Referee 1

Comments on the ACPD manuscript entitled "Variability of water vapour in the Arctic stratosphere by Laura Thölix, Leif Backman, Rigel Kivi and Alexey Karpechko.

The present paper discusses the variability of water vapour in the Arctic stratosphere. For that mainly simulations from FinROSE and ECMWF are used. In addition also observations from Aura/MLS, frost point hygrometers and CALIPSO are considered. The manuscript is quite comprehensive in the meaning that it touches upon a wide range topics that concern Arctic water vapour. This comprises water vapour variability in general, but focuses also on the winter season and polar stratospheric clouds. Particular in that sense it is an interesting manuscript. My main criticism is that it just touches upon all these interesting topics, scratching at the surface, many details and discussions are missing. There is much potential and I can easily see the manuscript being split in two, as there is so much interesting stuff. For time being I go along with major revisions. Please find my detailed comments below:

We thank the reviewer for his/her encouraging and detailed review. Following this review we have substantially revised the manuscript providing more insights into the processes behind water vapour variability in the Arctic stratosphere.

Comments:

- *Abstract in general: There are a few abbreviations here, but none of them is defined. As this is typically the first encounter I prefer to have them here already. Later in the manuscript there some abbreviations that remain undefined. This should be not the case.*
  Abbreviations in the abstract have been defined

- *page 1, line 5 to 7: I presume you are referring here to the top panel of Fig. 4. That is the only time observations are involved at where the timing matches. This should be made clear.*
  Yes, this part refers to Fig. 4. We have rewritten the sentence to make the message clearer:
  '*A FinROSE chemistry climate model simulation covering years 1990–2014 is compared to observations (satellite and frostpoint hygrometer soundings) and the sources of stratospheric water vapour are studied. In the simulations, the Arctic water vapour shows decadal variability with a magnitude of ~0.6 ppm. Both observations and the simulations show an increase in the water vapour concentration in the Arctic stratosphere after year 2006, but around 2012 the concentration started to decrease.*'

- *page 1, line 9 to 12: There are two sentences in a row that convey almost the same information. In the first sentence the message comes across more uncertain or speculative though.*
  The first sentence have been taken off.

- *page 2, lines 35 and 36: Somehow the sentence concerning NAT clouds does not fit the natural flow here.*
  The sentence have been reformulated with the previous sentences

- *page 2, line 41 to 44: You could add a reference to the model evaluation study by*

Gettleman et al. (2009) that shows the simulated change of the tropical tropopause. Also increasing methane could be added.
We added a sentence: '*However, stratospheric water vapour is expected to increase due to climate change caused warming of the tropical tropopause (Gettleman et al., 2009) and to an increase in the atmospheric methane concentration.*'

- *page 2, line 51: "... is therefore controlled by ..." - Somehow I would squeeze in here "largely" or "to a first order" as there are other processes that can contribute on different scales.*
  Done, the sentence is now: '*The variability in the entry of water vapour into the stratosphere is largely controlled by the variability in the tropical cold point temperature.*'

- *page 3, line 61 to 63: Satellite measurement across the tropopause are challenging, not only for water vapour. But this is not the reason for why there are no long-term observations.*
  The sentence have been rewritten and is now:.
  '*The exceptional dryness of the stratosphere makes observation of stratospheric water vapour challenging. Long-term time series of stratospheric water vapour are rare, which complicates the study of concentration trends.*'

- *page 3, line 69: "... continuous ..." - This is really a question how do you define that. If you use the daily coverage of Aura/MLS as reference, then UARS/MLS was not as continuous. Typically there was coverage between 34 ° on one hemisphere and 80 ° on the other hemisphere, switching roughly every five weeks by a 180 ° yaw manoeuvre of the spacecraft. Hence in the tropics and subtropics there was "continuous" (daily) coverage while at mid- and high latitudes this was not the case. The balloon measurements at Boulder are typically performed only once a month, just to give another example.*
- *page 3, lines 69 and 70: "... since 2004 ..." - This only applies for Aura/MLS but not for UARS/MLS.*
  The sentence is modified, word 'continuous' has been taken off.
  '*Additionally, global data is available from satellite instruments, but only for a limited time span, for example from Microwave Limb Sounder (MLS) on board the Upper Atmosphere Research Satellite (UARS) (1991—1993) and the Earth Observing System on Aura (EOS-Aura) (2004—today) allows a monitoring of the northern hemispheric stratospheric water vapour distribution.*'

- *page 3, line 70 to 72: In the list also POAM III (1998 - 2005), SAGE III (2001 - 2005) and SOFIE (since 2007) are missing. POAM and SOFIE focused actually only on the polar regions. MIPAS and SMR (at least in boreal winter) had/have coverage all the way to the poles, while MLS only goes to 82 ° latitude.*
  POAM III, SAGE III and SOFIE have added to the list.

- *page 3, line 87 to 89: There is more to these negative trends as they are related to the sudden water vapour in 2000 (e.g. Hegglin et al., 2014). After a few years with very low water vapour mixing ratios a recovery started in 2005. In 2011 again a substantial drop was observed, but this one was more short-lived (Urban et al., 2014).*
  The sentence in the manuscript have been modified and references have added:

'*Based on satellite and sounding measurements e.g. Solomon et al. (2010) reported negative trends in Boulder and generally in the mid-latitudes at 18 km altitude between 2000 and 2009, while e.g. Hegglin et al., (2014) showed that these negative trends are mainly related to the sudden drop in the water vapour in 2000 and that after a few years with very low water vapour mixing ratios a recovery started in 2005. Recently Urban et al. (2014) reported another drop in the tropical water vapour during 2011-2012.*'

- *page 3, line 89 to 91: The study by Hegglin et al. (2014) should me mentioned here. Even though there is no focus on polar latitudes, they show at least water vapour trends up to 80° latitude for the time period between the late 1980s and 2010. The reported trends in the lower stratosphere are actually negative. On the other hand one should acknowledge that the coverage before 1998 using HALOE and SAGE II was far from optimal and that some caution is warranted.*
  Following sentence have inserted:
  '*Hegglin et al. (2014) show water vapour trends up to 80° latitude for the time period between the late 1980s and 2010. On the other hand one should keep in mind that the coverage before 1998, which was based on HALOE and SAGE II, was not good, which warrants some caution to the results. The reported trends in the lower stratosphere are negative.*'

- *page 4, line 108: "ctm" - Does this refer to CTM = Chemistry Transport Model?*
  Corrected

- *page 4, line 117: For me prescription of the number density profile for the individual PSC types seems like a profound restriction. Has that been quantified?*
  The PSC scheme is not a microphysical scheme, but it is based on thermodynamic equilibrium equations. In this case there are basically two choices, either prescribe the particle size or the number density. We have chosen the latter: i.e. when the temperature decreases there becomes more particles, in the other case the particles would become larger. In both cases the sedimentation increases and the surface area increases. The number density profile for LBA and STS is estimated from McLinden et al 1999. The number density of NAT particles is initially assumed to be 1 cm-3 (Krämer at al 2003), the number density is reduced for large NAT particles. The ICE number density is assumed to be 0.04 cm-3, estimated from synoptic scale PSCs (Dye et al. 1992). More detail on the PSC scheme were added to the text:
  '*The composition of LBA and STS are calculated using the method by Carslaw et al. (1995). The STS are not considered below the ICE PSC formation temperature. The number density profile for LBA and STS is estimated from McLinden et al (1999) and the sulphuric acid distribution [$\mu m^2\ cm^{-3}$] is based on 2-D model data Bekki and Pyle (1992). NAT formation is based on the thermodynamic equilibrium equations by Hanson and Mauersberger (1988). The model includes an option to include a supersaturation requirement for NAT and ICE formation, but this option was not used in the simulations reported in this paper. The choice was made due to the relative modest resolution of the model. Co-extistence of NAT and STS is allowed. A scheme for growth of NAT particles is included based on Fahey et al (2001). The number density of NAT particles is initially assumed to be 1 cm-3 (Krämer at al 2003), the number density is reduced for large NAT particles. The temperature threshold for ICE particle formation is based on expressions by Marti and Mauersberger (1993). The equilibrium pressure of nitric acid above ICE is calculated according to Hanson and*

Mauersberger (1988). The ICE number density is assumed to be 0.04 cm-3, estimated from synoptic scale PSCs (Dye et al. 1992).'

- *page 4, line 123 to 125: Where is the boundary for the prescribed tropospheric water vapour? If it is too close to the tropopause, in particular in the tropics, you may get a dry bias due to the cold bias of ECMWF there. A more general question at this point regards the complexity of the methane oxidation scheme? Depending on that you may get different trend estimate, in particular in the upper part of the stratosphere were methane oxidation is more effective. Does FinROSE include water vapour production from the molecular hydrogen reservoir (Wrotny et al., 2010)?*
  Methane is oxidized by OH, O1D, Cl and photodissociation is also included. The intermediate formaldehyde is also included as well as molecular hydrogen. The text was revised ...
  '*The tropopause height is calculated at every time step using potential vorticity as defining parameter. Model levels below +-2 PVU are considered to be in the troposphere. The 380 K potential temperature level further is used to define the tropopause height near the equator. The tropopause is thus changing with time depending on meteorological conditions. The tropospheric concentrations of the chemical species are not calculated in the model but prescribed via model boundary conditions. Tropospheric water vapour and ozone were obtained from the ECMWF ERA-Interim reanalysis (Simmons et al. 2007, Dee et al. 2011).*'

- *page 5, line 138 to 140: This sentence seems to imply that satellite measurements are not accurate, which I would definitely argue against. Please rephrase.*
  Word accurate have been changed to '*High resolution sounding*'

- *page 5, line 143 to 159: This whole part needs a better structure. There is some jumping between campaigns and instruments; back and forth. Maybe a summary table with the two campaigns and the relevant instruments could be helpful. CFH observations are mentioned for both campaigns but then only used for the second campaign. Why? In the paragraph following these lines Aura/MLS and CALIPSO are described, but they only contribute to the second campaign. That should be made clear.*
  We agree that the part needs to be rewritten and we will provide a better version. In the paper we have used measurements from both campaigns and in addition CFH observations in between the campaigns. In this paper we have only used the CFH observations, although also the FLASH measurements have been made (Khaykin et al., 2013).

- *page 6, line 176 to 178: Given this statement here, the section description in the final part of the introduction and earlier experiences of mine with ECMWF water vapour I wondered a couple of times along the manuscript why ECMWF water vapour is shown at all. I have to admit that compared to earlier incarnations of this data product the current water vapour data set looks relatively fair but you should have in mind that is based on a simple methane oxidation parametrisation and relaxes to 6 ppmv at the stratopause. Overall, for this analysis here, I do not see the value and would focus more on the observations.*
  We fully agree with the reviewer that the quality of the ECMWF water vapour distribution suffers from a too simplified treatment of chemistry. However we see no reason to conceal this from the readers and we'd rather keep it in the figures. Note

that the reasons for the discrepancy between ECMWF and observations are discussed in the text. Moreover we believe the transport in ECMWF is well represented. Therefore any trends arising from changes in the transport would be captured by ECMWF even if absolute values are biased.

- *page 7, line 205 to 207: I guess the standard deviation is simply derived from all the profiles that fitted your coincidence criteria. Maybe the approach could be made clearer. The standard deviation can be quite tricky to interpret. For the observations measurement and retrieval characteristics contribute to the standard deviation (it is not all natural variability); for the simulations the model setup plays a role. That should be kept in mind!*
  Thank you for this comment. Yes, the standard deviation is calculated across the individual profiles. To make it clearer a corresponding statement is added to the revised manuscript:
  '…From MLS all the profiles measured in the Sodankylä gridpoint and flagged as good quality are used. Standard deviation is calculated across the individual profiles for each data set and thus represents uncertainty due to natural variability and random errors. Figure 2 compares January–February-mean water vapour…'

- *page 8, lines 252 and 253: Why does the time axis in Fig. 4 starts first in 1994?*
  Figure 4 (and new figure 5) have redrawn for years 1990-2014 and text about it have been modified. The water vapour tracer has recalculated using better upper boundary conditions, and the upper levels in this figure are now better and can be shown. (The upper boundary condition of the tracer is now always 65% of water vapour. The value is the average of the upper level in the long simulation.)

- *page 8, line 257 to 260: This discrepancy between the simulations and observations certainly warrants more attention. Effects of the coarser altitude resolution of Aura/MLS compared to the simulations certainly, I think, can be neglected here. The only exception in general would be if there are dehydration features or if you would look closer to the hygropause. But 56 hPa seems fine given a typical MLS altitude resolution of about 3 km for water vapour in this altitude range. Also in the figure it looks like as there may be a time delay between the simulations and the observations that may hint on different transport time scales.*
  We agree with reviewer that the time delay suggest different transport time scales. We also note that the water vapour increase in FinROSE and ERA-Interim, as well as the discrepancy with MLS, is most pronounced in the lower stratosphere, while the difference is smaller in the upper stratosphere. This suggest that the difference maybe associated with transport processes within the stratosphere as represented by ERA-Interim during this period. In the revised manuscript we discuss the discrepancy between the simulations and observations in more detail.

- *page 8 and 9, line 270 to 288: I definitely think there should be more analysis and discussion of the variability here. After all it is the main key topic of the manuscript. The analysis may involve a thorough regression analysis. In terms of discussion there is more than these linear short-term changes (the term trend feels somewhat exaggerated), like those drops in water vapour (e.g. Randel et al., 2006; Urban et al., 2014), influence of sudden stratospheric warmings (e.g. Straub et al., 2012; Tschanz and Kämpfer, 2015) or the QBO that shows up quite prominently. Also considering more the Aura/MLS measurements would be great.*

Following this comment, MLS anomalies have been added to the figure. We have also performed regression analysis where we considered influences on the Arctic water vapour of BD circulation, QBO as well as tropical tropopause temperatures. Please see more discussion on this below. We have also tried to identify the impact of sudden stratospheric warming on the water vapour based on our timeseries. However one should note that we consider monthly mean values whereas analysis of SSW require daily values. Therefore we cannot detect any clear signal of SSWs in our long term timeseries based on monthly values.

- *page 9, lines 277 and 278: After the drop in 2000/2001 there was a recovery afterwards.*
  Thank you for this specification. We reformulated the sentence as follows:
  '*Solomon et al. (2010) found a positive trend in the water vapour data until about year 2000 and a negative one after that over Boulder at the mid-latitudes around 80 hPa. The negative trend was mainly caused by a drop of the concentrations in 2000/2001 (Randel et al. 2006) which was somewhat compensated by a slower recovery afterwards.*'

- *page 9, line 278 to 280: "As for ..." - Somehow this does not sound the right way. The implication by Hegglin et al. (2014) that observations at Boulder should not be generalised in to describe the global stratosphere has in my opinion two sides. There could be local effects that would make this location different from the global behaviour. However, for the time being, it seems that there is more a discrepancy between two sets of data, i.e. the data from the frost point hygrometers and the satellite data merged using a nudged model. The last word has certainly not been spoken regarding this inconsistency.*
  Thank you for this note of caution. We reformulate the interpretation of the Hegglin et al. result as follows:
  'However, Hegglin et al. (2014) showed that the water vapour trends over Boulder might be associated with local patterns of changes and not necessarily representative of the global stratosphere.'

