Reply to Referee 2 Comments

Manuscript-No: acpd-2015-172

Sensitivity of polar stratospheric cloud formation to changes in water vapour and temperature

We thank reviewer 2 for the constructive, helpful criticism and the suggestion for revision. We followed the suggestions of reviewer 2 and revised the manuscript accordingly. Especially, section 5 and 6 have been throroughly revised.

To start with, I would like to state that I have not worked in this field in recent years and only followed the development from a sideline. Therefore, I am not fully updated with the recent literature, and I haven't been able to go through the very comprehensive list of references given in this paper in the frame of such a review. This paper describes investigations of the Arctic stratosphere, with a focus on polar stratospheric cloud (PSC) formation processes and conditions, both using case studies during the exceptional stratospheric winter of 2010/11 and long-term data sets derived from composed satellite data records.

The paper addresses an issue, which in my opinion is both very interesting and relevant (although interest in stratospheric research has dropped strongly in the recent decade). The two most important parameters influencing the formation of PSCs - stratospheric temperature and water vapour concentration are hypothesized a lot about, but not settled. In particular, trends of the stratospheric water vapour concentration are highly uncertain, with only one ground-based long-term measurement series from mid-latitudes and a number of satellite-derived data series with considerable uncertainties, as confirmed in this paper.

So the topic is relevant, but I have some critical remarks about the method applied and the conclusions. The most important source of information, the water vapour records from various satellite instruments, should be discussed in much more detail than is done here. The figures 11 and 12 (lower panels) very clearly demonstrate the problems of this issue: the discrepancies between the instruments are almost as large as the inter-annual variability, and then, of course, it becomes very difficult to derive any trends. There seems to be a shorter period, from about 2006 to 2011, where the agreement between the various instruments is good, but before and after this period, the quality is definitely not sufficient to allow trend analyses. I have looked into the very comprehensive paper of Hegglin et al. (2013), but not found any clear statement whether one can combine many satellite instruments to derive a trend in the case of water vapour.

It is possible to combine many satellite instruments and derive a trend for water vapour as shown in the Nature paper by Hegglin et al. published in 2014. Nevertheless, in our study no merging of satellite data has been done! All satellite instruments are considered individually. Irrespective of if the data sets are merged or if the data sets are considered individually it is possible to derive trends in stratospheric water vapour as shown in earlier studies by e.g. Rosenlof et al. 2001. and references therein as well as Scherer et al. (2008). We refer now to these studies at several places in the manuscript and the text has been revised accordingly as given below in our answer to the comment on P17763, line 19.

Another issue is brought up by the authors themselves: The water vapour concentration anti-correlates to the temperature in the same altitude range, which in turn depends on the dynamical conditions, such as the stability and strength of the polar stratospheric vortex. In the Arctic, these vortex properties are extremely variable (from year to year), so that they introduce a large year-to-year variability in water vapour concentration, even if one uses equivalent latitude to select data. In my opinion, one should investigate water vapour concentrations separately for certain potential vorticity/temperature intervals and look for trends in these sub-sets rather than showing the whole time series without even distinguishing between summer and winter and concluding there is no trend.
So far, trend studies on water vapour were performed using the year-round data sets. Separations were only done concerning the latitude regions. However, we agree that a separation in the polar stratosphere into summer and winter could be worth considering. Attached to this reply is a figure showing the linear trend analyses for winter (DJF). Considering the linear trend analyses for solely the winter months does not change our results. The resulting areas where the changes are positive and significant within the 2 σ uncertainty are quite similar to the changes we found when all seasons are considered.

Concerning instrument-to-instrument comparison, which is shown in Figure 13, why didn't the authors compare the MIPAS and Aura/MLS data for the same period (2004-2012)? That should give a good indication of how well these two satellite instruments agree.
This seems to be a misunderstanding. The purpose and intention of this figure is not to show or state how well MIPAS and MLS agree with each other. Such comparisons have already been performed and published elsewhere. The intention of this figure is to investigate if in the MIPAS or MLS data any linear changes in water vapour are found. We have chosen these two instruments since these are, from the ones considered in this study, the ones with best spatial and temporal coverage. Further, the trend estimates have been derived for both data sets individually. Therefore, for each trend

estimate 12 years could be considered instead of 7 years as in the case when we solely would have used the overlap period. In our study no merging of satellite data has been done. We have slightly changed the text and hope that this becomes more clear now.

The other major methodological critics I have, concerns the two case studies. My impression is that the results have not been exploited properly. Both cases are based on observations of mixed PSCs, combined with back-trajectory calculations. The two cases resemble each other in the fact that during the six days covered by the calculation there are two periods with T sufficiently low to allow the formation of PSCs. However, in both cases these two periods are separated by 60 and 80 hours, respectively, with T up to 10 degrees above the T_{NAT} threshold. Then I wonder how relevant the first period is for the PSC display. If it is not, they should focus their analysis on the second period.

Both periods where the temperature drops below the threshold temperature are of importance. The back trajectories follow the flow within the polar vortex. Thus, the air masses are once or twice transported around in the polar regions. For the trajectories shown in case 1 and 2 the air masses were transported around twice during the past 6 days and the two time periods reflect this. It simply shows that the air mass passed twice through the cold region in the Arctic which is cold enough to allow PSC formation. So far, we only have mentioned this in the manuscript in section 4.2. We added now the following sentence to section 4.1.1 and 4.1.2, respectively: *During the course of the 6 days the trajectories followed the circular flow within the polar vortex and thus the air masses were transported twice around in the polar regions (see figure in supplement).* Further, we added two figures in the supplement showing the trajectories for case 1 and case 2, respectively.

On the other hand, the conclusions drawn from the two case studies are partially trivial: In one case, simulating a T decrease and/or [H_2O] leads to very little changes regarding the lifetime of a PSC, while in the other case it is noticeably extended. From the figure, this is very simple to derive: it is a consequence of the T variations along the trajectory. In the second case, there is a longer period with T above, but close to T_{NAT}, so decreasing T or increasing T_{NAT} naturally leads to big changes regarding PSC existence duration, while in case 1 T varies much more rapidly so that the simulated T and [H_2O] shifts do not have a large impact on the PSC lifetime.

What I would have liked to see here, was a study of whether the observed existence of the various types of PSCs agrees with the thermal and [H_2O] conditions observed and used in the calculation. If the authors did a calculation at 22 km altitude in case 1, i.e. where there is ice in the observation, why don't they show that calculation in Figure 3, or, even better, temper-

ature history figures from slightly outside and different altitudes inside the PSC, say at 19, 20, 21, 22, 23 and 25 km? That would give substantially more information about conditions for the existence of the different types of PSCs. Can, for example, a comparison between the back-trajectory from 20 km altitude (STS PSC) and the back-trajectory at 22 km (pure ice PSC) allow conclusions about the water vapour concentration in this case? Are there satellite data supporting the [H_2O] value found?
We find a good agreement between the observed existence of the various PSC types with the thermal conditions derived from the trajectories as well with the H_2O observed by the satellite instruments (for our base case applying 5 ppmv). We did not use the trajectory at 22 km from case 1 where also ice was measured, because this is one of the few examples where trajectory temperatures have been too high compared to the PSC types observed by CALIPSO. This can happen when waves are involved in the formation process. To account for the different compositions of the PSCs at different altitudes we calculate three trajectories for each PSC observed by CALIPSO, corresponding to the top, middle and bottom of the cloud. The altitudes have been selected so that the different PSC types within the cloud were considered. In our earlier Arctic winter studies (Achtert et al., 2011 and Blum et al., 2006) we calculated trajectories at every km of the observed PSC. In these studies, the development of certain PSCs was investigated in more detail (together with box model simulations). However, also in these studies trajectories at three altitudes corresponding to the top, middle and bottom of the cloud would have been sufficient. Therefore, for a statistic as it is performed here, the three trajectories per observed PSC calculated are more than sufficient. To derive water vapour concentrations from the trajectories is not within the scope of this study.

A few concrete comments and questions:

Throughout the paper, the authors should be more thorough in using the right terminology for concentrations/mixing ratios, e.g., write H_2O concentration or [H_2O], and not just H_2O
At several places in the text we clarify now what we mean and write H_2O mixing ratios instead of just H_2O.

P. 17757, line 3: Are the starting coordinates of the first back-trajectory calculation given wrong? (71N, 61E) is not on the trajectory; from Figure 2 (upper panel) I conclude that it should be (71N, 51E). If the authors used the wrong coordinates in their calculation, this might have important consequences for their calculation.
The starting coordinates for the back trajectory given in the text are correct. However, although we intended to start the trajectory at some point along the CALIPSO track, we accidentally started the trajectory shifted by a few

degrees to the east. However, this does not change our results since the trajectory was nevertheless started within the PSC and crosses the CALIPSO track just a few hours later (see Figure in supplement).

P. 17757, lines 12ff: What does the sentence The temperature history along the trajectory is in agreement with the CALIPSO observations mean? Are there CALIPSO measurements from the time-space points along the backward trajectory which show such agreement?

What we actually meant is, that the PSC formation threshold temperatures reached along the trajectory agree with the PSC type observed by CALIPSO. Note: The start point of the trajectory (at t=0) coincides with the CALIPSO measurement. However, as mentioned above, for this trajectory the coincident time with the CALIPSO measurement is somewhat later, at t=−5 h. STS was observed at the altitude where the trajectory was started (20 km). Temperatures along the trajectory dropped sufficiently low below the NAT formation temperature to allow STS formation. The sentence has been changed as follows: *The temperature range T_2 corresponds to the time period when a PSC was measured by CALIPSO on that day. The temperature drops sufficiently low below T_{NAT} to allow STS formation, which is in agreement with the CALIPSO observation at 20 km (Figure 2).*

P. 17759, lines 6 ff: Instead of speculating about the values of [H_2O], why dont the authors use measured values of this parameter inside the Arctic polar vortex from the satellite data series?

Although not stated explicitly, we do not speculate about the H_2O mixing ratios in the Arctic lower stratosphere. The 5 ppmv we use for our base case is the typical water vapour mixing ratio observed in the Arctic polar lower stratosphere by the satellite observations considered in this study as well as by other observations. The 0.5-1 ppmv increase we consider is based on the trends in stratospheric water vapour reported by Rosenlof et al. (2001) and Hurst et al. (2011). To make clear that these values were not arbitrarily chosen, we changed the sentence as follows: *Using the entire trajectory ensemble the total time (sum over all 738 trajectories) where the temperature was below T_{NAT} and T_{ice}, respectively, was estimated applying an H_2O mixing ratio of 5 ppmv, same as in section 4.1.1 and 4.1.2, typical water vapour mixing ratio for the Arctic polar lower stratosphere (Achtert et al. [2011] and references therein, Khosrawi et al. [2011]) and observed by the satellite instruments considered in this study.). This calculation was repeated applying a H_2O increase of 0.25–1 ppmv (ΔH_2O=0.25 ppmv, as in section 4.1.1 and 4.1.2, according to the estimated trends from Rosenlof et al., 2001 and Hurst et al., 2011) as well as a decrease in temperature by 0.5 and 1 K.*

P. 17763, line 19: stratospheric water vapour exhibits a strong decadal vari-

ability: How can this be stated in light of the following statement ..with the lack of available long-term observations in line 20? With only one long-term observation series at a mid-latitude station, the first sentence is nothing more than a hypothesis.

We have removed this particular sentence and throughly rewritten section 5. Nevertheless, the Boulder time series is the longest "continuous" observed time series available up to now. However, Hegglin et al. (2014) derived by merging of satellite data sets a similar long time series than the Boulder time series. Additionally, several water vapour trend studies have been performed in the past using different in-situ and remote sensing data sets. Although most of these studies do not consider more than two or three decades, they revealed the decadal variability of water vapour as shown in e.g. Fueglistaler and Haynes, 2005; Randel et al., 2006, Fujiwara et al., 2010. We agree that we missed out to mention these earlier studies in our manuscript. We therefore have added these references in the introduction and added the following text: *Long-term balloon-borne measurements at Boulder/Colorado (40 N/105 W) indicate an increase of lower stratospheric water vapour abundances, on average by 1 ppmv, during the last 30 years (1980-2010) (Scherer et al., 2008; Hurst et al., 2011). Recently Hegglin et al. (2014) analysed a merged satellite time series spanning from the late 1980s to 2010, which did not confirm the findings from the Boulder data set, arguing the representativeness of these data on a larger spatial scale. In the lower stratosphere negative changes were dominating, while positive changes were found only in the upper part of the stratosphere. The decrease in the lower stratosphere was attributed to a strengthened lower stratospheric circulation.*

P. 17764, lines 14ff: Isn't this anti-correlation between stratospheric temperature and [H_2O] a consequence of a stronger subsidence of stratospheric air masses when the lower stratosphere is very cold? As the mixing ratio of water vapour increases with altitude (as nicely shown in Fig. 15), increased subsidence would pull down wetter air masses from above.

