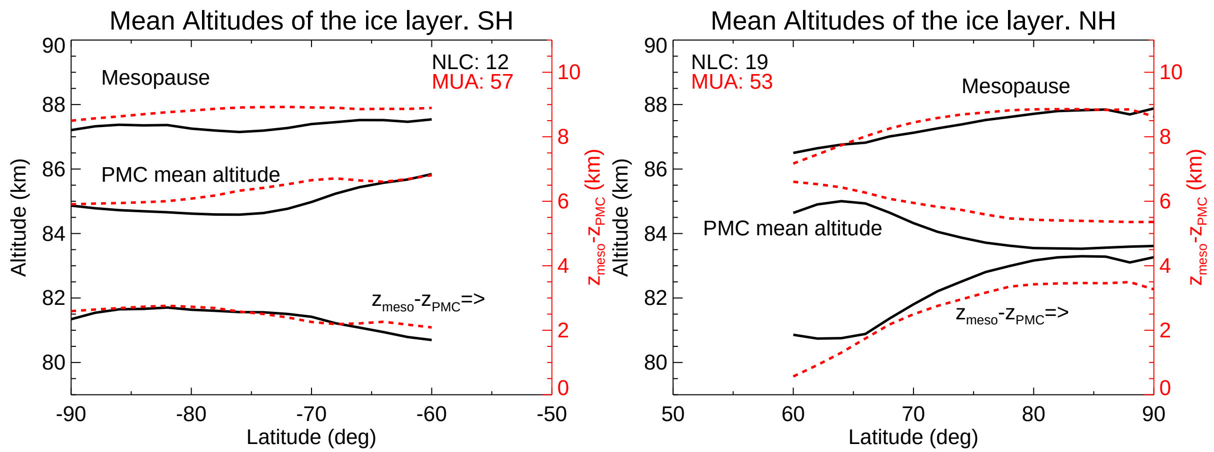

Figure 7. Mean altitudes of the mesopause (z_{meso}), of the PMC layer (z_{PMC}), and the difference $z_{\mathrm{meso}} - z_{\mathrm{PMC}}$ ~~shifted 79 km~~(right y-axis), for the SH (left) and the NH (right) seasons for all measurements. The different colors indicate the results for the NLC ~~and MA+UA~~ (black) and MUA (red) MIPAS observation modes (see Table 2).

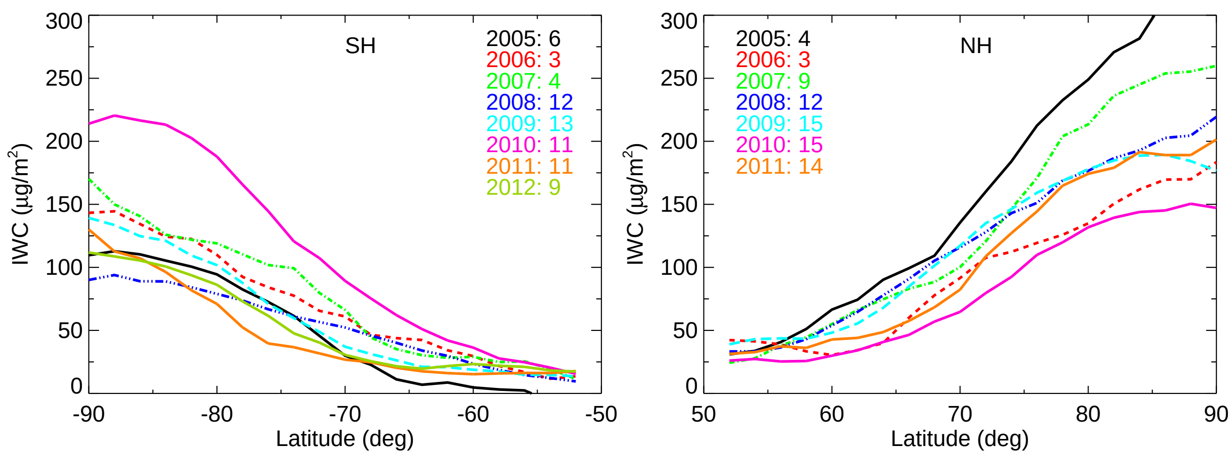

Figure 8. Latitudinal distribution of ~~the ice water content~~ IWC of the PMC layers for the SH (left) and the NH (right) seasons for all measurements. The colors indicate the data for different years and the number of days measured per year (see Table 2).