- *page 9, line 283 and 288: The QBO signal is more general due to its influence on the Brewer-Dobson circulation. That affects the tropical tropopause temperatures but also along the way there are variations of the transport. Mixing is certainly less important, except when the polar vortex breaks up.*

Following these comments we have elaborated the discussion of the water vapour variability. We performed regression analysis following Dessler et al. (2014). We used three proxies: qbo index (QBO, equatorial winds at 50hPa), Brewer Dobson circulation index (BD, residual vertical winds at 70hPa averaged from 30S to 30N), and cold point temperature (CPT). Unlike Dessler et al. (2014) we found that the use of tropical temperatures at 500 hPa was not enough to explain the variability of the cold point temperature, and therefore used it as one of proxies. Although, there is some correlation between CPT and QBO (0.36) QBO also affect the transport of the water vapour not directly influenced by CPT; therefore the use of both proxies is justified. We apply multiple regression analysis with all three proxies to water vapour time series averaged north of 70N and at 82 hPa and 56 hPa. Cross-correlation analysis shows bread peaks at lags 6-12 months for the proxies. The maximum of the correlations of QBO and CPT with water vapour at 56 hPa is at about 10 months lag,

and with 82 hPa is at 8-9 month lags, suggesting that propagation of the tropical anomalies in the lower stratosphere is faster than that in the middle stratosphere, likely due to more efficient mixing. We use 10 month lag for all proxies for regression at 56 hPa and 9 month lag for the regression at 82 hPa.

The individual correlation coefficients with our proxies are shown in the Table below. The main contribution to the polar water vapour variability is CTP, followed by QBO. We found very weak contribution of BD proxy to the variability of the water vapour. One reason is that the effect of BD contribution is accumulated over time and this is not well represented by the monthly proxy. The multiple regression coefficients are 0.57 and 0.51 at 82 hPa and at 56 hPa correspondingly, showing that our models only explain 25-30% of the variability. This is considerably less than that of Dessler et al. suggesting that different processes contribute to the polar water vapour variability in comparison to those in the tropics. Note that the regression somewhat explains the increase of the water vapour from 2005 to 2010, which is more clear at 82 hPa. However the peak of the water vapor during 2011-2013 is not explained by these proxies.

Table: Correlation coefficients

	CPT	QBO	BD	Multiple
56 hPa	0.454073	0.315499	-0.209597	0.51
82 hPa	0.518588	0.399678	-0.180337	0.57

- *page 10, line 328 to 339: I seek more discussion on Fig 6. I am definitely not a PSC expert. Hence my first order expectation would be a linear relationship between the cold area and the PSC area. Hence the large cold areas with small PSC areas stick out for me. Why is that? I do not think that water vapour is the decisive factor here and there are reddish, greenish and orange colours visible there. The relationship between large cold areas and PSC areas accompanied by high water vapour seems more clear. A large cold area means you have a stable vortex where moist air from the stratopause is brought down to the lower stratosphere. This has been recently addressed by Khosrawi et al. (2015). In that regard it makes sense to me to look at the vortex average water vapour volume mixing ratio. Beyond that I really wondered why this was used given the more localised dehydration layers in connection with PSC. What temperatures do you use to get the area for T < 190 K for CALIPSO? At least I am not aware that CALIPSO provides temperatures.*
  Following this comment, and a related comment by R2, Figure 6 has been updated and more discussion has been added. Instead of using area with T<190K we use area with T<188K which is tighter related to ice PSC. We get correlations between temperature and ice PSC of 0.93 for the model and 0.72 for CALIPSO, consistent with expectations. To better illustrate the dependence of ice PSC on water vapour we add panel (b) and also support the dependence by providing mean values of ice PSC area conditioned on water vapour and temperature. In statistical sense the dependence clearly emerges, so that increase of water vapour leads to larger PSC. The correlations between water vapour and ice PSC is 0.21 in FinROSE and 0.41 in CALIPSO. Although we agree that the link between local water vapour and PSC should be clearer, the use of mean vortex water vapour is justified by the obtained correlation. It is important to demonstrate this relation in the context of the paper. In

the revised version we use ERA-Interim temperatures in connections with ice PSC from both FinROSE and CALIPSO. Water vapour is from FinROSE.

- *page 11, line 346: "... the vortex moved to the south ..." - Really to the south? At least my simple expectation would be different. Or was this something filament-like?*
- *page 11, lines 346 and 347: "... mixing with moister mid-latitude air ..." - Under typical conditions, leaving dehydration aside, the water vapour mixing ratios in the lower stratosphere are lower outside the polar vortex than inside (e.g. Nassar et al., 2005; Lossow et al., 2009). If there is dehydration than things may be the opposite, but it is unclear if there was still dehydration by 11 February 2011.*
  Thanks for noticing the inaccuracy. Meteorological conditions of winter 2009/2010 have discussed lot (e.g. Khaykin et al. 2013, Pitts et al. 2011, Dörnbrack et al. 2012). We added references to those studies, and changed these sentences as: '*A major warming around 24 January started the vortex break up.*'

- *page 12, line 390 to 394: I find that that the changes in water vapour are very difficult to see. Frost point temperatures are certainly not optimal here.*
  Frost point temperatures have changed to water vapour mixing ratios in the maps. Profile pictures still show frost point temperature.

- *figure 2: Could you use the x-axis range more efficient? Also a legend would be very helpful!*
  X-axis ranges have modified and also a legend is inserted.

- *figure 4: I wondered if it is an idea to split Fig. 4 into two figures, one showing the absolute volume mixing ratios at Sodankylä (top panel) and the other showing the residuals for 70 °N - 90 °N. This change in latitude, data sets shown and lacking legends made it difficult to digest. I do not know how often I read the caption. Having Aura/MLS data in the residual plots would be great too.*
  Thanks for suggestion. Figure 4 have now split into two. Also MLS data is inserted. Legends are also inserted.

- *figure 7: The colour bars have no annotation of what is shown. Also there is some overlap of the x-axis labels, which does not look particular nice.*
  The units have been added to the colour bars and also the x-axis labels have now more space.

Technical corrections:

- *page 4, line 94: replace "... polar regions and the mesosphere ..." by "polar regions, the mesosphere...".*
  Corrected
- *page 4, lines 127 and 128: "Carbon dioxide CO2 ..." should likely be "Carbon dioxide (CO2) ...".*
  Corrected
- *page 5, line 143: Something seems to be missing here at the beginning of the sentence.*
- *page 9, line 205: "... ration ..." should read "... ratio ... " or "... ratios ...".*

Corrected

- *page 10, line 336: "... allways ..." should read "... always ...".*
  Corrected
- *page 11, line 367: "... at level 56 hPa ..." should read "... at the level of 56 hPa ...".*
  Corrected
- *page 11, line 368: "... timeperiod ..." should read "... time period ...".*
  Corrected
- *page 13, line 435: "... AURA ..." should read "... Aura ...".*
  Corrected
- *page 25, line 435: "All the maps are from 56 hPa altitude" could read "All maps consider the 56 hPa pressure level.".*
  Corrected

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Referee 2

L. Thölix and co-authors discuss in their study “Variability of water vapour in the Arctic stratosphere” sources, variability, and distribution of stratospheric water vapor in the Arctic (70N-90N) and above Sodankylä together with the formation of polar stratospheric clouds (PSCs). The chemistry climate model FinROSE has been used and results have been compared against balloon-borne and satellite-borne observations for the period from 1994 until 2013. The authors focus in particular on the Arctic winter 2009/2010. The manuscript is generally well structured and easy to read. However, I have some major comments, which I am going to specify below.

First of all, I have difficulties to extract the main conclusions of this study. Unfortunately,I cannot spot any novel concepts, ideas, or tools. Please rewrite the Introduction and Conclusions of the manuscript in a way that the goal of this study and any highlights related to your methods become evident. If the main goal of your study is to prove already discussed trends in stratospheric water vapor, I would like to see a more profound trend analysis. Highlighting the model’s availability of PSC formation, the reader needs much more details about how PSCs are treated within the model and how nitric acid concentrations compare to observations. This leads me to my second major concern, which refers to the analysis. Some methodical details are missing, which could be helpful to interpret the results and to judge the quality of the simulations. Sometimes, results are presented in a very coarse way, which might cover differences between simulations and observations. The corresponding description of the analysis is often weak, too. Examples are “measured temperatures” (Measured by which instrument?), “near Sodankylä” (What does “near” mean? 1 km? 100 km? 5 degree?) I will pick up some of these weaknesses again as specific comments in the following part of this review. In summary, I would recommend to publish this study only after major revisions have considerably improved the manuscript.

We thank the reviewer for his/her thorough review. We have substantially revised the manuscript: in particular we provide a more detailed trend analysis, add more details about PSCs in FinROSE model, provided more detailed comparison between observations and simulations, and tightened the language in every occasion spotted. Our point-to-point replies to reviewer's comments are provided below.

P22015/L13ff
Kirner et al. (2015) found that “in high southern latitudes, heterogeneous chemistry on ice particles causes only up to 5 DU of additional ozone depletion in the column”, which would not call “remarkable”. Since your study focuses on the Arctic, it would also be better to cite a study related to the Arctic such as Wohltmann et al. (2013).
New text has inserted to the manuscript:
'*ICE PSCs contribute only to a minor part of the chlorine activation. According to a model study by Kirner et al. (2015) 90 % of the ozone depletion in the Antarctic spring is caused by halogen activation on liquid particles. In a model study of the Arctic winter 2009/2010 Wohltmann et al. (2013) showed that chlorine activation on liquid aerosols explained the changes in the ozone column to within 10 %. The additional chlorine activation caused by ICE PSCs is modest. However, when ICE PSC particles sediment to lower altitudes, a reduction of water vapour, i.e. dehydration occurs (Kelly et al., 1989).'*

P22015/L18ff

Your statement implies that denitrification always occurs due to the sedimentation of ice particles, which is not the case. Please reformulate this paragraph and cite an appropriate paper for denitrification.

The paragraf is reformulated andFahey et al., 1990 is cited:

'*In addition, the reaction with atomic chlorine has some significance as a sink for methane, but also as a termination reaction of ozone depleting cycles especially in the Antarctic vortex where denitrification reduces the importance of the reaction between ClO and NO2 (Fahey et al., 1990).*'

P22015/L26

Tian et al.(2009) predicted that "increasing the stratospheric H2O is likely to accelerate the recovery in the northern high latitudes".

The sentence have rewritten and is now:

'Tian et al.(2009) used a climate model to study the over all effect, the results indicated that the total column of ozone in Arctic would increase in the future despite increased active chlorine in the polar spring regions, while in the Antarctic the ozone recovery would be delayed. The distribution of stratospheric water vapour and its effect on the formation of PSCs are therefore of interest.'

Section 2.1 FinROSE

I am missing a detailed description of how PSCs are simulated within FinROSE. Since PSCs are a main focus of your study, the reader needs to know details about their formation, growth, sedimentation behavior etc. to judge the results presented. Number densities and particle sizes are important to explain dehydration. In my opinion, it is not sufficient to just refer to Damski et al. (2007).

The description of PSCs in FinROSE have inserted.

'*The composition of LBA and STS are calculated using the method by Carslaw et al. (1995). The STS are not considered below the ICE psc formation temperature. The number density profile for LBA and STS is estimated from McLinden et al (1999) and the sulphuric acid distribution [µm2 cm-3] is based on 2-D model data (Bekki and Pyle 1992). NAT formation is based on the thermodynamic equilibrium equations by Hanson and Mauersberger (1988). The model includes an option to include a supersaturation requirement for NAT and ICE formation, but this option was not used in the simulations reported in this paper. The choice was made due to the relative modest resolution of the model. Co-extistence of NAT and STS is allowed. A scheme for growth of NAT particles is included based on Fahey et al. (2001). The number density of NAT particles is initially assumed to be 1 cm-3 (Krämer at al 2003), the number density is reduced for large NAT particles. The temperature threshold for ICE particle formation is based on expressions by Marti and Mauersberger (1993). The equilibrium pressure of nitric acid above ICE is calculated according to Hanson and Mauersberger (1988). The ICE number density is assumed to be 0.04 cm-3, estimated from synoptic scale PSCs (Dye et al. 1992).*'

P22020/L27 and P22021/L1

The term "water ice" includes also wave ice. You probably wanted to distinguish wave ice and synoptic-scale ice.

Thanks for focusing. The sentence have now changed to:

'*The CALIPSO PSC algorithm classifies PSCs by composition. Six different classes are defined: supercooled ternary solution (STS), two classes of liquid/NAT mixtures and mix 2*

enhanced and water ice (including synoptic-scale ice and wave ice) (Pitts et al., 2011)'

P22021/L17
There are also significant differences between FinROSE and MLS from January until April in the same altitude range as mentioned for the summer months. FinROSE is too moist compared to MLS, which favors of course PSC formation.
The MLS data is changed to be level3 overpass data and all of the climatologies have been recalculated using years 2004 to 2014. The text is modified for matching the figure.
'The largest differences are between 10 and 1 hPa, in winter/spring the concentration in FinROSE is about 1 ppm higher compared to MLS but in summer MLS is about 0.3 hPa moister than FinROSE. The too moist air in the spring in FinROSE can lead for effective PSC formation.'

P22023/L5
The model is about 0.7 ppm drier at 20 hPa (not at 30 hPa).
Thanks for mention the error. The MLS data have been changed to level3 MLS overpass data. Now the biggest difference is at 3 hPa. It has been corrected to the text.

P22023/L8
ERA-Interim is also at 30 hPa drier than MLS and the soundings!?
Thank you – corrected.

P22023/L18ff
It would be possible to compare sounding to model data only at those times and locations at which balloon soundings are available instead of calculating a multi year average.
The differences have been calculated first and after that the averages. For FinROSE and ECMWF all the MLS profiles could have been used, but for sounding the number of soundings were the restrictive thing. Text have been modified:
'The differences have been calculated using all the available datapairs during Januaries and Februaries between 2004 and 2014 and after that the differences have averaged. For FinROSE and ECMWF all the MLS profiles could have been used, but for sounding the number of soundings were the restricted thing.'