Yes, it is correct, that the anti-correlation between stratospheric temperature and H_2O is a consequence of a stronger subsidence during cold Arctic winters. For example, Manney et al. (2008) showed that during cold Arctic winters the subsidence in the vortex is strongly enhanced compared to other years and that thus moister air is "pulled down" from above. Further, during years where the QBO is in its westerly phase the vortex is more stable and colder (Holton and Tan, 1908). The following sentences have been added: *During polar winter vigorous descent occurs within the polar vortex, transporting air masses from the upper stratosphere and mesosphere down to the lower stratosphere (Bacmeister et al., 1995). As water vapour typically exhibits a maximum around the stratopause this descent also transports moister air towards the lower stratosphere. Sonkaew et al. (2013) analysed*

SCIAMACHY data from 2002-2009 and found that the QBO west phase is associated with larger PSC occurrences and stronger chemical ozone destruction than the QBO east phase. Their findings are in agreement with the Holton-Tan mechanism (Holton and Tan, 1980) which relates the QBO west phase to a colder and more stable vortex. During cold Arctic winters, as 2010/2011, the subsidence within the polar vortex is strongly enhanced as shown e.g. by Manney et al. (2008), causing positive water vapour anomalies.

P. 17765, lines 9 ff: I do not agree with this conclusion. In case of a relatively warm polar vortex with, say, extended areas of temperatures just above T_{NAT}, a decrease of T_{air} by 1 degree might have as dramatic consequences as described here.
We agree that in a relatively warm polar vortex a decrease by 1 K would have as dramatic consequences as during a cold winter as the 2010/2011 winter as was investigated in our study. This is exactly what we wanted to say with our statement. We changed the text as follows and hope that we get the message through now: *As a consequence the total times where the temperature was below T_{NAT} or T_{ice}, respectively, would have been shorter as for the Arctic winter 2010/11. However, the resulting increase in time due to a decrease in temperature and an increase in water vapour can be expected to be similar, thus as dramatic as for the 2010/11 winter.*

P. 17765, last paragraph: The main question that remains unanswered still is whether the H_2O concentration changes in the polar stratosphere. In my opinion, such cold winters with lots of PSCs could be used to shed additional light on that question.
The focus of our study is on the past 15 years, thus we can only give some answers on this time period. In our study we consider the correlation between observed water vapour variability and the recent temperature evolution in the Arctic together with PSC observations to investigate a possible connection between an increase in stratospheric water vapour and the occurrence of cold winters that lead to extreme PSC formation and denitrification. As mentioned before, there is a strong decadial variability found in the observed water vapour time series, and we also found some signifcant positive trends so far. How water vapour and Arctic winter dynamics will change in the future can only be ruled out with taking into account climate model simulations which however is beyond the scope of this study.

P. 17766, lines 20 ff: Here the authors suddenly open a completely new issue that is not discussed before - the sudden drop of lower stratospheric water vapour concentration in 2000-2001 in the tropical tropopause region and its delayed manifestation at higher latitudes. Without a more detailed discussion of it, they should remove it from the conclusions. Besides that,

this drop at high latitudes is only seen clearly in one of the satellite records (ODIN), but not in HALOE, MIPAS and SCIAMACHY.
The respective sentences in the conclusion have been removed. Additionally, section 5 and section 6 thoroughly revised. In the introduction the following text has been added: *A decisive role here played a pronounced drop in water vapour in 2000 (also known as the millennium drop)(Randel et al., 2006; Scherer et al., 2008; Solomon et al., 2010; Urban et al., 2012), that first started to recover in 2004 to 2005. This drop was caused by a reduced transport of water vapour from the troposphere into the stratosphere in response to a colder tropical tropopause. The temperature decrease has been due to variations of the QBO (Quasi-biennial Oscillation), ENSO (El Niño Southern Oscillation) and the Brewer-Dobson circulation that collectively acted in the same direction lowering the tropopause temperatures. In 2011 such a drop happened again, however more short-lived (Urban et al., 2014).*
In section 5 we write now: *The signatures of the water vapour drops in 2000 and 2011 are not easy distinguishable in the Arctic. In the altitude range between 475 K to 525 K the decrease throughout 2003 may be attributed to the millennium drop. Arctic observations of POAM III indicated the drop already in early 2001 (Randel et al., 2004). This seems to be consistent with studies by Brinkop et al. (2015) that showed a delay of up to 12 months between the drop occurrence in the tropics and at 50° latitude at these low altitudes. The UARS/HALOE observations employed here do not show a clear sign of a decrease in 2001, however admittedly the measurement coverage of this instrument has not been optimal for these high latitudes. The decrease in the Arctic in 2011 may correspond to the drop observed in the tropics. Yet, the length of the decrease is shorter than observed at the low latitudes. Higher up, between 525 K and 825 K potential temperature, a longer delay to the drop occurrence in the tropics can be expected (Stiller et al., 2012; Brinkop et al., 2015). Thus, the decrease observed here in 2002 and 2003 is more likely attributed to the millennium drop. The decrease in 2011 on the other hand is unlikely to be connected to the tropical event.*

Figure 7: It would be better if all panels had the same y-axis scales; this would show the differences much better.
We have adjusted the y-axis scale, so that it is the same for all panels.

Figure 13: Why don't the authors show the trend altitude profiles of both instruments for the same period of time, i.e., 2004-2012? This would give a direct estimate of instrument-to-instrument agreement or discrepancy and to what degree trends from a composed sets of satellite data can be trusted. Adding two more years on either side of the overlap period covered by only one instrument only reduces the strength of the comparison. How does the result of this figure relate to the results of Hegglin et al. (2014) who see no positive trend in the lower stratosphere?

This seems to be a misunderstanding. The purpose and intention of this figure is not to show or state how well MIPAS and MLS agree with each other. Such comparisons have already been performed and published elsewhere. The intention of this figure is to investigate linear changes (thus trends) in both satellite instruments, MIPAS and MLS. Further, the trend estimates have been derived for both data sets individually. In our study no merging of satellite data has been done. We have slightly changed the text and hope that this becomes more clear now. A comparison to the Hegglin et al. (2014) results is not possible since in this study a different time period is considered. Further, the study by Hegglin et al. (2014) focuses on the mid-latitude and tropics while our study focuses on the polar regions.

Minor corrections:
P 17746, lines 5, 7: PSC existence temperatures (NAT, ice) are altitude dependent; the altitude of the given typical temperature value should be added
The typical value for the existence temperature of NAT and ice are given for 20 km. We altitude is now given in the text.

p. 17747, line 24: while, instead of although
We prefer to start the sentence with "although" rather than "while".

p. 17748, line 14/15: In the latter winter, denitrification also led to severe ozone depletion with a magnitude comparable to the Antarctic ozone hole
The sentence has been corrected.

p. 17754, line 20:....according to......
This has been corrected.

p.17756, line 9-10: ..... were calculated based on the CALIPSO observations.....
This has been corrected.

P. 17758, line 11: In this case, the temperatures drop.....
The sentence has been corrected.

P. 17758, line17:.....temperatures reach below T_{NAT} for 15 / 30 h with an increase in.....
This has been corrected.

p. 17760, line 13: This must be Fig. 9, not Fig. 7.
Yes, that's correct, we meant Fig. 9 here and not Fig 7. Thanks for pointing this out.

P. 17762, line 28 p. 17763, line 3:..... period 2002-2012. E.g., the transport.....(e.g., 6 ppmv) reaches much further down.....and 2010/11 than in the other years.
The sentence has been corrected.

p. 17764, line 16: enhanced
In this context "enhance" should be correct.

p. 17764, line 22: (McDonald et al., 2009; Alexander et al., 2011 & 2013). Temperature perturbations that.....
This has been corrected.

P.17765, line 8:.....to mid-January, and PSCs were.....
This has been corrected.

Figure caption of Figure 11, 3rd line: remove completely "Shown is is"
This has been corrected.

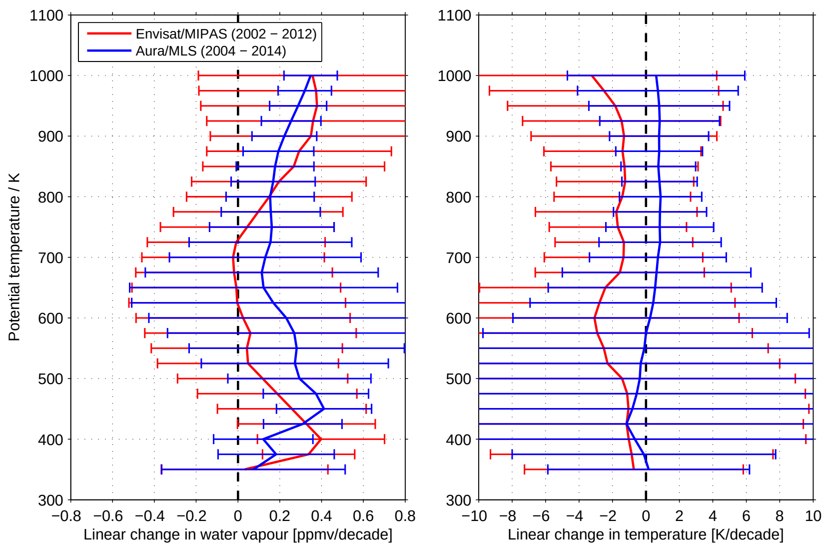

Figure 1: Linear change in water vapour (left) and temperature (right) vs. potential temperature derived from Envisat/MIPAS (2002–2012) and Aura/MLS (2004–2014) for winter (DJF). For the linear change in water vapour derived from Envisat/MIPAS an offset of 0.1 ppmv between the two measurement periods has been considered. As error bars the 2σ uncertainty is given.

Reply to Referee 1 Comments

Manuscript-No: acpd-2015-172

Sensitivity of polar stratospheric cloud formation to changes in water vapour and temperature

We thank reviewer 1 for the constructive, helpful criticism and the suggestion for revision. We followed the suggestions of reviewer 1 and revised the manuscript accordingly. Addionally to this reply, a supplementary document is provided where we show the results of repeating our sensitivity study on single back trajectories for other Arctic winters. Further, in this supplement it is documented (also on single back trajectories) how the sensitivity study would look like if we take into account a temperature bias of ±2 K. Additionally, due to the comments given by both referees Section 5 and 6 of the manuscript have been thoroughly revised.

This study examines the impact of changes in the concentration of stratospheric water vapour (increases up to 1ppmv) and temperature (decreases of 1K) on the time that air parcels might be below various PSC existence thresholds in the Northern hemisphere. This study also examines a range of satellite datasets to identify trends in the temperature and water vapour concentrations over the period 2000-2014 at high equivalent latitudes. While the central premise of the work is interesting, the amount of analysis shown seems to be too cursory for major conclusions to be drawn with certainty. In particular, Section 5 which examines the trends in the water vapour concentration and temperature over the period 2000 to 2014 lacks sufficient depth in my opinion. Thus, I think this work needs major revision before it is accepted for publication. I identify a number of key points below that concern me about the analysis and suggestions for further analysis which might help the authors tune this work for publication.