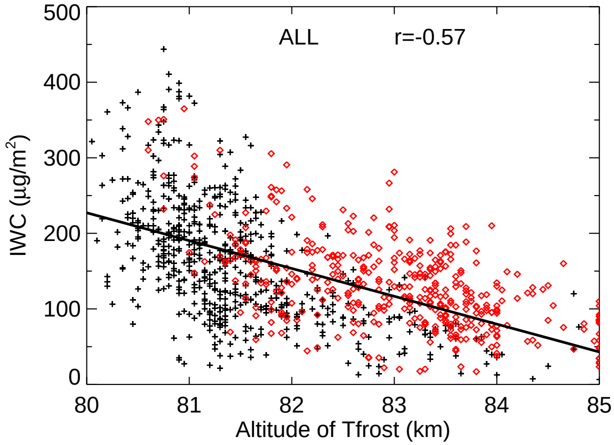

Figure 9. Correlation between ~~the ice water content (~~IWC ~~)~~ and the altitude of the lower branch of the frost point temperature contour (see Fig. 1) for ~~the~~ all data ~~taken in~~ including the NLC~~(left panel) and MA+UA (right panel)~~ MUA observation modes ~~in~~ for the NH (black pluses) and SH (red diamonds) ~~PMCs~~ PMCc seasons (see Table 2). The black line is a linear fit to the data and r the correlation coefficient.

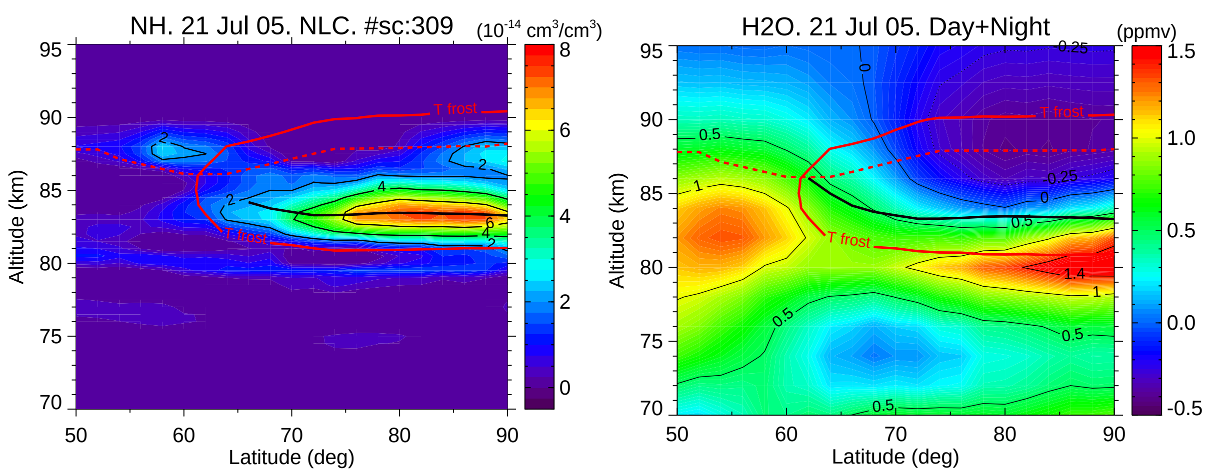

Figure 10. Zonal mean ~~of the~~ ice volume density (left) and of ~~the~~ H_2O concentration anomaly (the mean profile has been subtracted) (right) for 21 July 2005. The solid red lines indicate the frost point temperature~~(thick line) and frost point temperature plus 3 K (thinner line)~~. The red dashed line is the mesopause as measured ~~by~~ from MIPAS. The solid black line is an estimated mean altitude of the PMC layer (see ~~See.~~Section 4).

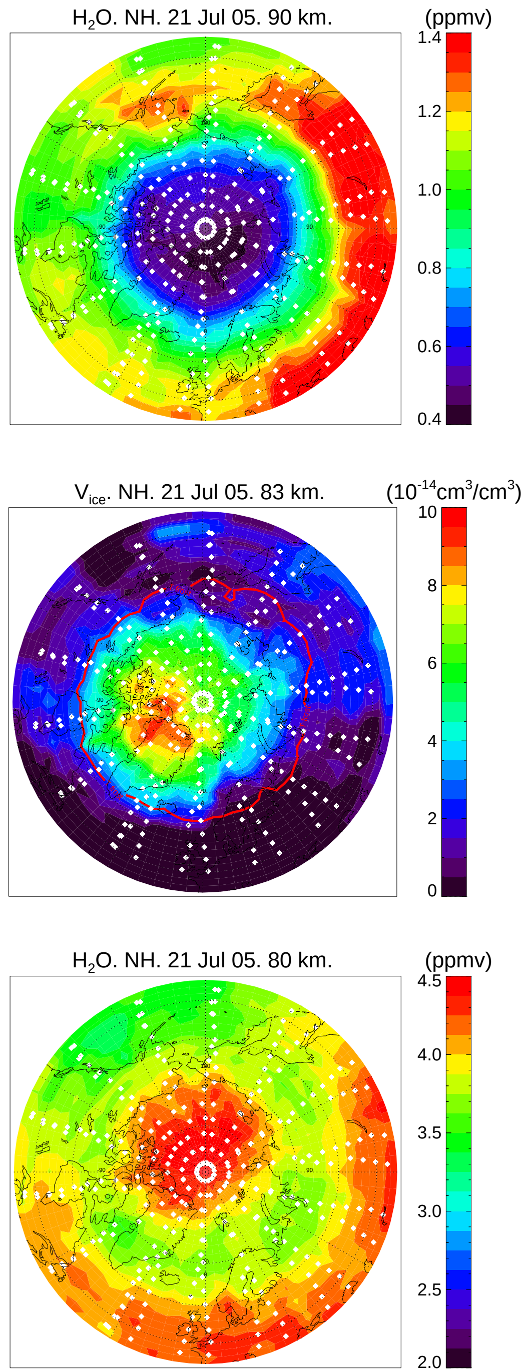

Figure 11. ~~Latitude/longitude distribution~~ Polar maps of H_2O vmr for altitudes of 90 km (top) and 80 km (bottom) (note the different ~~scale~~scales) and of ice volume density at 83 km (middle panel) for 21 July 2005 (see Fig. 10). The white diamonds represent the geolocations of MIPAS measurements.