P22024/L24ff and Figure 4
Please explain how you define "anomaly".
We defined the anomaly as a departure from the mean value for the period 1994-2013. This has been stated in the original version of the manuscript. Now the MLS anomaly have been inserted to the Figure and MLS anomaly have calculated using years 2004-2014 and all the other anomalies have recalculated using years 1990-2014. To make it clearer we rewrite the statement in the revised version as follows:
'*All the anomalies are calculated with respect to the mean values for the years period 1990-2014 for FinROSE and ERA-Interim and for the period 2004-2014 for MLS anomalies.'*

P22025/L17
If at all, the anomalies seen in FinROSE agree with Dessler et al. (2013) but not with Solomon et al. (2010), who see decreasing water vapor concentrations after the year 2000. The wording "also" is therefore misleading. However, Dessler et al. (2013) focuses on latitudes 30N-30S whereas you look at 70N-90N.
Following this and the related comments of R1 and Wang we have elaborated the discussion of the water vapour variability. We performed regression analysis following Dessler et al.

(2014). We used three proxies: qbo index (QBO, equatorial winds at 50 hPa), Brewer Dobson circulation index (BD, residual vertical winds at 70 hPa averaged from 30S to 30N), and cold point temperature (CPT). Unlike Dessler et al. (2014) we found that the use of tropical temperatures at 500 hPa was not enough to explain the variability of the cold point temperature, and therefore used it as one of proxies. Although, there is some correlation between CPT and QBO (0.36) QBO also affect the transport of the water vapour not directly influenced by CPT; therefore the use of both proxies is justified. We apply multiple regression analysis with all three proxies to water vapour time series averaged north of 70N and at 82 hPa and 56 hPa. Cross-correlation analysis shows bread peaks at lags 6-12 months for the proxies. The maximum of the correlations of QBO and CPT with water vapour at 56 hPa is at about 10 months lag, and with 82 hPa is at 8-9 month lags, suggesting that propagation of the tropical anomalies in the lower stratosphere is faster than that in the middle stratosphere, likely due to more efficient mixing. We use 10 month lag for all proxies for regression at 56 hPa and 9 month lag for the regression at 82 hPa.

The individual correlation coefficients with our proxies are shown in the Table below. The main contribution to the polar water vapour variability is CTP, followed by QBO. We found very weak contribution of BD proxy to the variability of the water vapour. One reason is that the effect of BD contribution is accumulated over time and this is not well represented by the monthly proxy. The multiple regression coefficients are 0.57 and 0.51 at 82 hPa and at 56hPa correspondingly, showing that our models only explain 25-30% of the variability. This is considerably less than that of Dessler et al. suggesting that different processes contribute to the polar water vapour variability in comparison to those in the tropics. Note that the regression somewhat explains the increase of the water vapour from 2005 to 2010, which is more clear at 82hPa. However the peak of the water vapor during 2011-2013 is not explained by these proxies.

Table: Correlation coefficients

	CPT	QBO	BD	Multiple
56 hPa	0.454073	0.315499	-0.209597	0.51
82 hPa	0.518588	0.399678	-0.180337	0.57

Figure 4
I am not able to detect the blue dots in Panel a, which are supposed to show the sounding data according to the figure caption. Do you see a trend in the MLS data? Why don't you show MLS data in Panel b - e of Figure 4?
Sounding observations were mistakenly missing from the figure 4. Now they are added and marked with red dots.

MLS anomalies were not in the panels b-e, because the climatology have calculated from years 1994-2013. We have added the MLS anomalies in the revised manuscript.

There is a positive trend in MLS data also, but it is weaker than in FinROSE. Text about it is added. Also the Figure 4 is now split into two figures: new Figure 4 shows timeseries interpolated to Sodankylä, which allows comparison to sounding, and new Figure 5 shows anomalies from 70-90N.

P22026/L21, P22027/L2

I don't understand the meaning of "an average frequency of 0.4 per winter". The description that 4 out of 10 winters offer conditions, which allow the formation of ice PSCs, is clear to me.
Thanks! Following this recommendation we have changed the sentence 'Which gives an average frequency of 0.4 per winter' to '*That means that nearly 5 out of 10 winters offer conditions, which allow the formation of ice PSCs*.'

P22027/L1ff
From 1990 - 1996, 4 out of 7 winters show a significant coverage of ice PSCs, too. Unfortunately, your water vapor time series start only in 1994. You mention also cold temperatures as possible reason, but you do not show temperature trends in your publication neither you cite any study, which shows that stratospheric temperatures show a negative trend in recent years.
Thank you for pointing to the cold period during 1990s. We will mention it in the text.
Now the water vapour timeseries in Figure 4 have started from year 1990 (and also year 2014 have been inserted). Additionally we have inserted minimum temperatures north of 50N to the Figure 5.

Figure 6
This figure is from my point of view meaningless. First questions, which arise: What temperature and water values did you take to calculate the CALIPSO crosses? Do you show total or gas phase water values? It is well known that ice formation is related to the frost point temperature. Taking a threshold temperature of 190 K means nothing, instead the frost point at 56 hPa varies from 188.6 K (4.6 ppm H2O) to 189.8 K (5.6 ppm H2O). Showing a vortex mean value of water vapor in the Arctic is also quite useless. In case dehydration occurs, this would be a localized event which evens out by calculating the mean. In summary, I cannot spot any relationship between temperature, water vapor and the area covered by ice PSCs in your figure, almost all colors are spread over the entire space.
Following this comment, and a related comment by R1, Figure 6 has been updated and more discussion has been added. Instead of using area with T<190K we use area with T<188K which is tighter related to ice PSC. We get correlations between temperature and ice PSC of 0.93 for the model and 0.72 for CALIPSO, consistent with expectations. To better illustrate the dependence of ice PSC on water vapour we add panel (b) and also support the dependence by providing mean values of ice PSC area conditioned on water vapour and temperature. In statistical sense the dependence clearly emerges, so that increase of water vapour leads to larger PSC. The correlations between water vapour and ice PSC is 0.21 in FinROSE and 0.41 in CALIPSO. Although we agree that the link between local water vapour and PSC should be clearer, the use of mean vortex water vapour is justified by the obtained correlation. It is important to demonstrate this relation in the context of the paper. In the revised version we use ERA-Interim temperatures in connections with ice PSC from both FinROSE and CALIPSO. Water vapour is from FinROSE, and we show total water content (gas+solid+liquid).

P22028/L17ff
For the Arcitc winter 2009/2010 and with Figure 7, you start a comparison not only of ice but also NAT PSCs. However, you never talk about HNO3 concentrations within FinROSE. Explaining differences between simulations and observations just by the model resolution is therefore not enough. HNO3 concentrations could be compared to MLS. Moreover, it would be nice to have some more details again about the "simplicity of the PSC parameterization". Why do you expect differences here? What are the consequences of fixed NAT number

densities, supersaturations etc.?
More details of the PSC parameterization have been added to the model description part. In order to focus the manuscript on water vapour and ice PSC we have taken NAT PSCs off the Fig. 5 and 7.

Figure 7
You show areas of ice and NAT PSCs above Sodankylä? I assume that the values refer to total areas observed in the vortex, right? At least they are about the same magnitude than the areas shown in Figure 5. Why do you compare those to temperatures above Sodankylä?
You are right, total areas of ICE PSCs and NAT PSCs in the Northern Hemisphere were shown in Figure 7. All the NH CALIPSO observations during winter 2009/2010 were taken into account in the calculation of the areas. In the revised manuscript, instead of Sodankylä temperatures we show total areas with temperatures colder than 188 K. NAT PSCs have been taken off. Now the panels are compared. In particular one can see that area with temperatures colder than 188K is larger than PSC area as one could expect based on frost point calculations.

P22028/L25
What do you mean by CALIPSO temperatures? CALIPSO does not measure temperature.
In the original manuscript temperatures supplied together with CALIPSO PCS-mask-data files were used. In the revised manuscript only ERA-Interim temperatures are used.

Figure 8
It is nearly impossible to see any detailed structures in this figure. It would be for example useful to show temperatures below the frost point in the second and third row instead of the frost point temperature itself, which is in addition plotted with a different colorbar than the temperatures themselves. It would also be nice to see plots of water vapor itself. Since you often explain features by dehydration, it would be nice to see that FinROSE can simulate the observed reduction in water vapor, which is visible in the MLS data (Khaykin et al., 2013). The ice comparison between FinROSE and CALIPSO is also difficult. Looking at Pitts et al. (2011), almost no ice PSCs have been observed after 21 January 2010. Only single measurement points were classified (misclassified?) as ice. From your plot I get the impression that significant areas of the vortex are still covered by ice.
You are right. The panels in the figure were too small and it was difficult to see details. We choose only sounding dates to the picture and now the panels are bigger. Also the frost point temperature map from FinROSE were changed to water vapour mixing ratio maps and MLS frost point temperature have been taken off, because the MLS data is coarse without time averaging. The level of the maps have been changed to 35 hPa where the dehydration features are seen from FinROSE data. ICE PSC maps are also now from the level 35 hPa. CALIPSO PSC areas maybe form too large resulting the gridding of CALIPSO data. If there were any ICE in the gridbox the area of that box have been calculated into the area. We have had to show also small ICE areas.

P22029/L28ff
There is an important difference between the 17 and 23 January 2010. On 17 January, ice PSCs have been observed by balloon-borne measurements above Sodankylä. On 23 January, the dehydrated air masses prevent the formation of ice PSCs. Only STS clouds have been observed even though temperatures were as cold as the week before. Therefore, frost point temperatures on these two days were different (Khaykin et al., 2013).
After recalculating the frost points we have corrected in the Figure. The coldest dates are 17th

and 22nd January. It is corrected to the text. If FinRose indeed see the same frost point then we say there is difference with MLS/Khaykin.

P22031/L13ff
One of your main conclusions is that a positive trend in stratospheric water vapor and decreasing stratospheric temperatures have led to an increase in Arctic PSC coverage during the last decade. In this case, you cannot totally ignore literature by Markus Rex (e.g. Rex et al. 2006), the recent WMO report (2014) and also Rieder and Polvani (2013) with a controversial trend discussion.
Thank you for pointing us towards this important issue. In the revised manuscript we refer to this discussion. Note however that from our simulations and analysis of sounding/MLS observations, a long-term trend in stratospheric water vapour cannot be deduced. The positive trend that we discuss concerns the period between about 2006 and 2012, which was followed by a reduction of the concentrations.

P22031/L15f
"The area of [temperatures] colder than 190 K is much larger than the area of simulated ICE PSCs in FinROSE or the area of detected ICE with CALIPSO."! As you mentioned several times, water vapor concentrations are also important and ice formation depends on the frost point temperature. This is nothing new!
We have rewritten this statement. First in the revised manuscript, we use the 188 K temperature as a threshold for the cold air mass, which shows much closer agreement with ice PSC extent. Second we specify that a disagreement between areas with t<188 K and ICE PSC should be expected because of considerable influence of water vapour mixing ratio on PSC formation.

P22031/L19ff
De- and rehydration was indeed observed above Sodankylä in January 2010 and published by Khaykin et al.(2013). However, this cannot be part of your Conclusions (and Abstract) because you neither show balloon profiles of H2O nor FinROSE simulations of de- and rehydrated areas.
We have specified that our conclusions concern simulation of these events by FinROSE. In the revised text we write: '*The winter 2009/2010 was extremely cold in the Arctic stratosphere. Simulations by FinROSE reproduce ICE PSCs and associated dehydration and rehydration at lower altitudes in good agreement with observations reported by Khaykin et al. (2013).*'

Technical corrections

I would recommend to carefully check the English grammar again. Without being a native speaker, I realized mistakes (e.g. P22030/L7 and L8: was instead of were and vice versa; missing verb on P22031/L12; ...).
Thanks for these corrections. We have corrected these and other typos.

P22014/L14
The abbreviation for polar stratospheric clouds (PSC) has already been used before (Line 11 and Line 13). In addition, please ensure that every abbreviation has been explained before the abbreviation is used solely.
Abreviations are checked and corrected.

P22015/L15
remarcable → remarkable
Corrected

P22024/L12
Only the years 1994 - 2013 are shown in Figure 4. e.g.
Figure 4 (and new figure 5) have redrawn for years 1990-2014 and text about it have been modified. The water vapour tracer has recalculated using better upper boundary conditions, and the upper levels in this figure are now better. (The upper boundary condition of the tracer is now always 65% of water vapour. The value is the average of the upper level in the long simulation.)

P22027/L10
NATs -> NAT particles.
Corrected

e.g. P22028/L8
“and and”
Corrected

Figures 2 and 4
Please keep the colors for clarity (e.g. MLS =blue vs. MLS =orange vs. methane oxidation = blue).
Corrected

Figure 4
Please add the unit of Panel b - e to the y-axis.
Unit is added

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F. Khosrawi

The study presented by Thölix et al. is very interesting, but some of the references given are not correct in the context they are actually cited for. Further, I think the presentation of the results in this study would profit if more results from the the Arctic 2009/2010 winter published in the ACP special issue on "Chemistry, microphysics and dynamics of the polar stratosphere: ozone loss and climate-chemistry interactions" would be taken into account (http://www.atmos-chem-phys.net/special_issue228.html). Additionally, it should be made much clearer in the manuscript for which region the trend analyses is performed: Is it for the polar regions (70-90N) or for Sodankylä?

We thank Dr. F. Khosrawi for the review which we found very useful. We have revised the manuscript to address all the issues. In particular we took into account the results on winter 2009/2010 from the ACP special issue as advised, and corrected the text to make it clearer which area we refer to in the trend analysis.

P22015, l18: The Hanson and Mauersberger paper is not a correct reference for denitrification. An adequate reference would be Fahey et al. (2001) or if one aims on denitrfication in connection with dehydration, the Fahey et al. (1990) paper.
Reference changed to Fahey 1990.

P22015, l20-21: A reference is missing here. An adequate reference would be the paper book by Brasseur and Solomon on Aeronomy of the Middle Atmosphere published by Springer or the review paper by Solomon (1999).
Reference to Solomon (1999) paper is inserted.

P22016, l3: Sedimentation of what? Please be more clear.
Sedimentation of ICE particles

P22016, l26, P22018, l4: Abbreviations of the satellite instruments should be introduced as well as it should be mentioned on which satellites this instruments are operating.
P22018, l9: It should be added what the abbreviation LAPBIAT is standing for and when this campaign was performed?
Thanks for mentioning. The abbreviations of satellite instruments and the campaign and the time of it have been introduced.

P22020, 7-8: "LAUTLOS": the abbreviation for this campaign has not been introduced. When was this campaign performed?
LAPBIAT Upper Tropospheric Lower Stratospheric Water Vapour Validation Project (LAUTLOS-WAVVAP) measurement campaign in early 2004 was performed in the northern Finland (Deuber et al., 2005; Vömel et al., 2007a, Vömel et al., 2007b, Suortti et al., 2008)

P22025, l14-15: I would suggest to add here at which altitude/pressure level the postive long-term trend in water vapour is observed. Does this concern only certain altitude/pressure levels or the entire stratosphere?
P22025, l16: At which altitude do you derive a positive trend? At a certain altitude or ine the entire stratosphere?
Yes, this concerns the whole stratosphere as we specify in the revised version.