Sampling issue and interpretation of track statistics: The authors use trajectories derived from data in the 2010/2011 which they argue is sensible to use because there was a significant amount of PSC in this year. They then argue that this means that the statistics derived are effectively more robust because of the larger number of cases possible to derive back trajectories from. However, I would argue that this selection likely means that this study represents a worst-case scenario. Essentially a year with high PSC occurrence is used as the baseline to examine how even cooler temperatures and more water vapour will impact PSC formation. Whether the resultant statistics of an average year would be similar is not clear to me and not tested. The number of trajectories tracked (738) also seems rather small to me given the nature of the question that the authors wish to examine. Thus, I think this work would greatly benefit from analysis of at least some tracks *in another year to identify whether the enhancement in the time below the PSC thresholds is comparable in a relative sense. However, to significantly improve this study, I would suggest doing this type of analysis over a number of years to get a representative set of statistics.*

Although the Arctic winter 2010/2011 was quite extreme, our study does not represent a worst case scenario. For the temperature history along the trajectories, it does not matter which Arctic winter is considered. As soon as it gets cold and PSCs are formed, the trajectories resemble each other irrespective which year is considered. We have performed studies on PSC formation previously e.g. for the Arctic winter 2004/2005 (Blum et al., 2006), the Arctic winter 2008/2009 (Achtert et al., 2011) and the Arctic winter 2009/2010 (Khosrawi et al., 2011) and did see the same behaviour in the trajectories applied in these studies. We use the trajectories from our previous Arctic studies to demonstrate that the temperature history along the trajectory does not differ that much from year to year. Especially, we demonstrate that although the total time the temperature is below T_{NAT} or T_{ice} is changing for individual trajectories, that the increase in time temperatures are below T_{NAT} or T_{ice} due to an increase in H_2O mixing ratio or a cooling of stratospheric temperature is comparable for all years (see supplement to this reply). We discuss this in section 6 and based on the comment made by referee 2 we changed the sentence as follow and hope that we get the message through now: *As a consequence the total times where the temperature was below T_{NAT} or T_{ice}, respectively, would have been shorter as for the Arctic winter 2010/11. However, the resulting increase in time due to a decrease in temperature and an increase in water vapour can be expected to be similar, thus as dramatic as for the 2010/11 winter.*

Another issue with the analysis is the use of absolute values of time is somewhat meaningless given the arbitrary number of tracks selected. Thus, I would suggest identifying increases in relative terms (percentage increase relative to the base state). This relative analysis would also allow the trajectories from other years to be directly compared though obviously with less certainty given the likely fewer number of tracks to be calculated.

We agree and while writing the manuscript, we have already considered using the percentage of time increased relative to the base case, however we decided against it due to the following reasons: (1) for the most extreme changes considered in our study (T$-$1 K and H_2O+1 ppmv) we derive enhancements of 800-1000% which are not very handy numbers. (2) It is much easier to discuss in the text "total hours" than the "percentage time in relation to the total hours".

Small-scale processes and errors in the reanalyses: A number of studies have shown that the reanalyses temperature can be rather biased (e.g. Boc-

cara et al., 2008) and this means that the temperature values derived from NCEP can have uncertainties which might be comparable to the temperature variations considered. In addition, while it is mentioned that several studies have identified the impact of small-scale wave temperature perturbations on PSC occurrence this also builds uncertainty into the impact of the prescribed temperature decrease. Without consideration of these factors the uncertainty on the results from the trajectory analysis is unknown, but I would guess from previous studies might be sizable. Thus, some type of uncertainty analysis perhaps using Monte-Carlo analysis would add real value to the study in my opinion.

Small-scale processes as well as uncertainties in the reanalyses have the same effect on temperatures. Both cause temperatures to be somewhat higher or lower so that the threshold temperatures may in some cases where temperatures are close to the threshold temperatures may just be reached or just not reached. The temperature cooling of 1 K that we consider in our study shows on the other hand what a 1 K warm bias in e.g meteorological analyses would mean. This would cause an enhancement of the total time temperatures would be below T_{NAT} or T_{ice} and thus cause a prolongation of potential PSC existence. However, the increase in time where temperatures are below T_{NAT} or T_{ice} when H_2O mixing ratios are increased is comparable to our base case. Thus, uncertainties of meteorological analyses or small-scale variability have no influence on our conclusion that increase in H_2O or a cooling of the stratosphere will enhance the potential for PSC formation. To demonstrate this more clearly we picked two trajectories and repeated our sensitivity study on single trajectories with assuming a warm bias and a cold bias of 2 K (see supplement to this reply). In section 6 (P17764, l17ff) we added the following sentence at the end of the paragraph: *However, irrespective of if there is a warm or cold bias in the trajectory temperature or the water vapour mixing ratio in the stratosphere, an increase in water vapour mixing ratios or a cooling of temperature will definitely result in a prolongation of the potential for PSC existence as shown in our sensitivity study.*

Linear trend analysis: This analysis seems like an afterthought and given the difficulty in intercalibrating the various satellite datasets to the level required to observe a small trend makes me wonder whether this portion of the analysis is an unnecessary distraction. I would advise thinking seriously about whether this analysis really adds value. In particular, I would suggest that a rigorous trend analysis using this many satellite datasets is a large paper in its own right.

The reason why we have these two parts in the paper lies in the motivation of our study which is to investigate if there is a connection between increases in stratospheric water vapour and the widespread severe denitrification that was observed during the recent Arctic winters 2009/2010 and 2010/2011.

Therefore, we on one hand investigate the sensitivity of PSC existence on water vapour and temperature changes in the lower stratosphere, and on the other hand we investigate if there is a trend in water vapour observed in the lower stratosphere. Therefore, both parts of the paper are important. The motivation of our study is "not" to investigate a "long-term trend" in stratospheric water vapour. Such studies are currently being performed in the frame of SPARC Water Vapour Assessment (WAVAS) and will be published in the near future. In which order the results are presented seems to be a matter of taste. In the course of writing up our results we swapped the order several times but came in the end to the conclusion that the order as we have it now is the best. To remind the reader why we have these two parts in the paper we added the following sentences at the beginning of section 5: *In the previous sections we demonstrated that a water vapour increase and temperature decrease would increase the potential for PSC formation. More than a decade ago it was already suggested that a cooling of stratospheric temperatures by 1 K or an increase of 1 ppmv of stratospheric water vapour could promote denitrification (Santee et al., 1995; Tabazadeh et al., 2000). During the two Arctic winters 2009/10 and 2010/11, the strongest denitrification in the recent decade was observed (Khosrawi et al., 2011; Khosrawi et al., 2012). Here, we investigate the variability of Arctic water vapour and temperature since the new millennium to see if there is a connection to the severe denitrification observed in the past years.*

Reply to Referee 1 Comments - Supplement

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Sensitivity of polar stratospheric cloud formation to changes in water vapour and temperature

The sensitivity study performed on single back trajectories as presented in our paper for the Arctic winter 2010/2011 is repeated here applying trajectories from other Arctic winters, namely the Arctic winters 2009/2010, 2008/2009, 2007/2008 and 2004/2005. From our previous Arctic studies (Blum et al., 2005; Khosrawi et al., 2011 and Achtert et al., 2011) we have calculated trajectories with the HYSPLIT and the CLaMS (Chemical Lagrangian Model of the Stratosphere) model, respectively. The trajectories were calculated based on PSC measurements from the IRF lidar and the Esrange lidar, both located in Kiruna, Northern Sweden as well as the Alomar lidar located at Andøya Rocket Range in Northern Norway.

It does not matter for which Arctic winter the trajectories were calculated. They all show the same behaviour. A temperature decrease or water vapour increase will prolong the time periods where the temperature is below the threshold temperatures for T_{NAT} and T_{ice}.

The same holds if we take into account potential uncertainties of the trajectory temperatures. We perform our sensitivity study on single trajectories and assess the impact a potential temperature bias would have on our results.The temperatures along the trajectories were thus increased by 2 K (corresponding to a cold bias) and decreased by 2 K (corresponding to a warm bias), respectively. The total time the temperatures along the trajectory are below T_{NAT} and T_{ice}, respectively, is changing accordingly, but the increase in time is comparable to the times we derive without assuming a temperature bias.

1. Other Arctic winters

1.1 Arctic winter 2009/2010:

The Arctic vortex formed in December 2009. A Canadian warming in mid-December caused a vortex split. Nevertheless, the polar vortex recovered and gained strength again. Although the Arctic winter 2009/2010 was rather warm in the climatological sense, the 2009/2010 winter was distinguished by a cold phase extending over four weeks. Between mid-December and mid-January the vortex cooled down to temperatures below T_{ice} (both by orographic waves and synoptic cooling) leading to extensive PSC formation during this time period (Khosrawi et al., 2011 and references therein).

17 January 2010
On 17 January a PSC was measured by both the IRF and the Esrange lidar. The PSC was observed between 19 and 26 km and was mainly composed of STS. The trajectory considered here was calculated 6-days backward based on the PSC measured by the IRF lidar on 17 January and was started on 17 January 01 UTC at 22 km.

Along the trajectories temperatures drop below T_{NAT} twice (at t=−135 to t=−110, temperature range T_1, and at t=−10 to t=0, temperature range T_2). With increasing H_2O

mixing ratios (Case A), the time the temperatures drops below T_{NAT} is increasing by a few hours for both temperature ranges (Figure 1). If additionally the temperature is decreased by 1 K (Case B), the time where the temperatures drop below T_{NAT} is further prolonged and still slightly increasing when the H_2O mixing ratio is increased (Table 1).

Table 1: Time periods when T_1 and T_2 are below the NAT and ice threshold temperature along the trajectory. T_{NAT} and T_{ice} were derived for H_2O mixing ratios of 5, 5.5. and 6 ppmv for the back trajectory started on 17 January 2010 at 01:00 UTC. Water vapour increases (Case A) as well as an additional temperature cooling by 1 K (Case B) are considered.

	Case A				Case B			
H_2O (ppmv)	$T_1 < T_{\text{NAT}}$ (h)	$T_1 < T_{\text{ice}}$ (h)	$T_2 < T_{\text{NAT}}$ (h)	$T_2 < T_{\text{ice}}$ (h)	$T_1 < T_{\text{NAT}}$ (h)	$T_1 < T_{\text{ice}}$ (h)	$T_2 < T_{\text{NAT}}$ (h)	$T_2 < T_{\text{ice}}$ (h)
5	24	–	10	–	27	–	12	–
5.5	26	–	11	–	28	–	13	–
6	27	–	11	–	28	–	14	–

23 January 2010

On 23 January 2010 a PSC was observed by both the IRF and the Esrange lidar. The PSC was observed between 18 and 26 km and was composed of STS and NAT particles. The trajectory considered here was calculated 6-days backward based on the PSC observed by the Esrange lidar on 23 January and was started on 23 January at 19 UTC at 22 km.

Temperatures drop below T_{NAT} twice along the trajectory (at t=−140 to t=−95, temperature range T_1, and at t=−30 to t=0, temperature range T_2) and once below T_{ice} within the temperature range T_2 (at t=−140 to t=−125). With increasing H_2O mixing ratios (Case A), the time the temperatures drop below T_{NAT} and T_{ice}, respectively, is increasing (Figure 2). The temperature where the temperature is below T_{NAT} and T_{ice}, respectively, is prolonged by several hours. If additionally the temperature is decreased by 1 K (Case B), the time where the temperatures are below T_{NAT} is further prolonged and increasing when the H_2O mixing ratio is increased. For 5.5 ppmv and 6 ppmv also during the temperature T_2 temperatures drop below T_{ice} significantly (Table 2).

Table 2: Time periods when T_1 and T_2 are below the NAT and ice threshold temperature along the trajectory. T_{NAT} and T_{ice} were derived for H_2O mixing ratios of 5, 5.5 and 6 ppmv for the back trajectory started on 23 January 2010 at 19:00 UTC. Water vapour increases (Case A) as well as an additional temperature cooling by 1 K (Case B) are considered.

	Case A				Case B			
H_2O (ppmv)	$T_1 < T_{\text{NAT}}$ (h)	$T_1 < T_{\text{ice}}$ (h)	$T_2 < T_{\text{NAT}}$ (h)	$T_2 < T_{\text{ice}}$ (h)	$T_1 < T_{\text{NAT}}$ (h)	$T_1 < T_{\text{ice}}$ (h)	$T_2 < T_{\text{NAT}}$ (h)	$T_2 < T_{\text{ice}}$ (h)
5	48	18	29	–	49	26	31	–
5.5	48	21	30	–	50	27	32	6
6	49	26	33	–	51	29	32	14

1.2 Arctic winter 2008/2009:

Until 8 January the circulation in the stratosphere was undisturbed with a strong cyclonic vortex and very weak planetary wave activity. The vortex was very cold during that time period, with a minimum of −93°C at 10 hPa over Iceland. A major Warming occurred on 24 January 2009 and ended the Arctic winter abruptly. This major warming was the strongest and most prolonged warming on record (Manney et al., 2009, Labitzke and Kunze, 2009).

8 January 2009

A PSC was observed on 8 January 2009 with the Esrange lidar at 22-28 km. The PSC was composed of STS with NAT layers inbetween. The trajectory considered here was calculated 6-days backward based on the PSC observed by the Esrange lidar on 8 January and was started on 8 January at 22 UTC at 23 km.