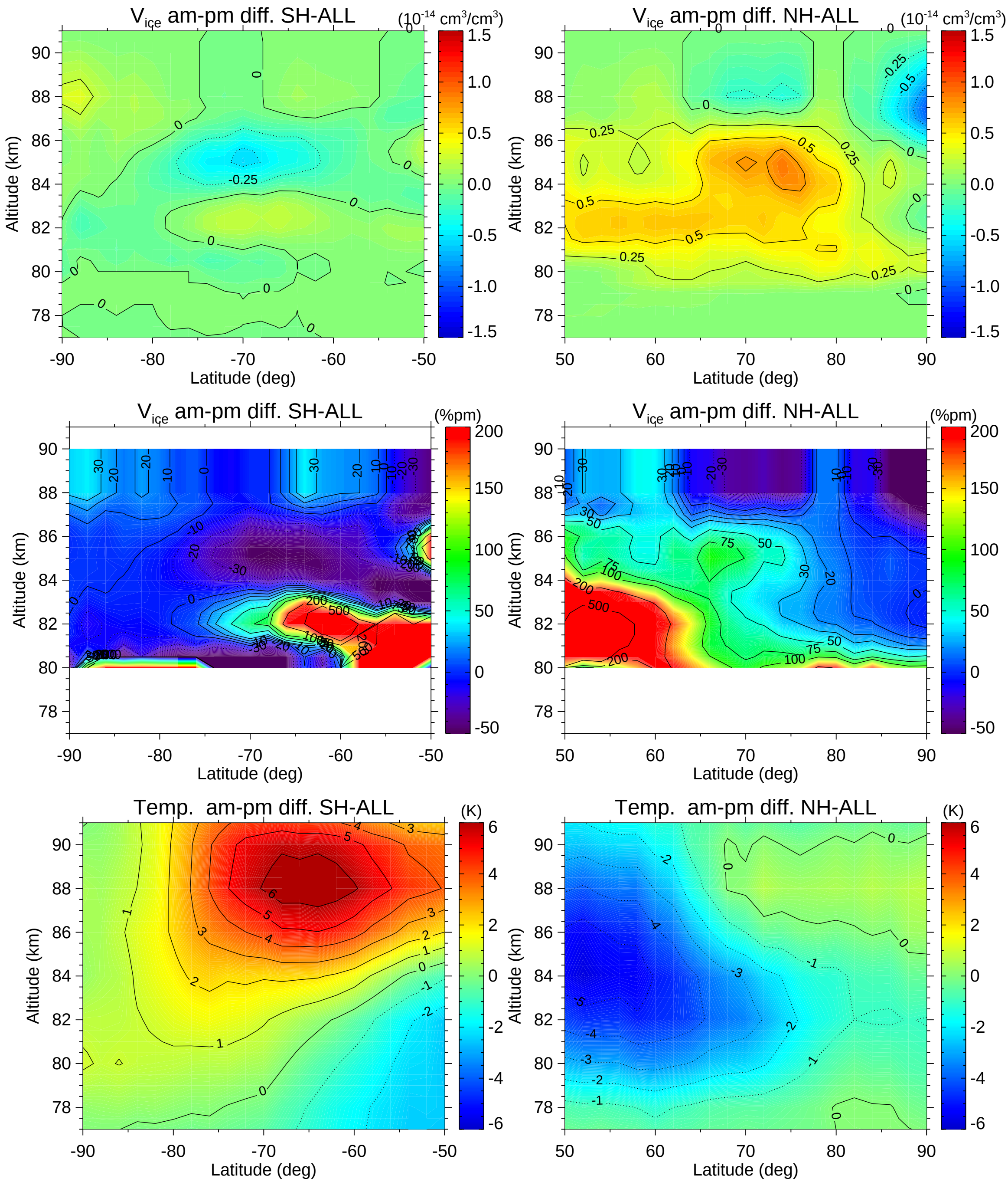

Figure 12. Top and middle panels: zonal mean ~~am-pm~~ am–pm ice volume density differences (in absolute and % of pm, respectively) for the SH (left) and NH (right)~~considering all measurements in each hemisphere~~. Bottom panels: zonal mean ~~am-pm differences in~~ am–pm temperature differences as measured by MIPAS for ~~January~~ the SH (left) and ~~July~~ NH (right).