P22026, l26: Although may derive this relationship from the formula given by Hanson and

Mauersberger (1993), there are other papers actually stating this and would be thus a more adequate reference.
We believe this comment refers not to P22026, l26, where it makes no sense to us, but to P22027, l26 where we state that water vapour increase '…would have increased the size of ICE PSC areas even if the temperatures have been the same.' To address the comment we add references to Kirk-Davidoff et al. (1999) here, which as we believe, was one of first to point to this mechanism.

P22026, I17: Also here a reference is missing. Observation of dehydration in the Arctic during was shown for e.g. the 2009/2010 winter was reported by Khaykin et al. (2013).
The reference to Khaykin is added.

P22026, L19-21: Does the simulated occurrence of ice PSCs during these 20 winters agree with observations?
We have revised the discussion of ice PSC in this section. The comparison of our simulations with PSC observations from CALIPSO is also improved. Unfortunately there is no other ice PSC observations with reasonable coverage except for CALISPO which is available only since 2007. Therefore we cannot comment on how the simulated occurrence of ice PSC agree with observations over the whole period. We are aware that some observation are available from earlier period as well, based on satellite and ground based platforms (Lidars, backscatter sondes, e.g. Stein et al., 1999; Kivi et al., 2001; Müller et al., 2001). Here we haven't used the other data sets for the comparisons. However, this can be done within the future studies.

P22031, I1-3: Are these long-term changes observed in the entire Arctic or solely at Sondaylä?
Yes, this concerns the whole stratosphere as we specify in the revised version.

P22031, I11ff: Do you see the increase in ice PSCs in both, the FinROSE simulations and the CALIPSO observations or only in the FinROSE simulations? Please clarify.
The increase is seen in both CALIPSO and FinROSE. Text is clarified.

P22041, Fig 4: I do not understand for which region the trend is estimated and shown in the Figure? Are you comparing here Sodankylä data with FinROSE simulations ECMWF data for the polar regions? If yes, is this an adequate approach?
The Sodankylä time series were in the Fig 4 only for comparison. The analysis have done from the anomaly panels. However, the figure 4 have now split into two figures. Figure 4 shows water vapour from Sodankylä and Fig 5 anomalies from 70-90N. The trends have estimated only from the anomalies. Also a lot of new analysis from the anomalies have done.

P22044, Fig 7: Why not doing this comparison for the Arctic? How many CALIPSO observations were actually available for creating such a plot? I guess not that many. I remember that CALIPSO passes through certain Arctic stations locations very infrequently. What does "near Sodankylä" actually mean? What was the allowed maximum distance from Sodankylä?
In the Figure 7 there was total areas of ICE PSCs and NAT PSCs in the northern hemisphere. All the NH CALIPSO observations during winter 2009/2010 were taken into account in the calculation of the areas.
Only the temperature panels in the figure 7 were from Sodankylä gridpoint (6*3 degrees). The Figure was confusing and now the temperature panels have changed to the total areas

of colder than 188K. (Also the NAT areas have totally taken off.)
Now the ICE panels can more easily be compared to the temperature.

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Wang

This is a very interesting paper that is well written with a clear story line. I have a few minor comments, and I hope those will help polishing the paper toward final publication.

Comments on paper ACPD-15-22013-2015 entitled “Variability of water vapour in the Arctic stratosphere”

For years the topic of stratospheric water vapor in high-latitudes was indeed less reported. That’s why I was immediately intrigued by this interesting topic (also because I have seen similar results from our trajectory model). Unlike other simulations that mainly based on cold-point temperature regulations (e.g., Fueglistaler et al., [2005]; Schoeberl et al., [2002]; Wang et al., [2015]), the FinRose model has interactive chemistry included over the polar region, which makes this research more valuable to the UTLS and stratosphere community. However, I have a few comments to the authors and I hope those can help polishing the entire story.

We thank Dr. T.Wang for the encouraging review which we found very helpful indeed. We have revised the manuscript to address all the comments.

1. There should be more details to the model description. For example, besides implicit chemistry and circulation from ERA interim, is there any mixing considered? How about wave activity? Also, I am confused at the relations between “tropospheric concentrations” and the “boundary conditions” mean. What does “boundary conditions” mean in this paper?
The tropopause height is calculated at every time step using potential vorticity as defining parameter. Model levels below +-2 PVU are considered to be in the troposphere. Close to the tropics the 380 K potential temperature level is further used to define the tropopause. The tropopause is thus changing with time along meteorological conditions. The tropospheric concentrations of the chemical species are not calculated in the model but prescribed via model boundary conditions. These details are added to the revised manuscript.

2. About the description of (using) ERA interim water vapor field. This mainly occurs on P22021/L8-10, which is quite misleading. The authors mentioned about the improvement on ERA interim H2O after adopting the new linear scheme for stratospheric methane, but this was only limited to the experiments conducted on year 2000 (Monge-Sanz et al., [2013]). Therefore, the boundary condition water vapor (if I understand it correct) used in FinROSE model is still the official H2O field available on ERA interim. Be noted that ERA interim doesn’t assimilate H2O at the altitude range covered in this paper, so humidity field might primarily reflect the model simulation, and therefore comparison to observations is itself less meaningful. I mean, how much credibility should we lay on its range?
Please note that we state in P22021/L8-10 of the manuscript that ‘*The description of stratospheric H2O in the ECMWF model is however simplified (Monge-Sanz et al., 2013)…*’, therefore we believe there is nothing misleading in theses lines. We are aware about limitations imposed by using ERA-Interim. In the revised manuscript we specifically add that biases in ERA-Interim water vapour affect our simulations (see below). However it provides continuous and global coverage needed for initializing transport models, which is not available from observations. That is why it is used in ours as well as in other papers such as Schoeberl et al. (2012). The Reviewers concern about ‘how much credibility should we lay on its range’ is partly addressed in the manuscript by evaluating FinROSE simulations against observations from satellites (MLS) and soundings. We show that in many cases FinROSE

compares favorably to observations, which adds credibility to ours methodology. To further address Reviewers concern we add a note of cautious on the quality of ERA-Interim boundary conditions:
'The FinROSE-ctm has been run using ERA-Interim meteorology and ERA-Interim water vapour data as tropospheric boundary condition. Thus, the evolution of water vapour in the FinROSE model is strongly constrained by the water vapour at the ERA-Interim tropopause. Kunz et al (2014) recently compared Era-Interim water vapour in UTLS against independent sounding observations and found that while in the majority of the cases the agreement is satisfactory, in some cases the discrepancies between Era-Interim and observations are large. Thus one can expect that these biases would affect FinROSE simulations in the stratosphere. Nevertheless, since the description of stratospheric H2O in the ECMWF model is simplified (Monge-Sanz et al., 2013), the chemistry scheme in FinROSE produces a more realistic water vapour distribution, as we show in the manuscript.'

3. When comparing to MLS observations, did the authors apply averaging kernels? This might not be important since the focus is only on polar region that has lower reliance on H2O from below and upper levels (this could also be told from the figure below that applied AKs to the Fig. 4 in this paper), but it is worth to do a sanity check in order to do an apple-to-apple comparison.
MLS data used for Sodankylä were now changed to MLS overpass data figures 1, 2 and 4a. The area averages for figure 4 b-e are calculated from level 2 data, and are gridded without averaging kernels. Some text about the overpass-data have been inserted to the Water vapour and PSC measurements-section.

4. When comparing to MLS observations, please also pay attention to the cold-biases in ERA interim temperatures (Fueglistaler et al., [2011]), since those would affect the trajectory results tremendously (Schoeberl et al., [2012]).
We have commented on this in the original manuscript as follows: *'The dryness in the reanalysis data is likely a consequence of cold bias in the tropics in the ERA-Interim data (Schoeberl et al., 2012).'*

5. I hope the authors could also double check on Fig. 2b green line (ERA interim –MLS) around the tropopause. An eye-ball check, and also my own calculations a few years ago tells me that the difference should be at least around 10-14% at 100-hPa.
In the figure 2a there is water vapour from winter 2010 and in Fig 2b climatologies of the differences between MLS -sounding, MLS -ERA-Interim and MLS -FinROSE. The differences don't have to be the same in these figures. However, we have changed the MLS data to the overpass data and taken year 2014 along to the climatology. Now the difference between ERA interim –MLS is about 8+-6 % at 100 hpa.

6. Fig. 4 panels b–e show the anomalous H2O and the components due to transport and chemistry, which is basically what we saw in previous figure (Fig. 3) and the Fig. 6 in Schoeberl et al., [2012]. Here, in order to support the analysis in P22024- 22025, it is better to add MLS to those panels despite different time range. What the authors could do is to subtract the cycle covering the MLS period, and the results would be essentially the same but it adds more credibility to the model's performance. For reference, below is H2O from our trajectory model, driven by reanalysis and controlled by purely temperatures. Note that this figure demonstrates results from using GPS RO temperatures; but results from using reanalyses temperatures would be basically the same since reanalyses capture the interannual variability of cold-point tropopause over the tropics very well and therefore the

predictions are similar that essentially match with MLS observations (refer Fig. 8 Wang et al., [2015] for details). On the other hand, this, from another perspective, supports many arguments in this paper about the origin of stratospheric air.

Figure. Arctic water vapor predicted from trajectories driven by MERRA (blue) and ERA interim (orange) circulation and GPS RO temperatures (refer Wang et al., 2015), compared to MLS observations. All trajectory results have been weighted by MLS averaging kernels.

Thanks for this comment and for sharing the results of your trajectory simulations not included into Wang et al. (2015). We have added MLS anomalies to the figure. We believe that this addition does improve the presentation of the results.

7. Discussions about the contributions to H2O from chemistry and transport (section 4) could be more easily understood by the H2O lifetimes (refer chap. 5 in the classic book by Brasseur and Solomon, [1986]).

Here the contribution from chemistry mainly refers to water vapour anomalies due to methane oxidation which takes place in the upper stratosphere. In the lower stratosphere where direct water vapour production from methane is negligible the variations arise from the transport of chemically produced water vapour from above. Therefore direct comparison of local chemical and transport life times of water vapour would not help much to understand contribution of these two sources to water vapour changes in the lower stratosphere. The rate of methane increases is more relevant here, as discussed in the paper. In the revised manuscript we specify what chemical contribution means as follows:
'*The chemical part (purple line), which is mainly due to the contribution of methane oxidation, has only a small positive trend …*'

8. Discussion in P22025/L17-23 is not exactly accurate. The stratospheric water vapor is more dominated by the Brewer-Dobson circulation instead of QBO. Please refer the multi-variate regression coefficients and the component time series in Dessler et al., [2013, 2014]). That's why the 2000-drop is believed to be related to the BDC (e.g., Randel et al., [2006]).

Following this and the related comments of R1 and R2 we have elaborated the discussion of the water vapour variability. We performed regression analysis following Dessler et al. (2014). We used three proxies: qbo index (QBO, equatorial winds at 50hPa), Brewer Dobson circulation index (BD, residual vertical winds at 70hPa averaged from 30S to 30N), and cold point temperature (CPT). Unlike Dessler et al. (2014) we found that the use of tropical temperatures at 500 hPa was not enough to explain the variability of the cold point temperature, and therefore used it as one of proxies. Although, there is some correlation between CPT and QBO (0.36) QBO also affect the transport of the water vapour not directly influenced by CPT; therefore the use of both proxies is justified. We apply multiple regression analysis with all three proxies to water vapour time series averaged north of 70N and at 82 hPa and 56 hPa. Cross-correlation analysis shows bread peaks at lags 6-12 months for the proxies. The maximum of the correlations of QBO and CPT with water vapour at 56 hPa is at about 10 months lag, and with 82 hPa is at 8-9 month lags, suggesting that propagation of the tropical anomalies in the lower stratosphere is faster than that in the middle stratosphere, likely due to more efficient mixing. We use 10 month lag for all proxies for regression at 56 hPa and 9 month lag for the regression at 82 hPa.

The individual correlation coefficients with our proxies are shown in the Table below. The main contribution to the polar water vapour variability is CTP, followed by QBO. We found

very weak contribution of BD proxy to the variability of the water vapour. One reason is that the effect of BD contribution is accumulated over time and this is not well represented by the monthly proxy. The multiple regression coefficients are 0.57 and 0.51 at 82 hPa and at 56 hPa correspondingly, showing that our models only explain 25-30% of the variability. This is considerably less than that of Dessler et al. suggesting that different processes contribute to the polar water vapour variability in comparison to those in the tropics. Note that the regression somewhat explains the increase of the water vapour from 2005 to 2010, which is more clear at 82 hPa. However the peak of the water vapor during 2011-2013 is not explained by these proxies.

Table: Correlation coefficients

	CPT	QBO	BD	Multiple
56 hPa	0.454073	0.315499	-0.209597	0.51
82 hPa	0.518588	0.399678	-0.180337	0.57

9. Some comments on figs. 2, 4, and 6. This is a personal preference: I always add legends to the figures, so that when someone else uses those figures in their presentations they don't need to add legends manually. On the other hand, with legends the vast information is easy to be spotted on.
Thanks for comment. We added legends to the figures.

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Manuscript prepared for Atmos. Chem. Phys.
with version 2014/07/29 7.12 Copernicus papers of the LaTeX class copernicus.cls.
Date: 11 January 2016

Variability of water vapour in the Arctic stratosphere

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Abstract.

This study evaluates the stratospheric water vapour distribution and variability in the Arctic. A FinROSE chemistry ~~climate~~ transport model simulation covering years ~~1990–2013~~ 1990–2014 is compared to observations (satellite and frostpoint hygrometer soundings) and the sources of stratospheric water vapour are studied. ~~According to~~ In the simulations, the Arctic water vapour shows decadal variability with a magnitude of 0.8~~0.6~~ ppm. Both observations and the simulations show an increase in the water vapour concentration in the Arctic stratosphere ~~started to increase~~ after year 2006, but around ~~2011~~ 2012 the concentration started to decrease. Model calculations suggest that ~~the~~ this increase in water vapour ~~during 2006–2011 (at 56 hPa)~~ is mostly explained by transport related processes, while the photochemically produced water vapour plays a relatively smaller role. The ~~water vapour trend in the stratosphere may have contributed to increased ICE PSC occurrence. The~~ increase of water vapour in the ~~precense~~ presence of the low winter temperatures in the Arctic stratosphere led to more frequent occurrence of ~~ICE PSCs~~ice polar stratospheric clouds (PSCs) in the Arctic vortex. The polar vortex was unusually cold in early 2010 and allowed large scale formation of the polar stratospheric clouds. The cold pool in the stratosphere over the Northern polar latitudes was large and stable and a large scale persistent dehydration was observed. Polar stratospheric ice clouds and dehydration ~~were~~ observed at Sodankylä with accurate water vapour soundings in January and February 2010 during the LAPBIAT ~~atmospheric sounding campaign . The observed changes in water vapour were~~ (Lapland Atmosphere-Biosphere facility) atmospheric measurement campaign were well reproduced by the model. ~~Both~~ In particular, both the observed and simulated decrease of the water vapour in the dehydration layer was up to 1.5 ppm.