Along the trajectory temperatures drop below T_{NAT} once (at t=−18 to t=−0, temperature range T_2) (Figure 3). With increasing H_2O mixing ratios (Case A), the time the temperatures drop below T_{NAT} is increasing by a few hours (from 16 to 20 h for an increase in H_2O mixing ratios of 1 ppmv). Temperatures also start to drop then below T_{NAT} for the temperature range T_1, though only for 1 h, which in this case can be neglected. However, this temperature drop becomes more important when additionally the temperature is decreased. If additionally the temperature is decreased by 1 K (Case B), the time where the temperatures drop below T_{NAT} is further prolonged and still slightly increasing when the H_2O mixing ratio is increased. For the temperature range T_1 the increase is quite significant from 2 h for a H_2O mixing ratio of 5 ppmv to 9 h for a H_2O mixing ratio of 6 ppmv (Table).

Table 3: Time periods when T_1 and T_2 are below the NAT and ice threshold temperature along the trajectory. T_{NAT} and T_{ice} were derived for H_2O mixing ratios of 5, 5.5 and 6 ppmv for the back trajectory started on 8 January 2009 at 22:00 UTC. Water vapour increases (Case A) as well as an additional temperature cooling by 1 K (Case B) are considered.

	Case A				Case B			
H_2O (ppmv)	$T_1 < T_{\mathrm{NAT}}$ (h)	$T_1 < T_{\mathrm{ice}}$ (h)	$T_2 < T_{\mathrm{NAT}}$ (h)	$T_2 < T_{\mathrm{ice}}$ (h)	$T_1 < T_{\mathrm{NAT}}$ (h)	$T_1 < T_{\mathrm{ice}}$ (h)	$T_2 < T_{\mathrm{NAT}}$ (h)	$T_2 < T_{\mathrm{ice}}$ (h)
5	–	–	16	–	2	–	21	–
5.5	1	–	19	–	6	–	22	–
6	1	–	20	–	9	–	23	–

9 January 2009

A PSC was observed on 9 January 2009 with the Esrange lidar at 22-25 km. The PSC was composed of STS with NAT layers inbetween. The trajectory considered here was calculated 6-days backward based on the PSC observed by the Esrange lidar on 9 January and was started on 9 January at 01 UTC at 22 km.

Along the trajectory temperatures drop below T_{NAT} once (at t=−16 to t=−0, temperature range T_2) (Figure). The time period where the temperatures drop below T_{NAT} is increasing by a few hours if the H_2O mixing ratios are increasing (Case A), e.g. from 16 to 20 h for an increase in H_2O mixing ratio by 1 ppmv. If additionally the temperature is decreased by 1 K (Case B), the time where the temperatures drop below T_{NAT} is further prolonged and still slightly increasing when the H_2O mixing ratio is increased. If a cooling of 1 K and an increase of H_2O mixing ratio of 0.5-1 ppmv is considered, temperatures also drop below T_{ice} for a few hours during temperature range T_1 (Table).

Table 4: Time periods when T_1 and T_2 are below the NAT and ice threshold temperature along the trajectory. T_{NAT} and T_{ice} were derived for H_2O mixing ratios of 5, 5.5 and 6 ppmv for the back trajectory started on 9 January 2009 at 01:00 UTC. Water vapour increases (Case A) as well as an additional temperature cooling by 1 K (Case B) are considered.

	Case A				Case B			
H_2O (ppmv)	$T_1 < T_{\mathrm{NAT}}$ (h)	$T_1 < T_{\mathrm{ice}}$ (h)	$T_2 < T_{\mathrm{NAT}}$ (h)	$T_2 < T_{\mathrm{ice}}$ (h)	$T_1 < T_{\mathrm{NAT}}$ (h)	$T_1 < T_{\mathrm{ice}}$ (h)	$T_2 < T_{\mathrm{NAT}}$ (h)	$T_2 < T_{\mathrm{ice}}$ (h)
5	–	–	16	–	–	–	20	–
5.5	–	–	19	–	2	–	21	–
6	–	–	20	–	3	–	22	–

1.3 Arctic winter 2007/2008:

The Arctic polar stratosphere cooled down as usual in November/December 2007 as the polar vortex grew in strength. Temperatures necessary for the formation of polar stratospheric clouds were reached by mid-December. The temperatures remained cold enough for PSC formation until late February 2008. Since mid January several minor warmings disturbed the polar stratosphere and a major warming in late February ended the conditions favourable for PSC formation (from: http://www.ozone-sec.ch.cam.ac.uk/EORCU/arctic_reports.html). In January 2008 the polar vortex was located over the Norwegian Sea and Barents Sea. In mid-January, the vortex moved slightly toward Scandinavia. Between 15 and 35 hPa (20-25 km) the temperatures above Esrange decreased below the existence temperature of STS and even reached below T_{ice} in mid January (Achtert et al., 2011).

22 January 2008

A PSC was observed on 22 January 2008 with the Esrange lidar at 19-26 km. The PSC was composed of STS with NAT layers inbetween. The trajectory considered here was calculated 6-days backward with HYSPLIT. The trajectory was started on 22 January at 22 UTC at 24 km.

Temperatures drop below T_{NAT} twice along the trajectory (at t=−141 to t=−82, temperature range T_1, and at t=−29 to t=0, temperature range T_2). With increasing H_2O mixing ratios (Case A), the time the temperatures drop below T_{NAT} is increasing (Figure 5). The time period where the temperature is below T_{NAT} is prolonged by 3-4 hours for an increase in H_2O mixing ratio of 1 ppmv. If additionally the temperature is decreased by 1 K (Case B), the time where the temperatures are below T_{NAT} is further prolonged and increasing when the H_2O mixing ratio is increased (Table 5).

Table 5: Time periods when T_1 and T_2 are below the NAT and ice threshold temperature along the trajectory. T_{NAT} and T_{ice} were derived for H_2O mixing ratios of 5, 5.5 and 6 ppmv for the back trajectory started on 22 January 2008 at 22:00 UTC. Water vapour increases (Case A) as well as an additional temperature cooling by 1 K (Case B) are considered.

	Case A				Case B			
H_2O (ppmv)	$T_1 < T_{NAT}$ (h)	$T_1 < T_{ice}$ (h)	$T_2 < T_{NAT}$ (h)	$T_2 < T_{ice}$ (h)	$T_1 < T_{NAT}$ (h)	$T_1 < T_{ice}$ (h)	$T_2 < T_{NAT}$ (h)	$T_2 < T_{ice}$ (h)
5	54	–	29	–	58	–	35	–
5.5	56	–	30	–	60	–	36	–
6	57	–	34	–	62	–	38	–

23 January 2008

A PSC was observed on 23 January 2008 with the Esrange lidar at 19-26 km. The PSC was composed of STS with NAT layers inbetween. The trajectory considered here was calculated 6-days backward with HYSPLIT. The trajectory was started on 23 January at 01 UTC at 24 km.

Temperatures drop below T_{NAT} twice along the trajectory (at t=−127 to t=−85, temperature range T_1, and at t=−21 to t=0, temperature range T_2). With increasing H_2O mixing ratios (Case A), the time the temperatures drop below T_{NAT} is increasing (Figure 6) for both T_1 and T_2 by 6 h. If additionally the temperature is decreased by 1 K (Case B), the time where the temperatures are below T_{NAT} is further prolonged and increasing by 4-5 h when the H_2O mixing ratio is increased (Table 6).

Table 6: Time periods when T_1 and T_2 are below the NAT and ice threshold temperature along the trajectory. T_{NAT} and T_{ice} were derived for H_2O mixing ratios of 5, 5.5 and 6 ppmv for the back trajectory started on 23 January 2008 at 01:00 UTC. Water vapour increases (Case A) as well as an additional temperature cooling by 1 K (Case B) are considered.

	Case A				Case B			
H_2O (ppmv)	$T_1 < T_{NAT}$ (h)	$T_1 < T_{ice}$ (h)	$T_2 < T_{NAT}$ (h)	$T_2 < T_{ice}$ (h)	$T_1 < T_{NAT}$ (h)	$T_1 < T_{ice}$ (h)	$T_2 < T_{NAT}$ (h)	$T_2 < T_{ice}$ (h)
5	42	–	21	–	50	–	28	–
5.5	47	–	23	–	53	–	29	–
6	48	–	27	–	54	–	33	–

1.4 Arctic winter 2004/2005:

A stable polar vortex was formed by mid-November. From early December on temperatures were low enough to allow PSC formation. The polar vortex remained cold until begin of March. In the beginning of January the vortex was centred above Greenland and northern Scandinavia, reaching temperatures below 190 K between the 15 and 25 km altitude. A minor warming occurred at the end of January, but temperatures still remained cold until 24 February where a major warming caused a vortex split. The vortex parts reunited by 1 March and by 11 March the vortex split a second time. The vortex finally broke up around 22 March (Blum et al., 2006; Rösevall et al., 2008)

5 January 2005

On 5 January 2005 a PSC was observed between 19 and 22 km simultaneously on the east and west sides of the Scandinavian mountains by ground-based lidars (Esrange and Alomar lidar). This cloud was composed of liquid particles with a mixture of solid particles in the upper part of the cloud. The trajectory considered here was calculated 5-days backward with CLaMS using UKMO meteorological analysis.

Temperatures drop below T_{NAT} twice along the trajectory (at t=−111 to t=−51, temperature range T_1, and at t=−30 to t=0, temperature range T_2). With increasing H_2O mixing ratios (Case A), the time where the temperatures drop below T_{NAT} is increasing (Figure 7) for both T_1 and T_2 by 4 h. If additionally the temperature is decreased by 1 K (Case B), the time where the temperatures are below T_{NAT} is further prolonged and increasing by 5 h when the H_2O mixing ratio is increased. For an increase in H_2O mixing ratio and an additional cooling of 1 K even temperatures even drop below T_{ice} for 5 h (Table 7).

Table 7: Time periods when T_1 and T_2 are below the NAT and ice threshold temperature along the trajectory. T_{NAT} and T_{ice} were derived for H_2O mixing ratios of 5, 5.5 and 6 ppmv for the back trajectory started on 5 January 2005 at 20:00 UTC. Water vapour increases (Case A) as well as an additional temperature cooling by 1 K (Case B) are considered.

	Case A				Case B			
H_2O (ppmv)	$T_1 < T_{\mathrm{NAT}}$ (h)	$T_1 < T_{\mathrm{ice}}$ (h)	$T_2 < T_{\mathrm{NAT}}$ (h)	$T_2 < T_{\mathrm{ice}}$ (h)	$T_1 < T_{\mathrm{NAT}}$ (h)	$T_1 < T_{\mathrm{ice}}$ (h)	$T_2 < T_{\mathrm{NAT}}$ (h)	$T_2 < T_{\mathrm{ice}}$ (h)
5	60	–	30	–	66	–	35	–
5.5	62	–	32	–	69	–	38	–
6	64	–	34	–	71	–	40	5

2. Sensitivity to temperature uncertainties:

Comparisons of different meteorological analyses (e. g. Manney et al., 2003) show that distributions of "potential PSC lifetime" and total time spent below a PSC formation threshold (T_{NAT} or T_{ice}) may vary significantly between the analyses. The data sets may have warm or cold biases which are not the same for every year or month considered. One specific data set may have in one month a positive bias, but in the other month a negative bias. The biases have usually the magnitude of a few degrees.

Although we found a good agreement between the temperatures at the start point of the trajectory (which coincides with the CALIPSO measurement) and the specific PSC type observed by CALIPSO at that time and altitude where the trajectory was started, we investigate the impact potential temperature uncertainties of the meteorological data set used for the trajectory calculation would have on our sensitivity study. We repeat our sensitivity study for one trajectory for the Arctic winter 2009/2010 and for one for the Arctic winter 2008/2009 assuming a potential warm and cold bias, respectively, of 2 K.

23 January 2010 - Assuming a warm bias

To investigate a potential warm bias, the temperature along the trajectory was decreased by 2 K. Since temperatures along the trajectory were already quite low, the total times where the temperature is below T_{NAT} and T_{ice} are even longer. Additionally, the ice threshold temperature is reached during the time period T_2. However, the increase in time due to increases in water vapour are comparable to the increases in time shown above (section 1).

Table 8: Time periods when T_1 and T_2 are below the NAT and ice threshold temperature along the trajectory when the temperature along the trajectory is decreased by 2 K. T_{NAT} and T_{ice} were derived for H_2O mixing ratios of 5, 5.5 and 6 ppmv for the back trajectory started on 23 January 2010 at 19:00 UTC.

H_2O (ppmv)	$T_1 < T_{\mathrm{NAT}}$ (h)	$T_1 < T_{\mathrm{ice}}$ (h)	$T_2 < T_{\mathrm{NAT}}$ (h)	$T_2 < T_{\mathrm{ice}}$ (h)
5	52	30	33	13
5.5	53	33	34	16
6	55	34	35	17

23 January 2010 - Assuming a cold bias

To investigate a potential cold bias, the temperature along the trajectory was increased by 2 K. Since temperatures along the trajectory were already quite low, the temperature still drops below T_{NAT} for T_1 and T_2. However, temperatures below T_{ice} are only reached when the water vapour mixing ratio is increased by 1 ppmv. Nevertheless, the increase in time where the temperature is below T_{NAT} due to a increase in the water vapour mixing ratio is comparable to the increases in time shown above when no bias in temperature is assumed (section 1).

Table 9: Time periods when T_1 and T_2 are below the NAT and ice threshold temperature along the trajectory when the temperature along the trajectory is increased by 2 K. T_{NAT} and T_{ice} were derived for H_2O mixing ratios of 5, 5.5 and 6 ppmv for the back trajectory started on 23 January 2010 at 19:00 UTC.

H_2O (ppmv)	$T_1 < T_{\mathrm{NAT}}$ (h)	$T_1 < T_{\mathrm{ice}}$ (h)	$T_2 < T_{\mathrm{NAT}}$ (h)	$T_2 < T_{\mathrm{ice}}$ (h)
5	40	–	25	–
5.5	42	–	25	–
6	43	2	26	–

9 January 2009 - Assuming a warm bias

The same sensitivity test as described above is performed for the trajectory started on 9 January. This trajectory was one of the warmest we considered here. Temperatures dropped only below T_{NAT} during T_2. If we assume a warm bias of 2 K in temperature, temperatures would get cold enough so that not only during T_2 temperatures drop below T_{NAT}, but also during the T_1. The increase in time due to an increase in water vapour is again comparable to the case considered in section 2.

Table 10: Time periods when T_1 and T_2 are below the NAT and ice threshold temperature along the trajectory when the temperature along the trajectory is decreased by 2 K. T_{NAT} and T_{ice} were derived for H_2O mixing ratios of 5, 5.5 and 6 ppmv for the back trajectory started on 09 January 2009 at 01:00 UTC.

H_2O (ppmv)	$T_1 < T_{\mathrm{NAT}}$ (h)	$T_1 < T_{\mathrm{ice}}$ (h)	$T_2 < T_{\mathrm{NAT}}$ (h)	$T_2 < T_{\mathrm{ice}}$ (h)
5	6	–	24	–
5.5	8	–	33	–
6	12	–	35	–

9 January 2009 - Assuming a cold bias

The temperature along the trajectory was increased by 2 K to investigate a potential cold bias. Temperatures drop below T_{NAT} once, for the time range T_2 as it was the case for this trajectory without considering any temperature biases (section 2). The total time temperatures drop below T_{NAT} is shorter when a cold bias in the trajectory temperatures is assumed, but the increase in time due to increases in H_2O mixing ratio is comparable.

Table 11: Time periods when T_1 and T_2 are below the NAT and ice threshold temperature along the trajectory when the temperature along the trajectory is increased by 2 K. T_{NAT} and T_{ice} were derived for H_2O mixing ratios of 5, 5.5 and 6 ppmv for the back trajectory started on 9 January 2009 at 01:00 UTC.

H_2O (ppmv)	$T_1 < T_{\mathrm{NAT}}$ (h)	$T_1 < T_{\mathrm{ice}}$ (h)	$T_2 < T_{\mathrm{NAT}}$ (h)	$T_2 < T_{\mathrm{ice}}$ (h)
5	–	–	7	–
5.5	–	–	8	–
6	–	–	11	–

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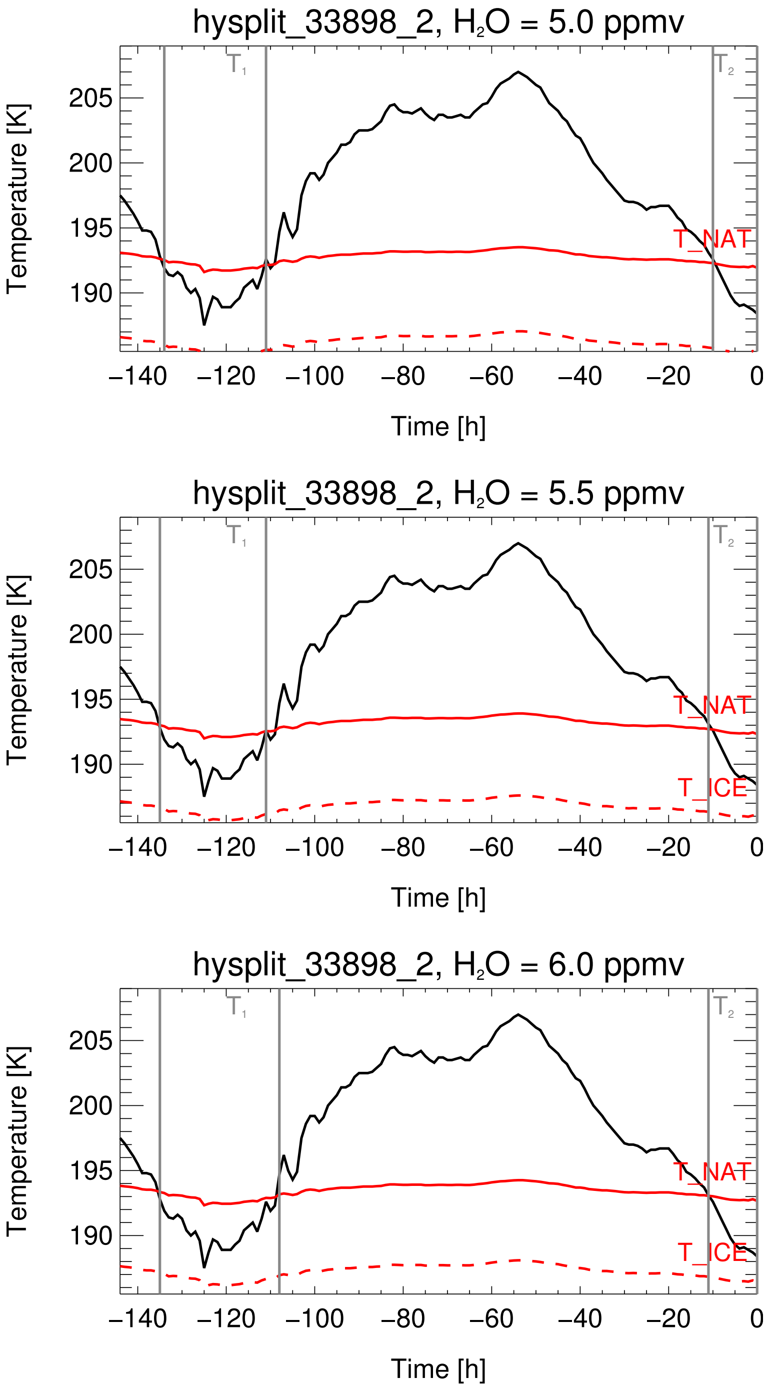

Figure 1: Temperature history of the back trajectory calculated with HYSPLIT based on the PSC measured with the IRF lidar in Kiruna, Sweden on **17 January 2010** (back trajectory started at 22 km at 01:00 UTC). Top: for a typical H_2O mixing ratio of 5 ppmv in the polar lower stratosphere, middle: for an H_2O enhancement of 0.5 ppmv (5.5 ppmv), bottom: for an H_2O enhancement of 1 ppmv (6 ppmv). The NAT existence temperature $T_{\rm NAT}$ and ice formation temperature $T_{\rm ice}$ are given as solid and dashed lines, respectively. The temperature ranges during the time periods where the temperature drops below $T_{\rm NAT}$ and $T_{\rm ice}$, respectively, are denoted by T_1 and T_2, respectively (grey solid lines).

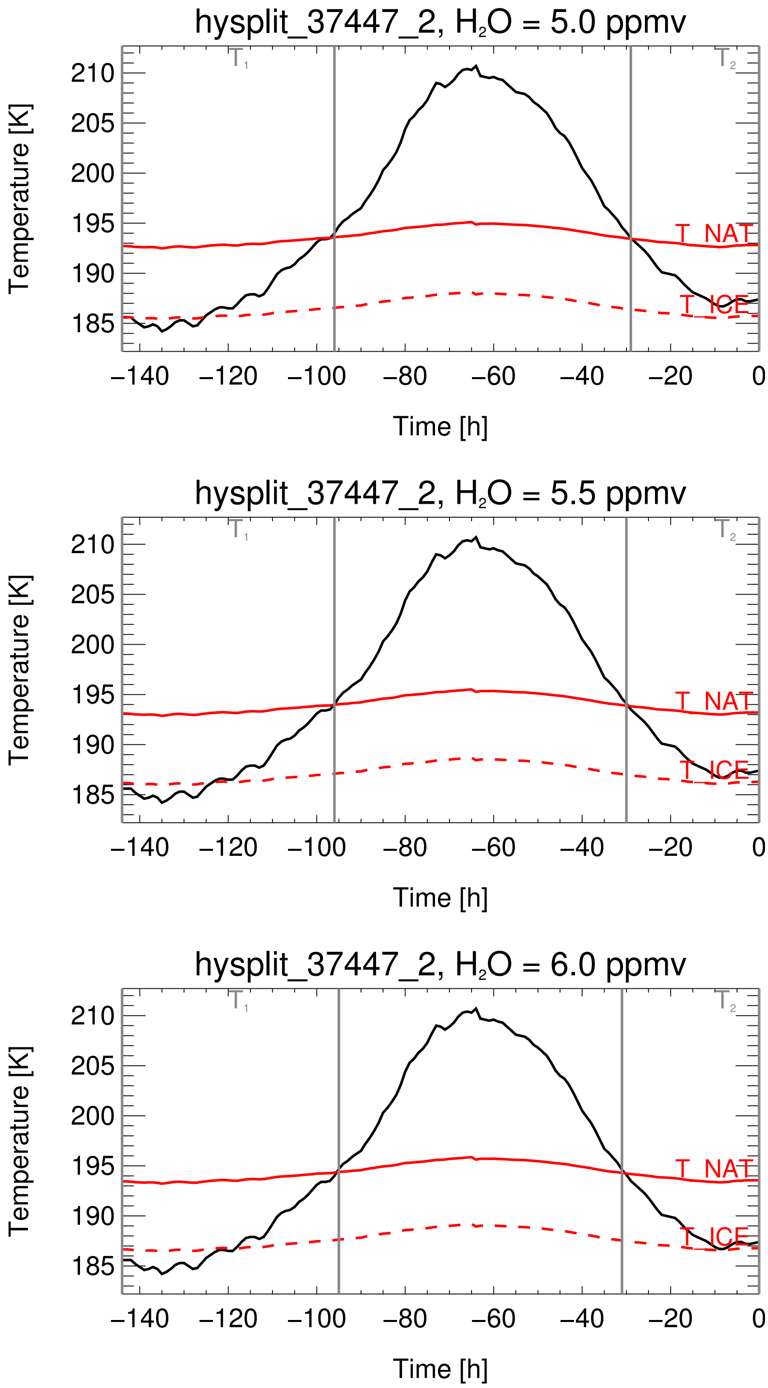

Figure 2: Temperature history of the back trajectory calculated with HYSPLIT based on the PSC observed with the Esrange lidar in Kiruna, Sweden on **23 January 2010** (back trajectory started at 22 km at 19:00 UTC). Top: for a typical H_2O mixing ratio of 5 ppmv in the polar lower stratosphere, middle: for an H_2O enhancement of 0.5 ppmv (5.5 ppmv), bottom: for an H_2O enhancement of 1 ppmv (6 ppmv). The NAT existence temperature T_{NAT} and ice formation temperature T_{ice} are given as solid and dashed lines, respectively. The temperature ranges during the time periods where the temperature drops below T_{NAT} and T_{ice}, respectively, are denoted by T_1 and T_2, respectively (grey solid lines).