1 Introduction

Water vapour is the most important natural greenhouse gas in the atmosphere accounting for about half of the current greenhouse effect (Schmidt et al., 2010). Although the majority of water vapour resides in the troposphere, it has been highlighted that stratospheric water vapour variations may play an important role in the decadal scale variability of the climate (Solomon et al., 2010). Recently the existence of a positive stratospheric water vapour feedback was shown based on observations, i.e. stratospheric water vapour increases with tropospheric temperature, which contributes to the climate sensitivity (e.g., Dessler et al., 2013). Therefore, investigating the changes in stratospheric water vapour abundance is helpful in the detection and attribution of the ongoing climate change.

Water vapour is also an important constituent in the stratospheric chemistry. It intensifies ozone destruction both by producing odd-hydrogen species, which can destroy odd-oxygen, and by formation of polar stratospheric clouds (PSC), which enable efficient conversion of halogen reservoir species to halogen radicals (e.g., Solomon et al., 1986). In the winter polar vortex ~~, water vapour condenses to form~~ water vapour can condense to form ice PSCs, i.e. type II PSCs~~(ICE PSCs). ICE PSCformation leads to heterogeneous chlorine activationand ozone depletion (e.g., Solomon et al., 1986). However, Kirner et al. (2015) show that the most efficient ozone destroyer are the heterogeneous reactions~~ . Increased water vapour may also affect the abundance of other PSCs as the formation of both NAT (nitric acid trihydrate, type Ia PSC) (Hanson and Mauersberger, 1988) and STS (super cooled ternary solution, type Ib PSC) (Carslaw, 1995) are dependent on nitric acid and water vapour concentrations. Furthermore, the reaction rates on/in STS depend on the composition of the particles, which is a function of water vapour (Sander et al., 2011, Section 5).

Ice PSCs contribute only to a minor part of the chlorine activation. According to a model study by Kirner et al. (2015) 90 % of the ozone depletion in the Antarctic spring is caused by halogen activation on liquid particles. In ~~the high latitudes also the~~ a model study of the Arctic winter 2009/2010 Wohltmann et al. (2013) showed that chlorine activation on ~~the ICE particles have a remarcable role. Heterogeneous chemistry on NAT particles causes only a minor part of the ozone depletion. When ice~~ liquid aerosols alone explained the observed changes in the ozone column to within 10 %. The additional chlorine activation caused by ice PSCs is modest. However, when ice PSC particles sediment to lower altitudes, ~~the~~ a reduction of water vapour, i.e. dehydration occurs (Kelly et al., 1989). ~~At the same time the airmasses are effectively denitrified (Hanson and Mauersberger, 1988), which~~ Sedimenting ice PSC particles also contribute to the denitrification (Hintsa et al., 1998), which can prolong the ozone depletion in the spring due to a slower conversion of active chlorine back to the reservoir species $ClONO_2$.

The Arctic polar vortex is often less stable and maintains higher temperatures than its Antarctic counterpart, and thus ~~ICE~~ ice PSCs and dehydration are seldom observed (Solomon , 1999). However, stratospheric water vapour is expected to increase due to climate change caused warming

of the tropical tropopause (Gettelman et al., 2009) and to an increase in the atmospheric methane concentration. This, in addition to the increased radiative cooling in the stratosphere ~~,~~ due to the increase of CO_2 ~~, as well as an increase in stratospheric~~ and water vapour, ~~due to climate change caused warming of the tropical tropopause can enhance the PSC formation. The increased PSCs could lead to more severe ozone depletion (e.g., Kirk-Davidoff et al., 1999) and delay then the ozone recovery (Tian et al., 2009).~~ might lead to enhanced PSC formation. For example Rex et al. (2006) found increased PSC volume trend in the lower Arctic stratosphere during dynamically quiescent winters since 1960s (see also Dameris et al. (2014)). However the potential of greenhouse gas increases to increase PSC occurrence remains controversial issue (Rieder et al., 2013; Langematz et al., 2014).

The combined effect of temperature and water vapour on ozone, through homogeneous and heterogeneous chemistry and dynamics, is complex. Overall the result of climate model study by Tian et al. (2009) indicated that the increased stratospheric water vapour would lead to increase total column of ozone in the Arctic in the future despite increased active chlorine in the polar spring regions, while in the Antarctic the ozone recovery would be delayed. The evolution of stratospheric water vapour and its effect on the formation of PSCs are therefore of interest.

The stratospheric water vapour concentration is controlled by atmospheric dynamics and photochemistry. Its main sources are intrusion from the troposphere via the tropical tropopause (Brewer, 1949) and production through ~~methane oxidation~~ oxidation of methane and also molecular hydrogen (Bates and Nicolet, 1950; Le Texier et al., 1988). When rising air masses pass through the cold tropical tropopause region, moisture is removed due to freezing and sedimentation of particles (Brewer, 1949). The variability in the entry of water vapour into the stratosphere is ~~therefore~~ largely controlled by the variability in the tropical cold point temperature. The oxidation of methane leads to formation of water through a series of reactions. The reaction with OH is the dominating methane loss reaction through most of the stratosphere, while the reaction with excited oxygen becomes increasingly important above 30 km, and photolysis is dominant above 65 km (Le Texier et al., 1988). In addition, the reaction with atomic chlorine has some significance as a sink for methane, but also as a termination reaction of ozone depleting cycles especially in the Antarctic vortex where denitrification reduces the importance of the reaction between ClO and NO_2 (Fahey et al., 1990).

Due to the cold tropical tropopause, only a small fraction of tropospheric water vapour propagates to the stratosphere. As a result, the stratosphere is very dry, but it exhibits considerable variability both in space and time. The ~~large gradient especially over the tropopause~~ exceptional dryness of the stratosphere makes observation of stratospheric water vapour challenging. ~~The observational challenges mean that long-term~~ Long-term time series of stratospheric water vapour are rare, which complicates the study of concentration trends. Frostpoint hygrometer soundings have been performed in Boulder, Colorado, since 1980 and for shorter periods of time also in other locations, including Sodankylä, Finland (Oltmans et al., 2000). Additionally, global data is available from satellite instruments, but only for a limited time span~~. For example, the~~ , for example from Microwave

Limb Sounder (MLS) on board the Upper Atmosphere Research Satellite (UARS) (1991–1993) and the Earth Observing System on Aura (EOS-Aura) (2004–today) ~~allows a continuous monitoring of the northern hemispheric stratospheric water vapour distribution since 2004~~ (e.g., Lambert et al., 2007). Also ~~SAGE II , HALOE, SMR, SCIAMACHY, MIPAS, and~~ the Stratospheric Aerosol and Gas Experiment II and III (ERBS/SAGE-II, Meteor-3M/SAGE-III), Polar Ozone and Aerosol Measurement (SPOT-4/POAM III), the UARS Halogen Occultation Experiment (UARS/HALOE), the Odin Sub-Millimetre Radiometer (Odin/SMR), the SCanning Imaging Absorption spectroMeter for Atmospheric ChartographY (Envisat/SCIAMACHY), the Envisat Michelson Interferometer for Passive Soundings (Envisat/MIPAS), Solar Occultation for Ice Experiment (AIM/SOFIE) and the SCISAT Atmospheric Chemistry Experiment Fourier Transform Spectrometer (SCISAT-1/ACE-FTS) have measured stratospheric water vapour in the Northern high latitudes, but the spatial and temporal coverage is limited.

Several studies have used these available measurements to look into water vapour trends, especially in the mid-latitudes. Oltmans et al. (2000) analysed frostpoint hygrometer measurements above Boulder Colorado and reported a trend of about $+0.048 \pm 0.001\,\mathrm{ppm\,yr^{-1}}$ between 1980 and 2000 at ~~level~~ the level of 18–20 km. Randel et al. (2004) compared the Boulder data to the HALOE measurements and reported differences between the Boulder data set and HALOE water vapour data. The seasonal and interannual changes were comparable, but the long term increase observed in soundings were not ~~shown~~ seen in HALOE data. Later Scherer et al. (2008) did corrections for the instrumental bias of the Boulder frostpoint hygrometer data~~and~~ , updated the Boulder trend and reported a trend of +0.03–0.04 $\mathrm{ppm\,yr^{-1}}$ between 1980 and 2000 at the same altitude, but noted a sudden drop in the stratospheric water vapour beginning in 2001. Hurst et al. (2011) presented a new trend analysis of the 30 year record of Boulder stratospheric water vapour measurements (1980–2010) and found a +1.0 ppm increase over that time period at 16–26 km altitude, with significant ~~shorter term variations~~short term variability. However, Hegglin et al. (2014) suggested, based on merged satellite data set, that the Boulder time series is not globally representative and instead reported negative trends in mid- and high latitudes at 16 km altitude between the end of 1980s and 2010. ~~Negative~~ Based on satellite and sounding measurements Solomon et al. (e.g., 2010) reported negative trends in Boulder and generally in the mid-latitudes at 18 km altitude between 2000 and 2009 ~~have also been reported in previous studies (e.g., Solomon et al., 2010).~~ while Hegglin et al. (e.g., 2014) showed that these negative trends are mainly related to the sudden drop in the water vapour in 2000 and that after a few years with very low water vapour mixing ratios a recovery started in 2005. Recently (Urban et al., 2014) reported another drop in the tropical water vapour during 2011–2012.

On the other hand, due to the lack of long term time series, there have been very few studies of stratospheric water vapour trends in the Arctic, where variations in the water content can have large effects on spring-time ozone depletion. Recently Hegglin et al. (2013) have compared wa-

ter vapour climatologies from 13 satellite products within the SPARC data initiative and analysed also the anomalies in the Northern extratropics water vapour. They found that the uncertainty in water vapour increases toward the polar regions~~and~~ , the mesosphere and the ~~UTLS region.~~ upper troposphere-lower stratosphere (UTLS) region. Hegglin et al. (2014) showed water vapour trends up to 80° N latitude for the time period between the late 1980s and 2010 and reported negative trends in the stratosphere. On the other hand one should keep in mind that the coverage before 1998, which was based on HALOE and SAGE II, was not good, which warrants some caution to the results.

In this study, we use the FinROSE chemistry transport model (~~FinROSE-ctm~~FinROSE-CTM) (Damski et al., 2007; Thölix et al., 2010) to investigate the stratospheric water vapour in the Arctic for the period ~~1990–2013.~~ 1990–2014. The model is described in Section 2. In Sect. 3 we describe the water vapour distribution in FinROSE simulations and observations. The modelled water vapour is evaluated against soundings at Sodankylä, Finland (67.4° N, 26.6° E) and MLS satellite observations. The studied period includes the exceptionally cold January ~~–~~2010 Arctic vortex with large scale ~~ICE~~ ice PSC formation, which was observed also by the ~~CALIPSO~~ Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), the primary instrument onboard Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) space-borne lidar (Pitts et al., 2011). Section 4 shows the long term variations of water vapour and its sources. Section 5 describes the dehydration frequency in the Arctic stratosphere from 1990 to ~~2013.~~ 2014. Section 6 deals with the Arctic winter 2010, including results from the ~~LAPBIAT atmospheric sounding campaign .~~ Lapland Atmosphere-Biosphere Facility (LAPBIAT–2) measurement campaign in January–March 2010.

2 Modelling and data

2.1 FinROSE

The ~~FinROSE-ctm~~ FinROSE-CTM (Damski et al., 2007) is a global off-line chemistry-transport model describing the stratosphere and mesosphere. The model produces the distribution of 36 species and the chemistry scheme ~~describes~~ consists of 110 gas phase reactions and 37 photodissociation processes. Water vapour is produced from oxidation of methane and molecular hydrogen. The PSC scheme includes liquid binary aerosols (LBA), super-cooled ternary solutions (STS, type Ib) and solid nitric acid trihydrate (NAT, type Ia) and ice (~~ICE~~ice, type II) PSCs. The model chemistry includes altogether 30 heterogeneous reactions on/in liquid binary aerosols and type Ia, Ib and II PSCs. Particle sedimentation, leading to dehydration and denitrification of the stratosphere, is also included in the model. The heterogeneous chemistry scheme in FinROSE is based on the calculation of the composition and volume of sulphate aerosols and PSCs and the partitioning of species between gas phase and condensed phase. The composition of LBA and STS are calculated using the method by Carslaw (1995). The STS are not considered below the ice PSC formation temperature. The number density profile ~~is prescribed for each PSC type (Damski et al., 2007) and~~

for LBA and STS is estimated from McLinden et al. (1999) and the sulphuric acid distribution [$\mu m^2\,cm^{-3}$] is based on 2-D model data (Bekki and Pyle, 1992). NAT formation is based on the thermodynamic equilibrium equations by (Hanson and Mauersberger, 1988). The model includes an option to include a supersaturation requirement for NAT and ice formation, but this option was not used in the simulations reported in this paper. The choice was made due to the relative modest resolution of the model. Co-existence of NAT and STS is allowed. A scheme for growth of NAT particles is included based on Fahey et al. (2001). The number density of NAT particles is initially assumed to be 1 cm^{-3} (Krämer et al., 2003). For large NAT particles the number density is reduced. The temperature threshold for ice particle formation is based on expressions by Marti and Mauersberger (1993). The equilibrium pressure of nitric acid above ice is calculated according to Hanson and Mauersberger (1988). The ice number density is assumed to be 0.04 cm^{-3}, as estimated from synoptic scale PSCs (Dye et al., 1992).

The chemical kinetics used in this work follow the recommendations by Sander et al. (2011) and Atkinson et al. (2007). Photodissociation coefficients were calculated using the PHODIS radiative transfer model (Kylling et al., 1997) and were used in the model through look-up tables. The model transport is calculated using a flux-form semi-lagrangian transport scheme (Lin and Rood, 1996).

The tropopause height is calculated at every time step using potential vorticity as defining parameter. Model levels below $\pm$ 2 PVU are considered to be in the troposphere. The 380 K potential temperature level is used to define the tropopause height between 20° S and 20° N. The tropopause is thus changing with time depending on meteorological conditions. The tropospheric concentrations of the chemical species ~~is~~ are not calculated in the model but prescribed via model boundary conditions. Tropospheric water vapour and ozone were obtained from the ECMWF ERA-Interim reanalysis (Simmons et al., 2007; Dee et al., 2011). Tropospheric methane (CH_4) is from Global view-data (~~ftp://aftp.cmdl.noaa.gov/products/globalview/ch4~~http://www.esrl.noaa.gov/gmd/ccgg/globalview/ch4), nitrous oxide (N_2O) from ~~Agage~~ Advanced Global Atmospheric Gases Experiment (AGAGE) data (Prinn et al., 2000),and halogens (Cly and Bry) are from Montzka et al. (2009) updated data. Carbon dioxide (CO_2) is based on global annual mean trend data (ftp://aftp.cmdl.noaa.gov/products/trends/co2). At the upper model boundary (0.1 hPa), climatological values averaged over ~~2005–2013~~ 2005–2014 from MLS data were used for water vapour and ozone. The model has also a tracer aimed for water vapour studies; a chemically passive tracer for describing the amount of water vapour entering through the tropopause.