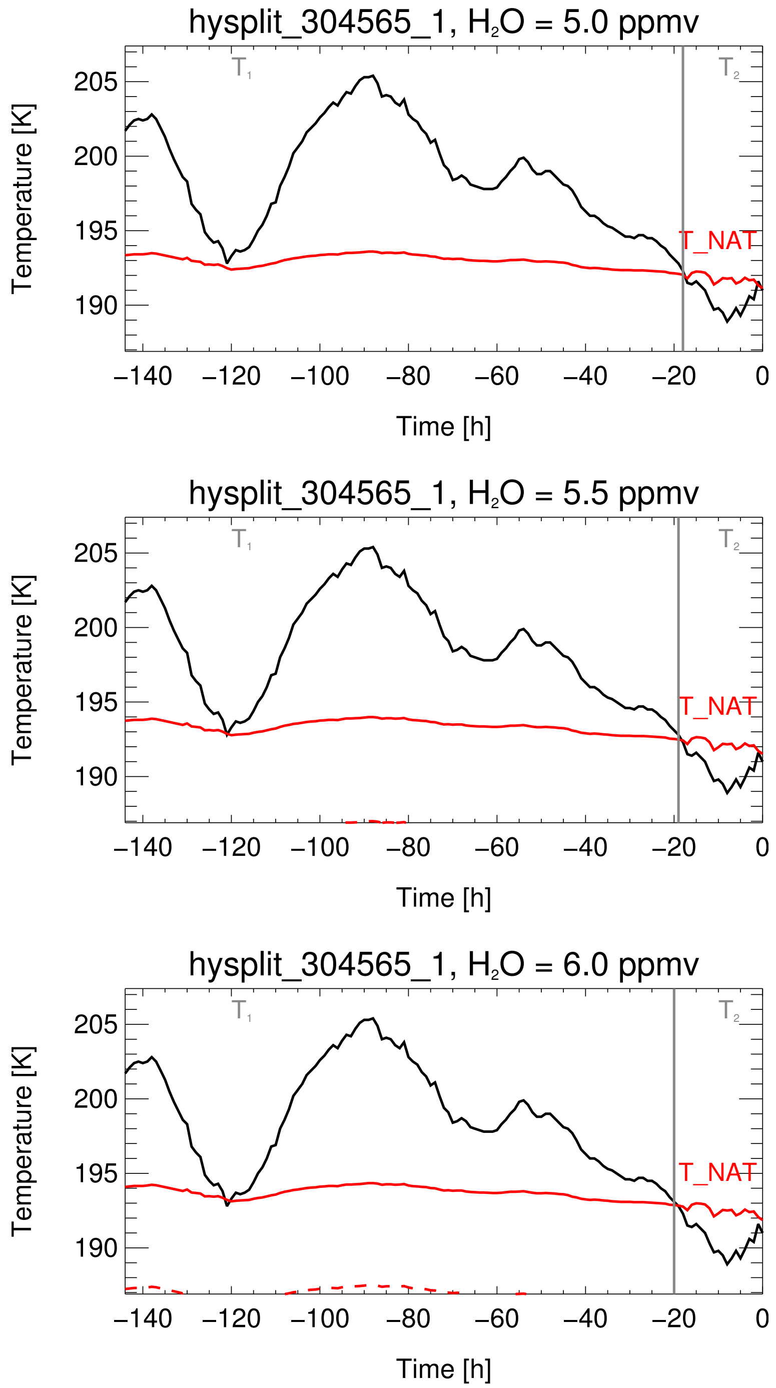

Figure 3: Temperature history of the back trajectory calculated with HYSPLIT based on the PSC observed with the Esrange lidar in Kiruna, Sweden on **8 January 2009** (back trajectory started at 23 km at 22:00 UTC). Top: for a typical H_2O mixing ratio of 5 ppmv in the polar lower stratosphere, middle: for an H_2O enhancement of 0.5 ppmv (5.5 ppmv), bottom: for an H_2O enhancement of 1 ppmv (6 ppmv). The NAT existence temperature T_{NAT} and ice formation temperature T_{ice} are given as solid and dashed lines, respectively. The temperature ranges during the time periods where the temperature drops below T_{NAT} and T_{ice}, respectively, are denoted by T_1 and T_2, respectively (grey solid lines).

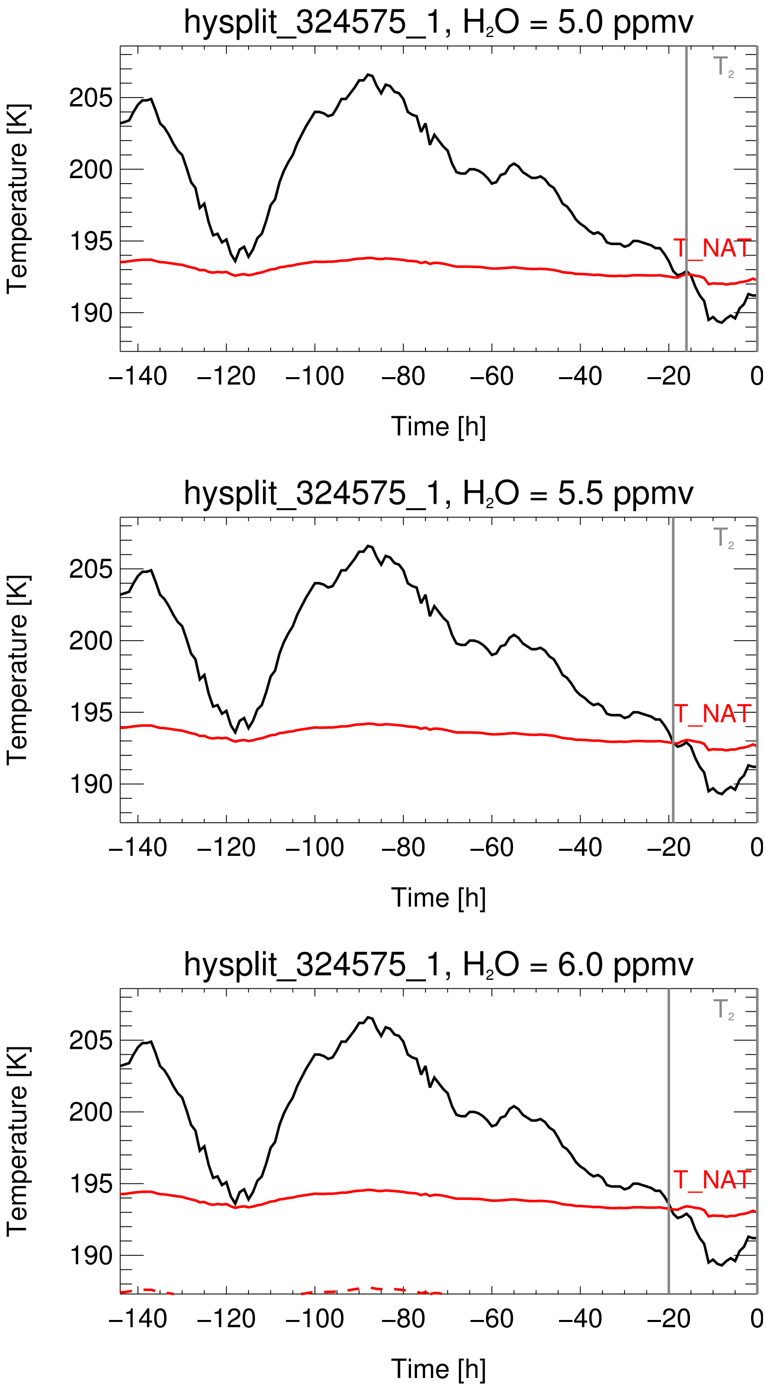

Figure 4: Temperature history of the back trajectory calculated with HYSPLIT based on the PSC observed with the Esrange lidar in Kiruna, Sweden on **9 January 2009** (back trajectory started at 22 km at 01:00 UTC). Top: for a typical H_2O mixing ratio of 5 ppmv in the polar lower stratosphere, middle: for an H_2O enhancement of 0.5 ppmv (5.5 ppmv), bottom: for an H_2O enhancement of 1 ppmv (6 ppmv). The NAT existence temperature T_{NAT} and ice formation temperature T_{ice} are given as solid and dashed lines, respectively. The temperature ranges during the time periods where the temperature drops below T_{NAT} and T_{ice}, respectively, are denoted by T_1 and T_2, respectively (grey solid lines).

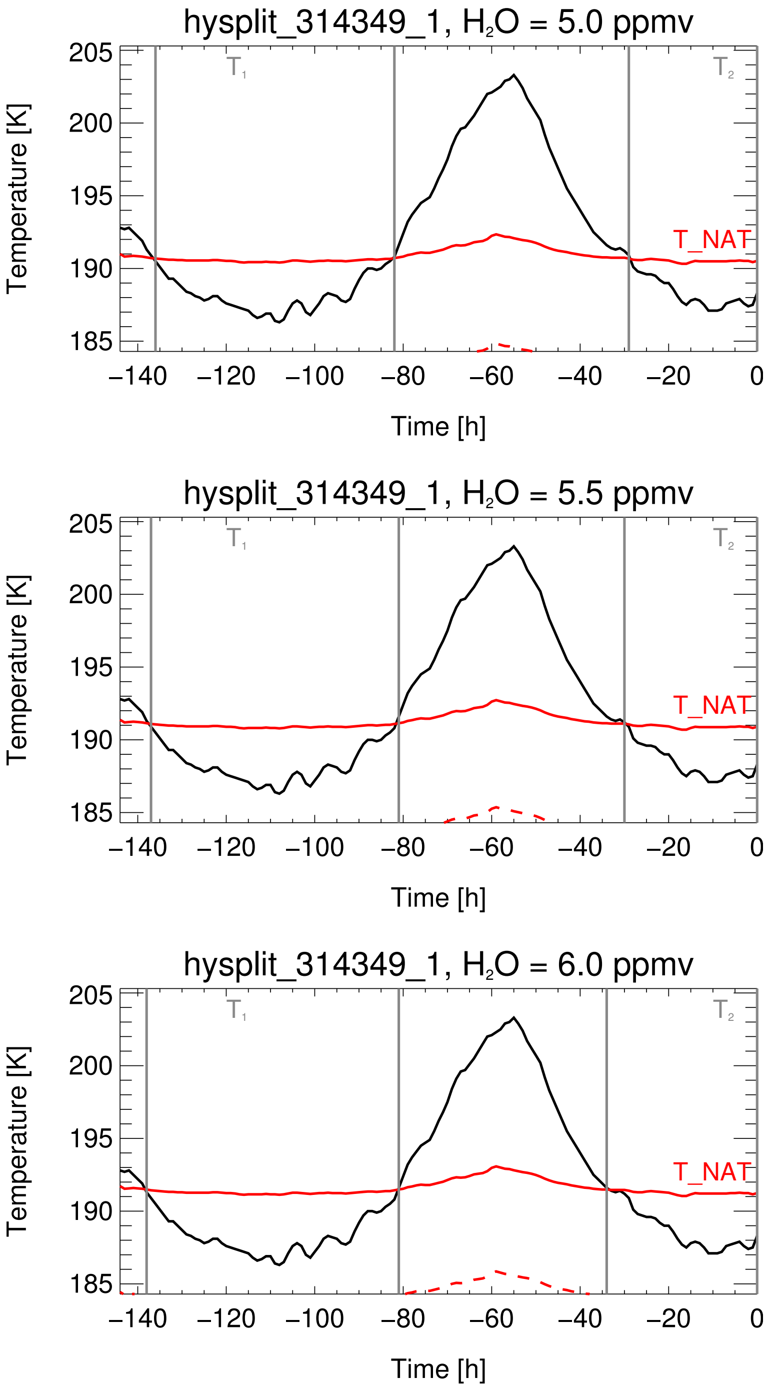

Figure 5: Temperature history of the back trajectory calculated with HYSPLIT based on the PSC observed with the Esrange lidar in Kiruna, Sweden on **22 January 2008** (back trajectory started at 24 km at 22:00 UTC). Top: for a typical H_2O mixing ratio of 5 ppmv in the polar lower stratosphere, middle: for an H_2O enhancement of 0.5 ppmv (5.5 ppmv), bottom: for an H_2O enhancement of 1 ppmv (6 ppmv). The NAT existence temperature $T_{\rm NAT}$ and ice formation temperature $T_{\rm ice}$ are given as solid and dashed lines, respectively. The temperature ranges during the time periods where the temperature drops below $T_{\rm NAT}$ and $T_{\rm ice}$, respectively, are denoted by T_1 and T_2, respectively (grey solid lines).