In this study, the model was run with a horizontal resolution of $6° \times 3°$ (longitude $\times$ latitude) at 35 hybrid-sigma levels, from the surface up to 0.1 hPa (about 65 km). The wind, temperature and surface pressure fields were obtained from the European Centre for Medium-range Weather Forecasts (ECMWF) ERA-Interim ~~reanalyses~~ reanalysis (Dee et al., 2011).

2.1.1 Water vapour and PSC measurements

~~Accurate measurements~~ High resolution soundings of stratospheric water vapour from ~~the~~ northern high latitudes are rare~~; however, such soundings are available at Sodankylä~~. However, such measurements have been been made at Sodankylä (67.4° N, 26.6° E), northern Finland since early 2000 (Vömel et al., 2007a, c). Sodankylä site is representative of high latitude conditions in the northern Europe, and the upper air soundings in winter and spring sample air both inside and outside the polar stratospheric vortex. Here we have used stratospheric water vapour measurements from two atmospheric sounding campaigns ~~. First~~ and some additional soundings obtained outside the major campaigns. First larger set of observations was obtained during the Lapland ~~Atmosphere–Biosphere~~ Atmosphere-Biosphere Facility (LAPBIAT) Upper Tropospheric Lower Stratospheric Water Vapour Validation Project (LAUTLOS-WAVVAP) campaign in early 2004 ~~(e.g., Deuber et al., 2005; Vömel et al., 2007a, b; Karpechko et al., 2007; Suortti et al., 2008)~~(e.g., Deuber et al., 2005; Vömel et al. The second campaign (the LAPBIAT-2 ~~(Lapland Atmosphere–Biosphere Facility)~~ Atmospheric Sounding Campaign) took place in January–March ~~–~~2010 (Kivi et al., 2010; Khaykin et al., 2013; Engel et al., 2014; Grooß et al., 2014). During these campaigns ~~three types of water vapour instruments~~ two types of frost point hygrometers were flown. The NOAA frostpoint instrument (Oltmans, 1985; Vömel et al., 1995) was flown during the first campaign~~. First flights of~~ , while the Cryogenic Frostpoint Hygrometer (CFH) ~~were also performed during the LAUTLOS campaign. The CFH flights were continued during the LAPBIAT-2 campaign in 2010.~~ was deployed during both campaigns. CFH is a well characterised instrument capable of accurate water vapour measurements in the lower stratosphere typically up to the altitude of 25–28 km ~~(Vömel et al., 2007a). Lyman-alpha fluorescence hygrometers (FLASH-B) were also flown during both campaigns (Vömel et al., 2007b; Khaykin et al., 2013).~~ (Vömel et al., 2007a, b). In this study we have used 13 NOAA frostpoint hygrometer profiles obtained during the first campaign and 13 CFH soundings obtained during the second atmospheric sounding campaign. In addition ~~, one NOAA profile from~~ we included 8 NOAA or CFH soundings outside the main campaign periods, in order to improve temporal coverage. These additional soundings were made during January-February in year 2003, ~~two NOAA profiles from~~ 2006, ~~as well as two CFH profiles from~~ 2008~~and one CFH profile from 2012 were used.~~ , 2013 and 2014.

In addition to the balloon soundings, observations from the Microwave Limb Sounder (MLS) on board the Aura satellite provide global profile measurements of H_2O, temperature and several trace gases (Lambert et al., 2007). In this study, we use the MLS version 3.3 Level 2 data, which are available from August 2004 to present. The data is published in EOS MLS Science team (2011) and it is accessed at http://disc.sci.gsfc.nasa.gov/datacollection/ML2H2O_V003.html. The Level 2 data are produced on pressure surfaces from 316 to 0.1 hPa with a vertical resolution of about 3 km. Each day about 3500 vertical profiles are measured along a sun-synchronous suborbital track. For Sodankylä we used MLS overpass-data from Aura validation data center. All profiles within 300 km from Sodankylä were averaged for getting daily profiles of water vapour.We also used polar stratospheric

cloud observations provided by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) space-borne lidar (Pitts et al., 2007). The CALIPSO PSC algorithm classifies PSCs by composition. Six different classes are defined: supercooled ternary solution (STS), two classes of liquid/NAT mixtures and mix 2 enhanced ~~, water ice~~ and water ice (including synoptic-scale ice and wave ice) (Pitts et al., 2011). We used these CALIPSO PSC composition classes for calculating the areas where PSCs were observed. The area is calculated separately for ~~ICE~~ ice and NAT. Both water ice and wave ice are included in the ~~ICE~~ ice area and all the NAT mix classes to the NAT area. CALIPSO data is available from June 2006 to present.

3 Water vapour distribution

The ~~FinROSE-ctm~~ FinROSE-CTM has been run using ERA-Interim meteorology and ERA-Interim water vapour data as tropospheric boundary condition. Thus, the evolution of water vapour in the FinROSE model is strongly constrained by the water vapour at the ERA-Interim tropopause. ~~The~~ Kunz et al. (2014) recently compared ERA-Interim water vapour in UTLS against independent sounding observations and found that while in the majority of the cases the agreement is satisfactory, in some cases the discrepancies between ERA-Interim and observations are large. Thus one can expect that these biases would affect FinROSE simulations in the stratosphere. Nevertheless, since the description of stratospheric H_2O in the ECMWF model is ~~however simplified (Monge-Sanz et al., 2013)and~~ simplified (Monge-Sanz et al., 2013), the chemistry scheme in FinROSE ~~can therefore be expected to produce~~ produces a more realistic water vapour distribution, as we show in the manuscript.

First, we evaluated the simulated stratospheric water vapour distribution from FinROSE against measurements above Sodankylä. Figure 1 shows simulated and measured climatologies of water vapour distribution over Sodankylä between 2004 and ~~2013.~~ 2014. Overall, the ~~FinROSE-ctm~~ FinROSE (top panel) is capable of reproducing the MLS observations (middle panel) of water vapour concentration and its vertical and temporal distributions. The maximum values of water vapour are located at the same altitude in both data sets. The largest differences are ~~in summer,~~ between 10 and 1 hPa~~,~~: in winter/spring the concentration in FinROSE is about 1 ppm higher compared to MLS ~~.~~ but in summer MLS is about 0.3 hPa moister than FinROSE. Too moist air in FinROSE in spring can lead to overestimated PSC formation. In comparison, the ECMWF ERA-Interim reanalysis (bottom panel) clearly underestimates the observed water vapour concentrations in the upper stratosphere, while the lower stratosphere compares well with MLS. The largest discrepancies between ERA-Interim and MLS are seen in the upper stratosphere where ~~the water vapour is underestimated~~ ERA-Interim underestimates water vapour by 1 ppm. The dryness in the reanalysis data is likely a consequence of cold bias in the tropics in the ERA-Interim data (Schoeberl et al., 2012). Also the methane parameterisation in the ECMWF model ~~lead~~ leads to too dry air (Dethof,

2003). It is also possible that too fast general circulation previously identified in the ECMWF model causes reduced moisture in the polar regions (Simmons et al., 1999; Schoeberl et al., 2012; Monge-Sanz et al., 2013). ~~The same general circulation is also in the FinROSE model~~ Note that these problems with the general circulation affect FinROSE simulations because ERA-Interim meteorology is used. However, the full chemistry of the ~~FinROSE-ctm~~ FinROSE improves the water vapour distribution of the model. During winter and spring the very top levels of ERA-Interim are too moist compared to observations. This is probably due to a too low model upper boundary; the ECMWF model does not extend to the upper mesospheric altitudes where photochemical processes destroy water vapour causing the observed dry upper stratosphere. This process is also missing from the ~~FinROSE-ctm~~FinROSE; however, it has been indirectly included by using a water vapour climatology calculated from MLS data as an upper boundary condition. Overall, Fig. 1 shows that FinROSE is capable of simulating the distribution and magnitude of stratospheric water vapour in the high northern latitudes, which gives us confidence in its applicability for a more detailed study of water vapour distribution, sources, and long-term variability.

For a more detailed comparison of model results with observations at northern high latitudes, we calculated the average mixing ratios and standard deviations of water vapour profiles above Sodankylä from the FinROSE model, ERA-Interim and observations. We chose January–February, because of the availability of balloon soundings during this time. In this comparison ERA-Interim and FinROSE data are available daily from all the January–February months between 2004 and 2013, MLS almost daily, but soundings are available less frequently (altogether ~~32~~ 34 profiles). From FinROSE and ERA-Interim the gridpoint ~~nearest Sodankylä have been chosen~~ closest to Sodankylä has been chosen (Lon=30° E, lat=69° N). From MLS all the profiles measured ~~in the Sodankylä~~ within 300 km from the Sodankylä gridpoint and flagged as good quality are used. Standard deviation is calculated across the individual profiles for each data set and thus represents uncertainty due to natural variability and random measurements errors. Figure 2 compares January–February-mean water vapour mixing ratios ~~above Sodankylä~~ and standard deviations above Sodankylä from the FinROSE simulation (black), ECMWF ERA-Interim reanalysis (green), MLS satellite measurements (blue), and frostpoint hygrometer soundings (red). The data are shown for seven different pressure levels; 100, 56, 30, 21, 10, 3 and 1 hPa. Left panel shows the mixing ratios in winter 2010 and right panel shows the relative differences compared to MLS observations calculated over winters ~~2004–2013~~2004–2014. The winter 2010 was chosen for ~~left panel~~ comparison because of the largest amount of soundings.

The modelled water vapour concentration profile agrees well with MLS measurements in winter 2010 (shown in Fig. 2 left panel). The model data is within 0–0.5 ppm of the MLS data, except at 3 hPa where the model gives ~~0.7~~0.8 ppm more water vapour. Compared to the Sodankylä soundings, FinROSE has about 0.7 ppm more water vapour at 100 hPa, but the difference decreases with altitude, except at 30 hPa altitude where the model is again about 0.7 ppm ~~drier~~moister. At the lev-

els between 100 and 21 hPa the soundings fit to the range of variation of MLS. The difference is less than 0.5 ppm. Balloon sounding data are not available above 20 hPa. ERA-Interim is generally drier compared to MLS and soundings throughout the studied altitude range~~except at level 30 hPa~~. ERA-Interim water vapour concentration is also always ~~more than~~ about 0.7 ppm lower than the FinROSE's ~~as can be expected based on~~ which is consistent with Fig. 1.

The right panel shows the differences between models and observations averaged over several winters. The differences have been calculated using all the available data ~~during Januarys and Februarys~~ pairs during Januaries and Februaries between 2004 and ~~2013.~~ 2014 and then averaged. For FinROSE and ECMWF all the MLS profiles could have been used, but for sounding only the coincident MLS profiles were used. The differences between FinROSE and MLS, ERA-Interim and MLS and soundings and MLS remain smaller than 10 % at all altitudes. ERA-Interim is drier than MLS also in this climatology but FinROSE is moister than MLS except at the 21 hPa level. Soundings are also drier compared to MLS, but the difference is smaller than the difference between ERA-Interim and MLS. Sounding ~~vs.~~ versus model comparisons are complicated, because firstly the number of soundings is limited and secondly, some of the soundings are obtained in the vicinity of the stratospheric vortex where the spatial water vapour gradients are large. Model to satellite differences have been calculated using all available data, both vortex conditions and non-vortex conditions included.

4 The origin and long term variability of water vapour

The sources of stratospheric water vapour are transport from the tropical troposphere and chemical production mainly from methane oxidation. Water vapour enters the stratosphere through the tropical tropopause and propagates then to the upper altitudes and higher latitudes. The FinROSE model has a tracer for studying these two water vapour sources. A passive H_2O-tracer, that is not affected by chemistry, represents the transported water vapour. The difference between H_2O-tracer and H_2O represents the amount of water vapour produced by chemistry, i.e. mainly through oxidation of methane, but also hydrogen. Figure 3 shows the fractions of water vapour due to transport (upper panel) and chemistry (lower panel) according to simulations. Transport from the troposphere covers more than a half of the water vapour. At lower altitudes the transported part is clearly the most important one. The chemically produced water vapour becomes more important at higher altitudes with a maximum ~~around~~ between 1 and 3 hPa~~in~~. In the summer and autumn, ~~where the fraction~~ the fraction of chemistry part reaches almost 50 % there.

The water vapour ~~trend above Sodankylä~~variability and trends above Sodankylä, was investigated from a FinROSE model simulation covering the years ~~1986–2013~~1986–2014. The first four years were discarded as spin-up and the period ~~1990–2013~~ 1990–2014 is analysed below. Figure ~~5~~ 4 compares monthly-mean water vapour mixing ratios ~~in the Arctic area, 70–90° N~~ at 56 hPa above

Sodankylä from the FinROSE simulation ~~(black line)~~, ECMWF ERA-Interim reanalysis ~~(green line)~~and MLS satellite measurements ~~(orange line)~~. The ~~data is from 56 hPalevel~~red dots denote individual sounding measurements. Throughout the investigated period, the water vapour amount in FinROSE and the observations varies within about 4–5.5 ppm. The modelled water vapour concentration agrees well with MLS measurements from 2005–2008; however, after that FinROSE shows higher concentrations than observed by MLS and thus reveals a stronger increasing trend in these last ~~five~~ four years. The growth rate is about 1 $\mathrm{ppm\,decade^{-1}}$ in FinROSE and but only 0.6 $\mathrm{ppm\,decade^{-1}}$ in MLS. As can be expected based on Fig. 1, the ERA-Interim water vapour concentration is about 0.5 ppm lower than in FinROSE. It is, however, noteworthy that the difference remains approximately the same throughout the study period. The increasing trend from 2007 to 2012 is very similar in FinROSE and ERA-Interim data, resulting from the use of ERA-Interim meteorology as driver data in the FinROSE simulation.

~~Panels b–c in Fig. 5 show~~ Figure 5 shows the anomaly of FinROSE water vapour and the sources of it between latitudes 70–90° N. ~~The anomaly of water vapour concentration is shown with a black line. The red line is the anomaly of the passive water vapour tracer and the blue line is the anomaly of the chemically produced part of water. The green line shows the anomaly of ECMWF ERA-Interim water vapour for comparison.~~ All the anomalies ~~are calculated from monthly mean data and the climatology for anomaly calculations has been calculated over the years 1994–2013~~in the figure are calculated with respect to the mean values for the years period 1990-2014 for FinROSE and ERA-Interim and for the period 2004–2014 for MLS anomalies. The altitudes of the panels are 1, 10, 56 and 100 hPa. At ~~the 1 and 10 hPa pressure levels there is no clear~~ all the levels there are small positive trend in the water vapour ~~before 2008. After that the anomaly of water vapour is positive and stays positive until the end of the timeseries . At the lower altitudes, levels 56 and 100~~from the beginning of the timeseries until years 1994–1995. In the lower stratosphere (100–56 hPa~~, there is decrease in the water vapour in the beginning of the time series, until year 1998. After that~~) the anomalies decrease until 1998 and then stay constant until 2007. Thereafter a strong increase lasted until 2012 followed by another decrease, in agreement with observations by Urban et al. (2014) in the tropics. In the upper stratosphere (10–1 hPa) the water vapour ~~anomaly does not show any trend until the mid 2000's. In the latter part of the decade the water vapour values starts to increase, however the most recent years again show a decrease in water vapour.~~

~~Solomon et al. (2010) found a positive trend in the water vapour data until about year 2000 and negative after that over Boulder at the mid-latitudes around 80~~decreased from 1995 until about 2004 before starting to increase around 2007. At 10 hPa~~. Hegglin et al. (2014) showed that the water vapour trends over Boulder should not be considered representative of the global stratosphere.~~ the increase stopped by 2014 but at 1 hPa it did not stop until the end of the time series. Since the air in the upper polar stratosphere is older than in the lower stratosphere (Stiller et al., 2012) the delay of

water vapour changes between lower and upper stratosphere suggest that these changes are driven by transport precesses.

In the FinROSE model results for the high northern latitudes the long term change of water vapour is positive in the stratosphere. The water vapour trends for mid-latitudes and tropics in FinROSE develop similarly as in higher latitudes (not shown). The anomalies seen in FinROSE also agree with the results by Dessler et al. (2013) for tropical water vapour between 2005 and 2013. ~~Also the approximately two year periodicity seen before year 2008 is similar as in the Dessler et al. (2013); Hegglin et al. (2013) and Randel et al. (2004) studies and is related to the tropopause temperature changes associated with the quasi-biennal oscillation (QBO). The QBO-signal has an influence on high latitude water vapour due to mixing processes~~ In order to attribute water vapour changes to physical processes we performed regression analysis following Dessler et al. (2014). We used three proxies: qbo index (QBO, equatorial winds at 50 hPa, Brewer Dobson circulation index (BD, residual vertical winds at 70 hPa averaged from 30° S to 30° N), and cold point temperature (CPT). Unlike Dessler et al. (2014) we found that the use of tropical temperatures at 500 hPa was not enough to explain the variability of the cold point temperature, and therefore used the cold point temperature as one of proxies. Although, there is some correlation between CPT and QBO (0.32) QBO also affect the transport of the water vapour not directly influenced by CPT; therefore the use of both proxies is justified. We apply multiple regression analysis with all three proxies to water vapour time series averaged north of 70° N and at 82 hPa and 56 hPa. ~~After 2008 the signal weakens at the high latitudes~~Cross-correlation analysis shows broad peaks at lags 6–12 months for the proxies. The maximum of the correlations of QBO and CPT with water vapour at 56 hPa is at about 10 months lag, and with 82 hPa is at 8–9 month lags, suggesting that propagation of the tropical anomalies in the lower stratosphere is faster than that in the middle stratosphere, likely due to more efficient mixing. We use 10 month lag for all proxies for regression at 56 hPa and 9 month lag for the regression at 82 hPa.

The individual correlation coefficients with our proxies are shown in the Table 1. The main contribution to the polar water vapour variability is CPT, followed by QBO. We found very weak contribution of BD proxy to the variability of the water vapour. One reason is that the effect of BD contribution is accumulated over time and this is not well represented by the monthly mean proxy. The multiple regression coefficients are 0.57 and 0.51 at 82 hPa and at 56 hPa correspondingly, showing that our models only explain 25–30 % of the variability. This is considerably less than that of Dessler et al. (2014) suggesting that different processes contribute to the polar water vapour variability in comparison to those in the tropics. Note that the regression somewhat explains the increase of the water vapour from 2005 to 2010, which is more clear at 82 hPa. However the peak of the water vapor during 2011–2013 is not explained by these proxies.

The ~~Sodankylä~~ Arctic water vapour concentration in ~~FinROSE-ctm~~ FinROSE increases by about 0.8 ppm at altitude 56 hPa from year 2004 until year 2012. This increase corresponds to ca 1 K

increase in the frostpoint temperature (Marti and Mauersberger, 1993). However, the concentration during recent years (2012 to 2014) has decreased more than 0.5 ppm. The FinROSE water vapour anomaly ~~(black line in the Fig. 5)~~ and the passive tracer anomaly ~~(red line)~~ have nearly the same changes as the water vapour, in line with the results presented in Fig. 1. The evolution of the FinROSE water vapour anomaly is similar to the ERA-Interim anomaly (green line), which is expected as the ~~FinROSE-ctm~~ FinROSE is driven by the ERA-Interim data. The chemical part (~~blue line)~~ purple line) which is mainly due to the contribution of methane oxidation, has only a small positive trend consistent with previous studies, because the ~~tropospheric~~ stratospheric methane concentration was nearly stable in the analysed time period. ~~The increase in the tropospheric methane concentration since 2007 is only about 0.05ppm . Furthermore, the effect of tropospheric methane concentrations on statospheric water vapour is seen with a delay.~~

5 Arctic dehydration frequency

In the polar vortex areas the concentration of water vapour can be changed also by dehydration. Water freezes into ice particles, sediments to lower altitudes and sublimates. Dehydration is frequently observed in the Antarctic polar vortex and there the magnitude of decrease of the water vapour by dehydration is several ppms. The water vapour mixing ~~ration~~ ratio can be reduced to 1.5 ppm in the cold stable Antarctic vortex (Vömel et al., 1995). In the Arctic vortex the dehydration is rare, because the temperatures are higher. However, ~~ICE~~ ice PSCs are formed also in the Arctic vortex and it is possible for dehydration to occur (Khaykin et al., 2013).

~~ICE~~ Ice PSC formation is controlled by temperature and water vapour concentration, which both exhibit considerable variability. FinROSE simulates significant ~~ICE~~ ice PSC conditions in the Arctic in ~~10 out of 24~~ 12 out of 25 winters (1990, 1993, 1995, 1996, 2000, 2005, 2008, 2010, 2011~~and~~ , 2012~~)~~, ~~which gives an average frequency of 0.4 per winter~~2013 and 2014). That means that nearly 50 % of winters offer conditions, which allow the formation of ice PSCs. However, they cover only a small fraction of the vortex. The largest extent of simulated ~~ICE~~ ice PSCs was seen in 1990, with an area of $3 \times 10^6\,\mathrm{km}^2$ at 56 hPa. In 1993, 2005, 2011~~and~~ , 2012 and 2014 an area of around $2.5 \times 10^6\,\mathrm{km}^2$ were reached. Figure 6 shows the area of the gridpoints where ~~ICE~~ ice PSC (black) ~~and NAT (green)~~ form in the FinROSE model and the minimum temperature of the area between 50° N and 90° N at 56 hPa level. From 2007 onwards the ice PSC areas from CALIPSO lidar observations are shown as comparison ~~, ICE in redand NAT in blue~~(red). Based on the timeseries in Fig. 6 it seems that there is an increase in ~~ICE~~ ice PSCs in the recent winters. Between ~~2008 and 2013 there are 4 ICE~~ 2007 and 2014 there are 6 ice PSC winters in ~~6 years~~FinROSE and 7 winters in CALIPSO, which leads to frequency ~~0.67~~0.75 (0.87 for CALIPSO), considerably higher than the mean frequency for the whole studied period. This is likely a ~~result~~ combined effect of cold conditions and the increase in the water vapour concentration. ~~Both the temperature and water vapour have varied,~~

~~and especially the variability in the temperature has been large~~Another period with frequent ice PSC occurrence was between 1990 and 1996 when ice PSCs occurred in 4 out of 7 winters. The temperature conditions were cold in the beginning of the 90's, but water vapour concentrations were lower than in the 2000's. The PSC areas in FinROSE agrees well with the ones calculated from CALIPSO data. However in some cases, e.g. beginning of winters, CALIPSO detects PSCs that are not simulated by FinROSE. This may indicate a warm bias in ERA-Interim in that period. Also in 2007 CALIPSO detects ~~ICE~~ ice PSCs, which are not seen in the model. This might be due to the resolution of the model (~~3 × 6~~3° × 6°, latitude × longitude), as the areas are quite small. ~~NATs are more common than ICE PSCs in the Northern high latitudes and they are simulated yearly. CALIPSO detects NATs at the same times as in the FinROSE simulations, but the areas are larger in the simulations.~~

Figure 7 left panel shows the relation of the area of simulated ~~(and observed) ICE~~ and observed ice PSCs and the area ~~of colder than 190~~with air colder than 188 K temperatures in ~~January at level~~ December–February at the level of 56 hPa. One point ~~(or cross) denotes one January~~ or X denotes one winter day between 2007 and ~~2013~~ 2014 in FinROSE simulation ~~(CALIPSO observation)~~or CALIPSO observation. The colour of the marks show the water vapour concentration averaged in the vortex. Figure 7 shows the dependence of ice PSC on water vapour. It can be seen that ~~the cold temperatures are not enough for the ICE PSC formation~~while temperature is the main factor controlling the ice PSC formation, the formation also noticeably depends on water vapour concentration. Higher water vapour concentrations produce larger areas of ~~ICE PSC and~~ ice PSC but in dry vortex no ~~ICE PSCs form although~~ ice PSCs form even when the temperature is low enough. The ~~cold temperature areas as well as the ICE PSC areas are larger in FinROSE than in CALIPSO. The difference is not so remarkable in case of ICE PSCs~~effect of both temperature and water vapour on ice PSC area is also seen in Table 2: for similar temperature conditions the ice PSC area increases when water vapour concentration increases. This holds for cases when areas with temperature below 188 K are small or large, and is seen in both FinROSE and CALIPSO. Consistent with expectations, the correlations between cold temperature area and ice PSC area are 0.89 for FinROSE and 0.64 for CALIPSO. The correlations between water vapour and ice PSC is 0.30 in FinROSE and 0.35 in CALIPSO, both statistically significant at 0.05 significance level. CALIPSO detects small ~~ICE~~ ice PSC areas with small cold temperature areas, but in case of FinROSE the ~~ICE~~ ice PSCs are not ~~allways~~ always created although the cold temperature area is large. The increase of water vapour in the vortex area have been ~~more than 0.5~~about 0.8 ppm after 2007. That would have increased the ~~size of ICE~~ ice PSC areas even if the temperatures have been the same, consistent with earlier estimations by (Kirk-Davidoff et al., 1999).

6 Case study: ~~winter~~ Winter 2009/2010

The winter 2009/2010 was unusually cold in the Arctic polar region. The temperature were below 190 K in a large area of the polar vortex. ~~Temperatures~~ In the lower stratosphere temperatures dropped below 195 K were simulated even south of 60° N. PSCs were formed and even persistent dehydration was observed over Northern polar latitudes for the first time (Khaykin et al., 2013). The vortex lasted until the beginning of April, and ~~near Sodankylä until 11 February. Colder than 195 K air occurred~~ it was located above Sodankylä until 11th of February. Cold conditions favouring PSC formations lasted until the end of January ~~2010. After 11 February~~ 2010 ~~the vortex moved towards the south and and a mixing with moister mid-latitude air has occurred~~but a major stratospheric warming around 24 January rise temperatures and precluded further PSC formation (e.g., Khaykin et al., 2013; Dörnbrack et al., 2012; Pitts et al., 2011).

The ~~FinROSE-ctm~~ FinROSE simulation was studied more thoroughly for the winter 2009/2010. The results were also compared to observations. Cold temperatures occurred between 20 km and 28 km in the ERA-Interim data and cold temperatures can be seen also in measured temperatures. Also a reduction of water vapour at around 56 hPa, seen both in the simulations and in observations, can be attributed to the formation of ~~ICE~~ ice PSCs. Indeed, also ~~ICE~~ ice PSC particles were simulated at the level 22–24 km by the model and also seen in the balloon sounding data from the LAPBIAT campaign (Khaykin et al., 2013).

Figure 8 shows the area of ~~ICE and NAT PSCs and the evolution of temperature above Sodankylä in the~~ ice PSCs from CALIPSO (top panel) and from FinROSE (middle panel) and the area of temperatures colder than 188 K (lower panel) in the Arctic winter 2009/~~2010 winter. ICE PSCs occur same time,~~ 2010. Ice PSCs occur at the coldest dates and the same time both in FinROSE ~~simulations~~ simulation and CALIPSO observations. ~~ICE~~ The ice PSC areas in ~~CALIPSO are larger than in FinROSE, but the clouds are seen at the same altitudes. Especially the ICE PSC episodes in~~ the beginning of January 2010 are ~~clearly weaker~~ smaller in FinROSE than in CALIPSO~~. The second row shows the area of NAT PSCs. FinROSE simulates larger areas than CALIPSO detects. Also the altitude differs; the maximum area of NAT PSCs in FinROSE is at 20 km altitude but at 22 km in the CALIPSO data~~, but after mid January the areas are larger in FinROSE than in CALIPSO. However, the clouds appear at the same altitudes in the model as in observations. The timing is also comparable. The ~~Sodankylä temperatures in ERA-Interim and CALIPSO are nearly the same, but can still cause some differences to the PSCs. The differences might be explained also by the model~~ differences might be attributed to the model coarse resolution and the simplicity of the PSC parameterization~~and the gridding of CALIPSO data~~. The area of cold temperatures in the lowest panel is larger than the modelled and observed ice PSC areas.

Figure 9 shows maps of temperature from ERA-Interim, ~~frostpoint temperature~~ water vapour mixing ration from FinROSE and ~~MLS and ICE~~ ice PSC from FinROSE and CALIPSO from ~~Northern Hemisphere vortex area between 17 and 23 January~~ northern hemisphere vortex area at the

sounding dates between 17th January and 23th January 2010 at the level 35 hPa (24 km). The level ~~56~~35 hPa ~~. The~~ was chosen because it was the coldest level with large ice PSCs. The minimum temperatures in the vortex (first row) are very low in this time period, even below 188 K. ~~In this figure the~~ The water vapour mixing ~~ratios from FinROSE and MLS are shown as frostpoint temperatures. The frostpoint temperature from FinROSE-ctm~~ ratio from FinROSE (second row) is the highest at the vortex boundary and the lowest in the middle of the vortex. The driest areas coincide both in space and time with the coldest temperatures. ~~The MLS frostpoint temperature (third row, 3 day average) also show the same dry areas as FinROSE.~~ Areas with very cold temperatures correlates with very low water vapour content areas because of ~~ICE~~ the ice PSC formation. The water vapour is condensed into ice particles, which are sedimented downwards resulting in dehydrated air masses. ~~The next two rows in Fig.~~

Figure 9 show ~~the area where ICE PSCs are simulated in FinROSE at 56~~that at 35 hPa ~~altitude and observed by CALIPSO also around 56 hPa . ICE PSCs can be seen in large areas in the vortex in the FinROSE simulation. ICE PSCs are seen in the areas in the CALIPSO observations, but the data coverage of the observations makes the shape less uniform~~ice PSCs were simulated by FinROSE in the same areas as they were observed by CALIPSO. To facilitate the comparison, CALIPSO observations have been gridded to the same grid than FinROSE, and the grid box is marked as having PSC if there were at least one PSC observation within the grid box area.