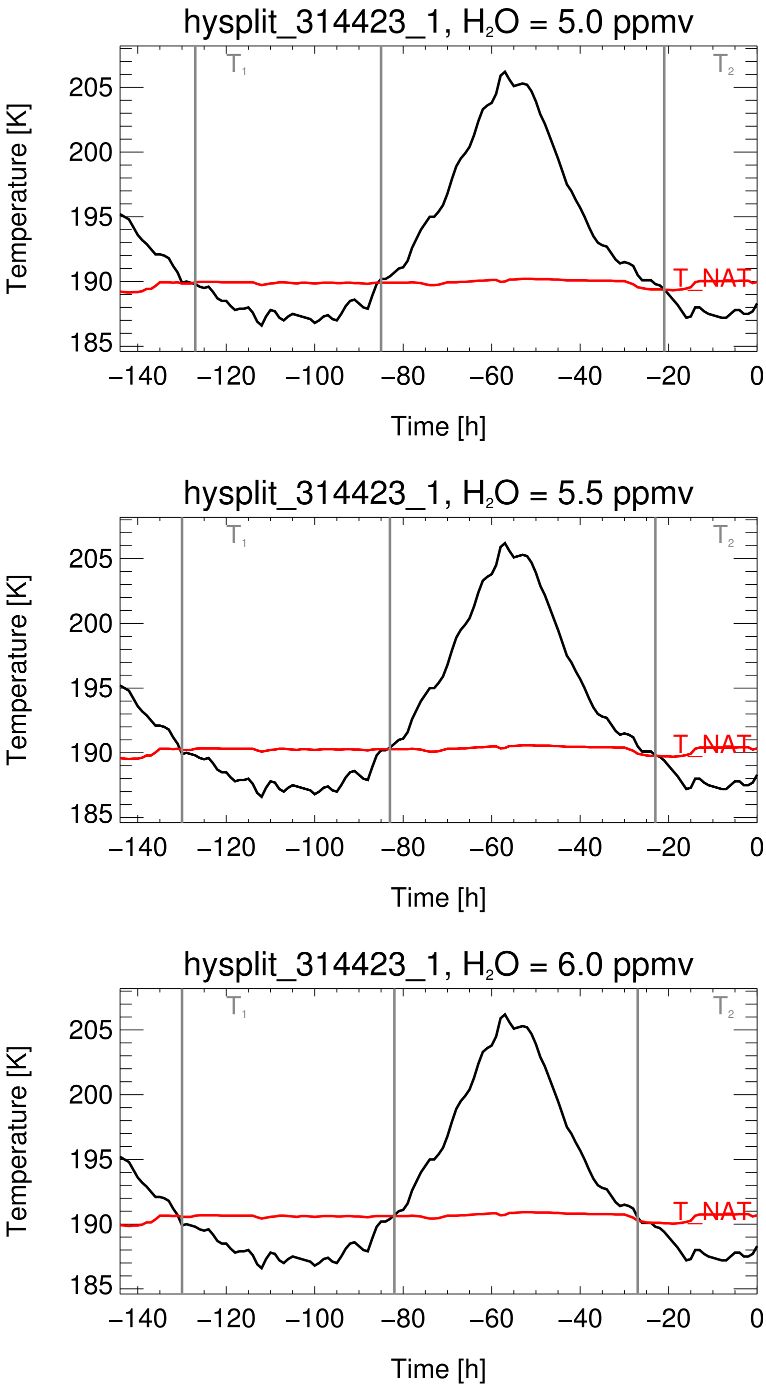

Figure 6: Temperature history of the back trajectory calculated with HYSPLIT based on the PSC observed with the Esrange lidar in Kiruna, Sweden on **23 January 2008** (back trajectory started at 24 km at 01:00 UTC). Top: for a typical H_2O mixing ratio of 5 ppmv in the polar lower stratosphere, middle: for an H_2O enhancement of 0.5 ppmv (5.5 ppmv), bottom: for an H_2O enhancement of 1 ppmv (6 ppmv). The NAT existence temperature $T_{textrmNAT}$ and ice formation temperature $T_{\rm ice}$ are given as solid and dashed lines, respectively. The temperature ranges during the time periods where the temperature drops below $T_{\rm NAT}$ and $T_{\rm ice}$, respectively, are denoted by T_1 and T_2, respectively (grey solid lines).

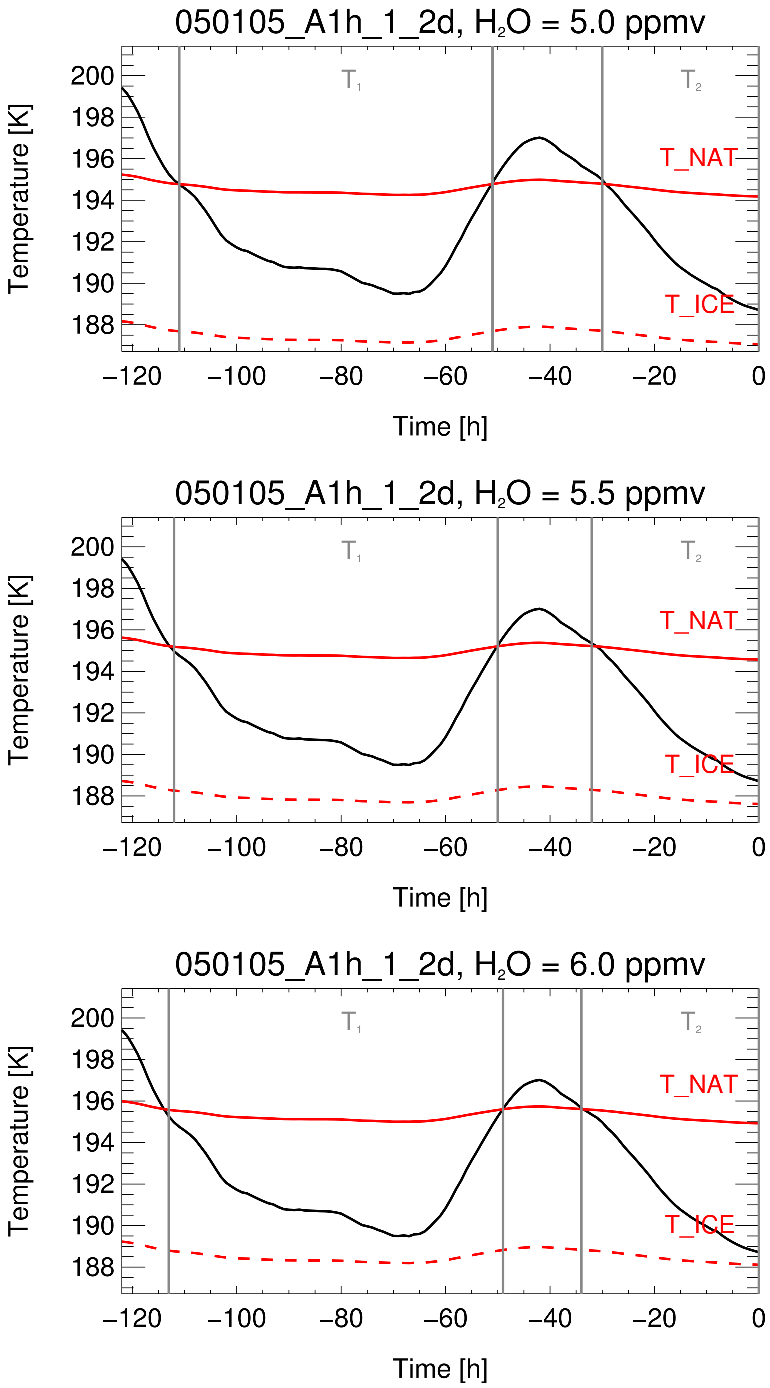

Figure 7: Temperature history of the back trajectory calculated with the CLaMS trajectory tool based on the PSC observed with the Alomar lidar in Norway on **5 January 2005** (back trajectory started at 18 km at 20:00 UTC). Top: for a typical H_2O mixing ratio of 5 ppmv in the polar lower stratosphere, middle: for an H_2O enhancement of 0.5 ppmv (5.5 ppmv), bottom: for an H_2O enhancement of 1 ppmv (6 ppmv). The NAT existence temperature T_{NAT} and ice formation temperature T_{ice} are given as solid and dashed lines, respectively. The temperature ranges during the time periods where the temperature drops below T_{NAT} and T_{ice}, respectively, are denoted by T_1 and T_2, respectively (grey solid lines).

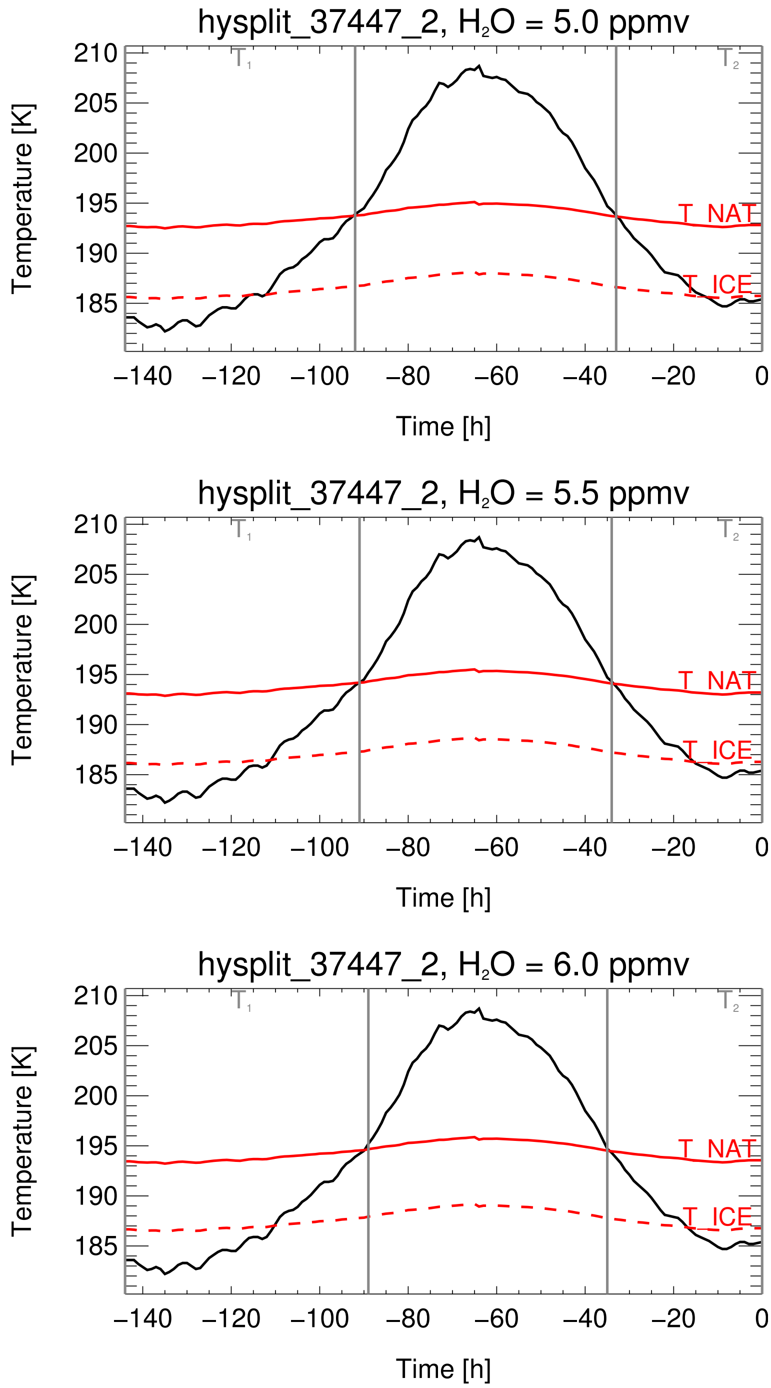

Figure 8: Temperature history of the back trajectory calculated with HYSPLIT based on the PSC observed with the Esrange lidar in Sweden on **23 January 2010** (back trajectory started at 22 km at 19:00 UTC). The temperature along the trajectory has been decreased by 2 K **(T−2 K)**. Top: for a typical H_2O mixing ratio of 5 ppmv in the polar lower stratosphere, middle: for an H_2O enhancement of 0.5 ppmv (5.5 ppmv), bottom: for an H_2O enhancement of 1 ppmv (6 ppmv). The NAT existence temperature T_{NAT} and ice formation temperature T_{ice} are given as solid and dashed lines, respectively. The temperature ranges during the time periods where the temperature drops below T_{NAT} and T_{ice}, respectively, are denoted by T_1 and T_2, respectively (grey solid lines).

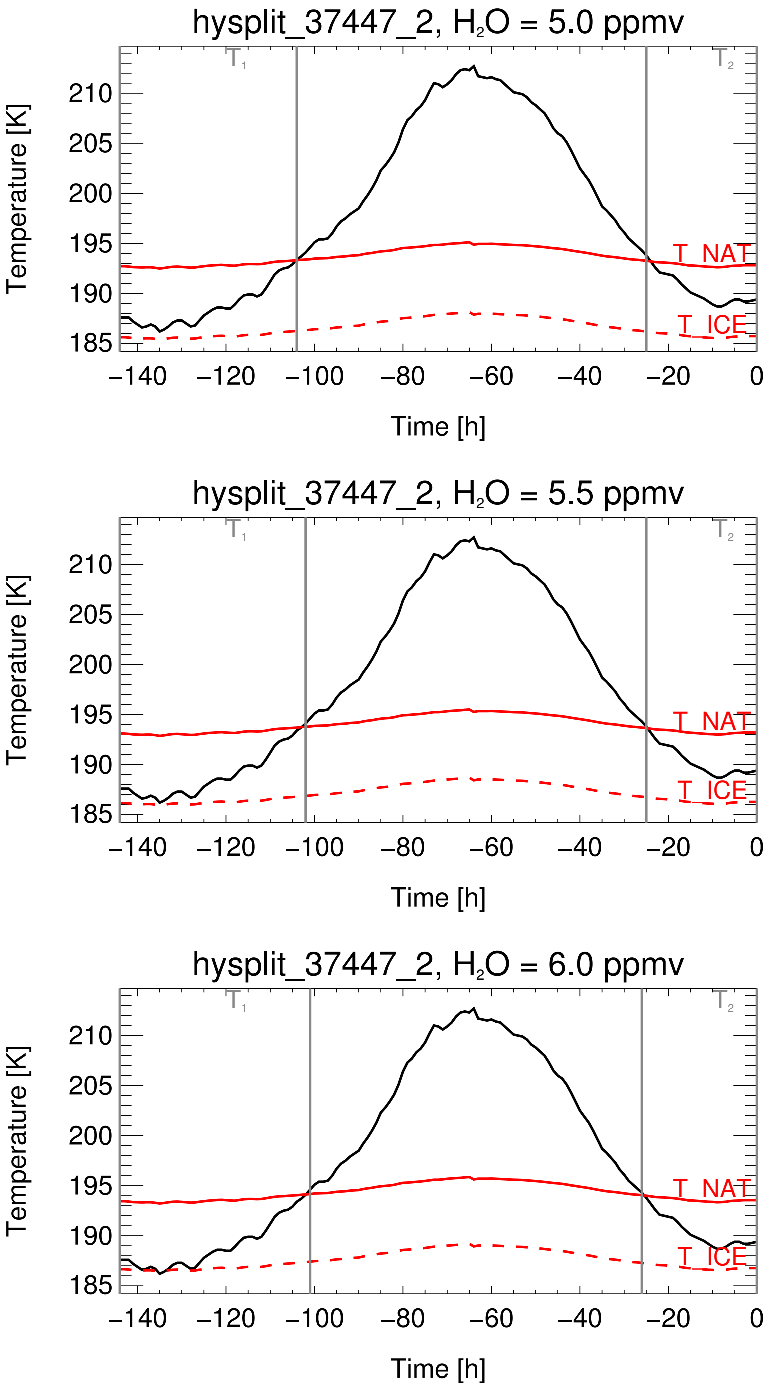

Figure 9: Temperature history of the back trajectory calculated with HYSPLIT based on the PSC observed with the Esrange lidar in Sweden on **23 January 2010** (back trajectory started at 22 km at 19:00 UTC). The temperature along the trajectory has been increased by 2 K **(T+2 K)**. Top: for a typical H_2O mixing ratio of 5 ppmv in the polar lower stratosphere, middle: for an H_2O enhancement of 0.5 ppmv (5.5 ppmv), bottom: for an H_2O enhancement of 1 ppmv (6 ppmv). The NAT existence temperature T_{NAT} and ice formation temperature T_{ice} are given as solid and dashed lines, respectively. The temperature ranges during the time periods where the temperature drops below T_{NAT} and T_{ice}, respectively, are denoted by T_1 and T_2, respectively (grey solid lines).

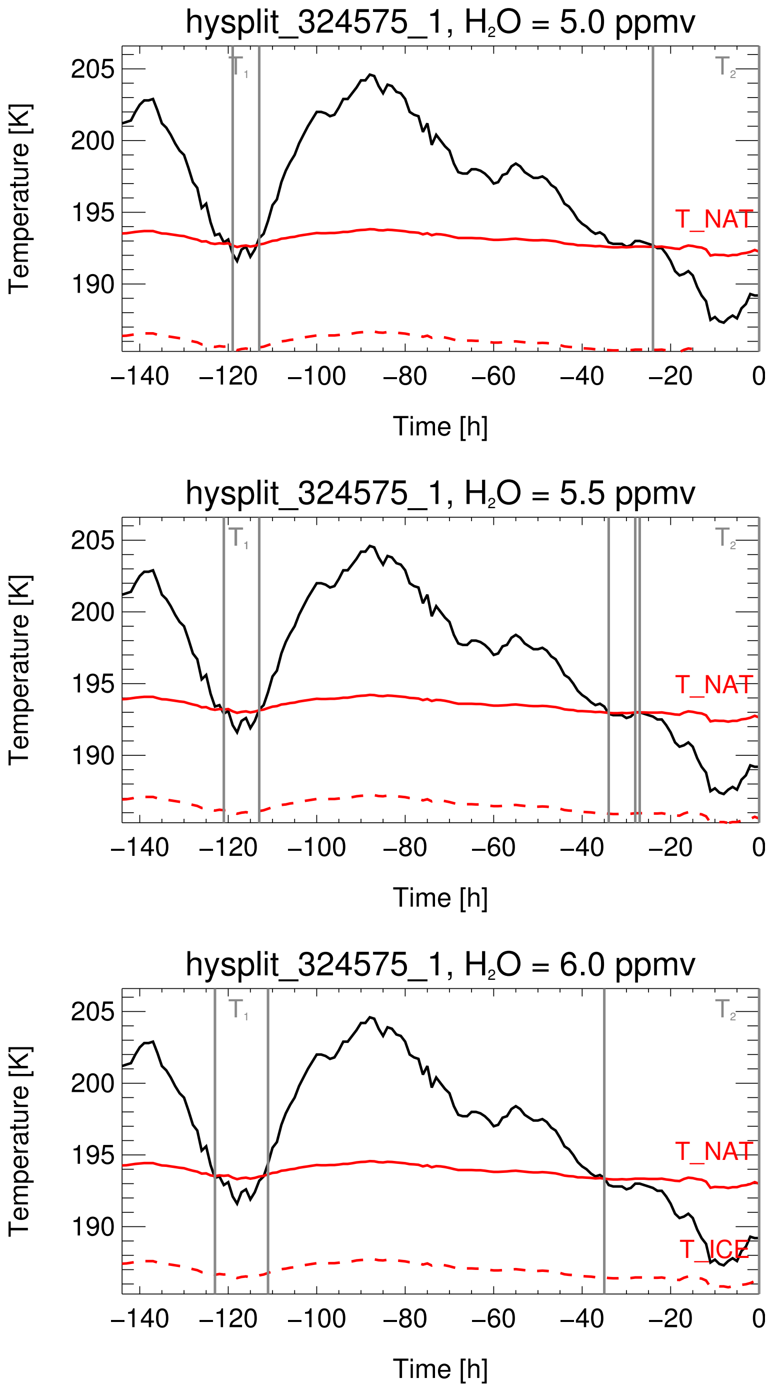

Figure 10: Temperature history of the back trajectory calculated with HYSPLIT based on the PSC observed with the Esrange lidar in Sweden on **09 January 2009** (back trajectory started at 22 km at 01:00 UTC). The temperature along the trajectory has been decreased by 2 K **(T−2 K)**. Top: for a typical H_2O mixing ratio of 5 ppmv in the polar lower stratosphere, middle: for an H_2O enhancement of 0.5 ppmv (5.5 ppmv), bottom: for an H_2O enhancement of 1 ppmv (6 ppmv). The NAT existence temperature T_{NAT} and ice formation temperature T_{ice} are given as solid and dashed lines, respectively. The temperature ranges during the time periods where the temperature drops below T_{NAT} and T_{ice}, respectively, are denoted by T_1 and T_2, respectively (grey solid lines).

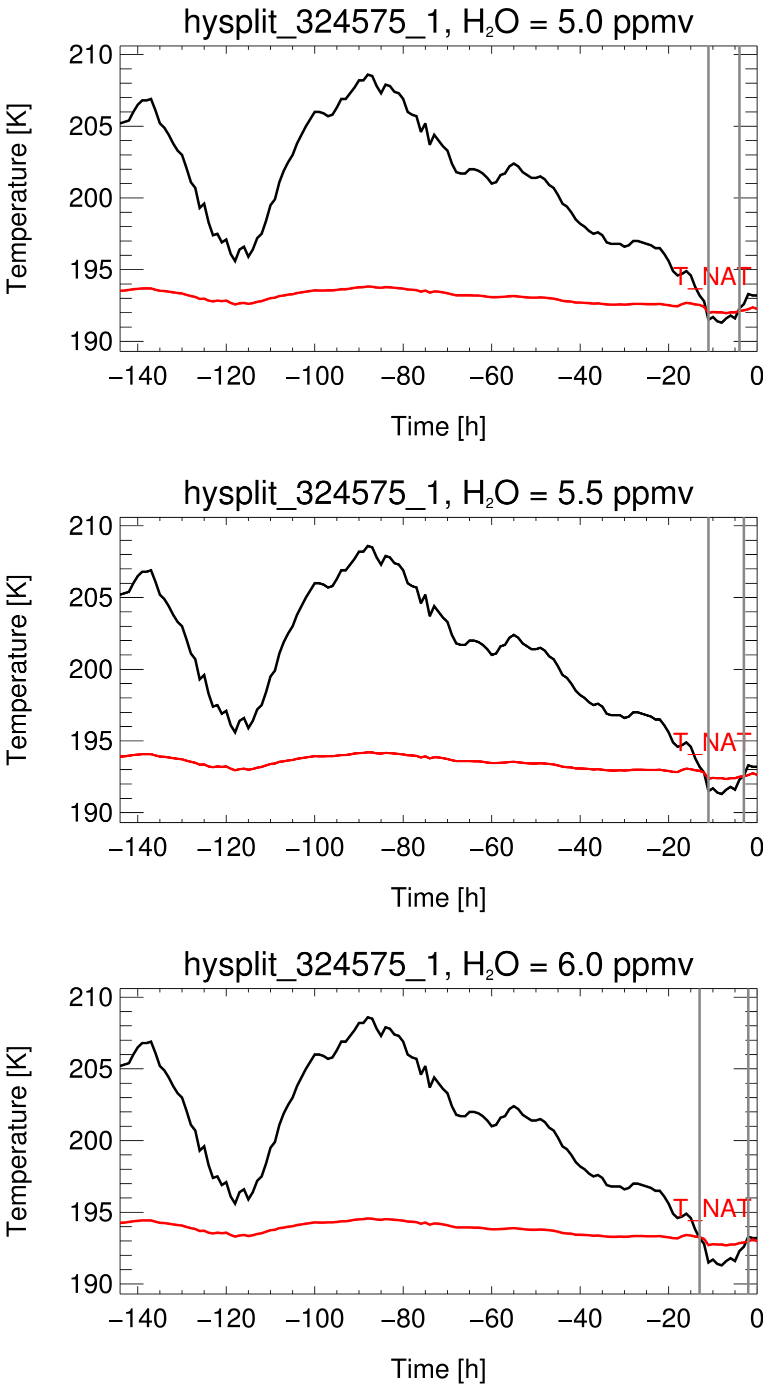

Figure 11: Temperature history of the back trajectory calculated with HYSPLIT based on the PSC observed with the Esrange lidar in Sweden on **9 January 2009** (back trajectory started at 22 km at 01:00 UTC). The temperature along the trajectory has been increased by 2 K **(T+2 K)**. Top: for a typical H_2O mixing ratio of 5 ppmv in the polar lower stratosphere, middle: for an H_2O enhancement of 0.5 ppmv (5.5 ppmv), bottom: for an H_2O enhancement of 1 ppmv (6 ppmv). The NAT existence temperature T_{NAT} and ice formation temperature T_{ice} are given as solid and dashed lines, respectively. The temperature ranges during the time periods where the temperature drops below T_{NAT} and T_{ice}, respectively, are denoted by T_1 and T_2, respectively (grey solid lines).