The bottom row in Fig. 9 shows modelled frostpoint temperature profiles above Sodankylä ~~from FinROSE-ctm~~ ä from FinROSE and temperature profiles from ECMWF ERA-Interim analysis, frostpoint temperature calculated from MLS satellite water vapour and frostpoint temperature from Sodankylä ~~water vapour~~ ä soundings. The ~~resolution of the FinROSE simulation used in this study is 6° × 3° and Sodankylä (lon~~ FinROSE output at lon 30° E, lat 69° N located next to Sodankylä (26.6° E, ~~lat~~ 67.4° N) is ~~located between four grid points. The panels in Fig. 9 represents averaged data from the four nearest grid points from Sodankylä.~~ shown. Overall FinROSE can simulate the frostpoint temperature quite well. The ECMWF ERA-Interim temperature reaches or almost reaches the frostpoint temperature during the analysed time period. Then the formation of ~~ICE~~ ice PSC is possible also in the ~~FinROSE-ctm. The cold time period lasts until 26 January. The polar vortex is split after the considered time period. The coldest dates in Sodankylä are 17 and 23 January, and very low frostpoint~~ FinROSE. The coldest date in Sodankylä is 17th of January. Very low frostpoint temperature values can be seen above 40 hPa altitudes ~~. The decrease of water vapour~~ also after 17th is likely a result of dehydration. This can be seen both in observations and in FinROSE. The water vapour concentration decreases about 1 to 1.5 ppm from the median values. A small increase of water vapour observed below 40 hPa on ~~23 January can be a sign of rehydration. However, it is not visible in the FinROSE results in the gridpoint closest to Sodankylä, but in some colder gridpoints it can be seen.~~ 23rd of January is interpreted as rehydration. It is not simulated by FinROSE at the grid point shown, but is simulated at other coldest grid points near Sodankylä (not shown). In summary,

FinROSE was able to reproduce well stratospheric water vapour and ICE PSC evolution during the record coldest period in winter 2010.

~~Winter 2010 was extremely cold and the temperature dropped below the frostpoint temperature. ICE PSCs was formed and observed on several days during the LAPBIAT campaign. The occurence of ICE PSCs were also succesfully simulated.~~

7 Conclusions

FinROSE has been shown to be capable of simulating the water vapour distribution and evolution in the Northern high latitude stratosphere. The representation of water vapour in FinROSE is improved compared to the ERA-Interim data, even though the ERA-Interim data is used as tropospheric boundary condition. The full chemistry in FinROSE can add the water vapour to the ECMWF ERA-Interim water vapour. The model gives results comparable to the MLS satellite measurements. However, some discrepancies compared to MLS remain.

The concentration of stratospheric water vapour in FinROSE is too high, especially in the summer time. Compared to the Sodankylä frost point hygrometer the model is too moist. However, the number of the comparisons is limited. In addition, some of the soundings have been made in the vicinity of the polar vortex, which further complicates comparison with the model data.

The main sources of the stratospheric water vapour are transport from the tropical troposphere and methane oxidation. A passive tracer was used in the FinROSE model for investigating the relative importance of the different sources of water vapour. The chemically produced fraction shows a maximum at altitudes between 6 hPa and 0.3 hPa. At these altitudes in the summertime the photochemical part is nearly as big as the transported part.

~~Long term changes~~ The considerable decadal variability can be seen in water vapour below 10 hPa; water vapour increases between ~~2006 and 2011~~2007 and 2012 by about 0.8 ppm in 5 years, which has been followed by a ~~decreasing trend. The increasing trend is about 1 ppm in 5 years .~~ decrease. In the upper stratosphere the ~~trend is less clear~~increase is smaller than in the lower stratosphere. In the MLS data the ~~trend~~ increase is smaller than seen in FinROSE. The ~~trends~~ increase can be attributed to water vapour transported trough the tropical tropopause ~~. The~~ while the contribution of the photochemically produced part of water vapour ~~shows less significant trends~~to the increase is neglible, due to comparably smaller changes in the ~~tropospheric~~stratosphericmethane concentration.

In the FinROSE simulation ICE PSCs occurred in Northern high latitudes ~~at~~ in 10 ~~winter of 24 simulated . NAT PSCs were simulated more often, at least a small area every year. CALIPSO instrumenthas~~ out of 25 simulated winters. Comparison with CALIPSO instrument, which measured PSCs since ~~2006.~~ 2006, shows that FinROSE simulates PSCs generally at the same time as observed by CALIPSO. Also the area of ~~ICE PSCs occurrence~~ ice PSCs occurrence is comparable to the

CALIPSO observations. ~~The NAT PSC area is larger in FinROSE than in CALIPSO. Both PSC types~~

ICE PSC have become more frequent in the recent years of the simulation. ~~ICE PSC occurrence depends on the temperature and the amount of water in the stratosphere. The area of colder than 190 K is much larger than the area of simulated ICE PSCs in FinROSE or the area of detected ICE with CALIPSO. Increased~~ While cold temperatures observed during these years favoured ice PSC formations, our results suggest that increased stratospheric water vapour concentration in high latitudes may have increased the ~~ICE~~ ice PSC occurrence after year 2006.

~~The~~ Finally, as a test for faithfulness of FinROSE simulations, we perform a case study of the extremely cold winter 2009/~~2010 was extremely cold in the Arctic stratosphere. At Sodankylä ICE PSCs were observed. The ICE PSCs caused~~ 2010. FinROSE is able to reproduce ice PSC extent and associated dehydration and rehydration at lower altitudes ~~. Balloon borne water vapour measurements were done at Sodankylä in winter–spring 2010. ICE PSCs were observed together with significant H_2O -reduction during the coldest period of January 2010. More than~~ in good agreement with observations reported by (Khaykin et al., 2013). FinROSE is also able to reproduce the observed magnitude of the dehydration associated with ice PSC formation, which is about 1 ppm~~reduction of water vapour was seen in the balloon borne sonde profiles as well as in the model simulations~~. These results add credibility to FinROSE's ability to reproduce stratospheric water vapour changes.

Acknowledgements. We want to thank the UARS reference atmosphere project and MLS/~~AURA~~ Aura teams for water vapour data and the Atmospheric Science Data Center for the CALIPSO data. The MLS data were obtained through the Aura MLS website (http://mirador.gsfc.nasa.gov/). CALIPSO data were obtained from the NASA Langley Research Center Atmospheric Science Data Center. The Sodankylä water vapour sounding providers are also thanked. The funding from the Academy of Finland through the UTLS project (140408) is gratefully acknowledged.

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Table 1. Correlation coefficients of regression.

	CPT	QBO	BD	Multiple
56 hPa	0.45	0.32	-0.21	0.51
82 hPa	0.52	0.40	-0.18	0.57

Table 2. Ice PSC areas in FinROSE (left) and CALIPSO (right). The number of hits are shown in parentheses.

	FinROSE			CALIPSO		
	Wet (>5.4)	5.2–5.4	Dry (<5.2)	Wet (>5.4)	5.2–5.4	Dry (<5.2)
Warm (0.5–1.5)	1.61 (10)	1.09 (10)	0.31 (4)	0.70 (4)	0.46 (9)	0.18 (2)
Cold (1.5–3.0)	2.49 (10)	2.48 (10)	1.28 (4)	0.96 (4)	1.20 (9)	0.24 (2)

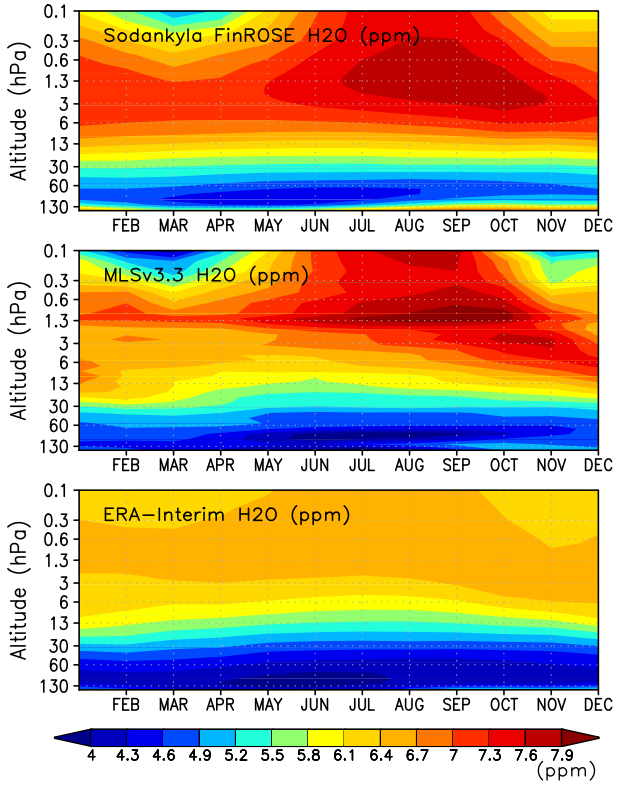

Figure 1. Climatology (~~2004–2013~~2004-2014) of the water vapour distribution from FinROSE, MLS v3.3 data and ECMWF ERA-Interim above ~~Sodankylä~~Sodankylä.

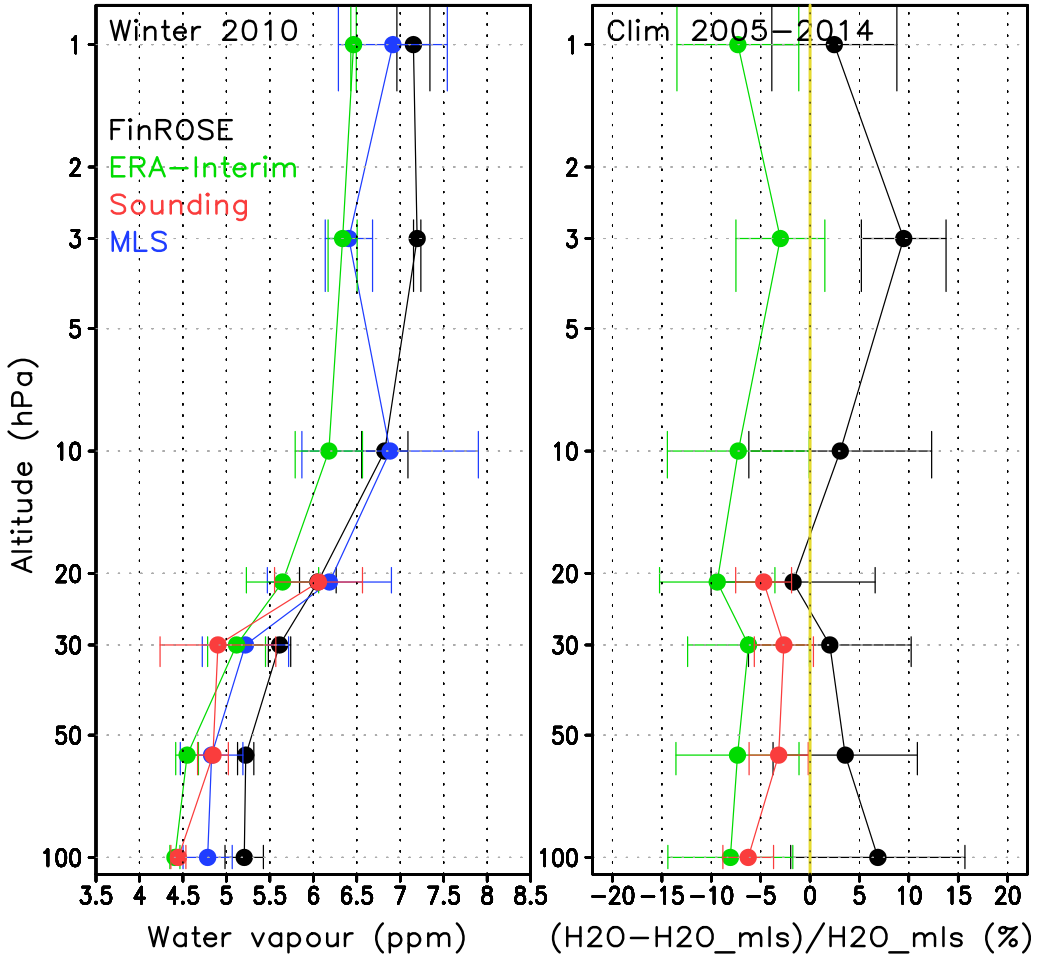

Figure 2. **(a)** 2010 mean January and February water vapour mixing ratio and standard deviation ~~at different pressure levels~~ above ~~Sodankylä~~Sodankylä as function of pressure. **(b)** Difference of the modelled or observed winter water vapour mixing ratio and MLS calculated over years ~~2004~~ 2005 to ~~2013 at different pressure levels~~ 2014 above ~~Sodankylä~~Sodankylä as function of pressure. FinROSE (black), MLS (blue), ECMWF ERA-Interim (green) and soundings (red).

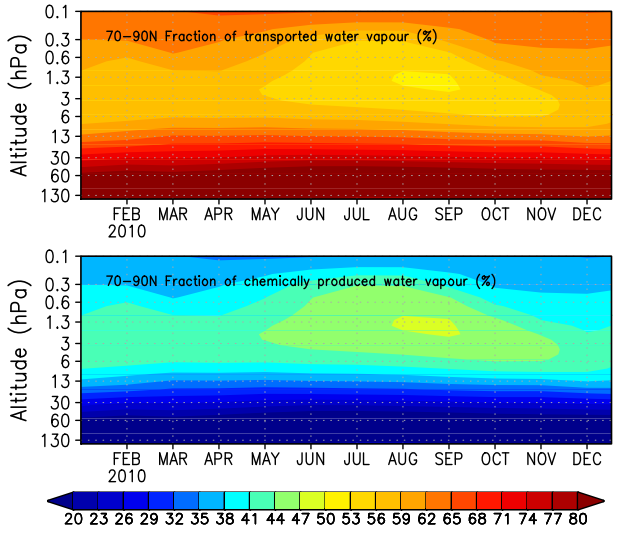

Figure 3. Monthly mean of ~~the~~ **(a)** fraction of transported water vapour and **(b)** fraction of chemically produced water vapour (%) for 2010 calculated over 70–90° N.

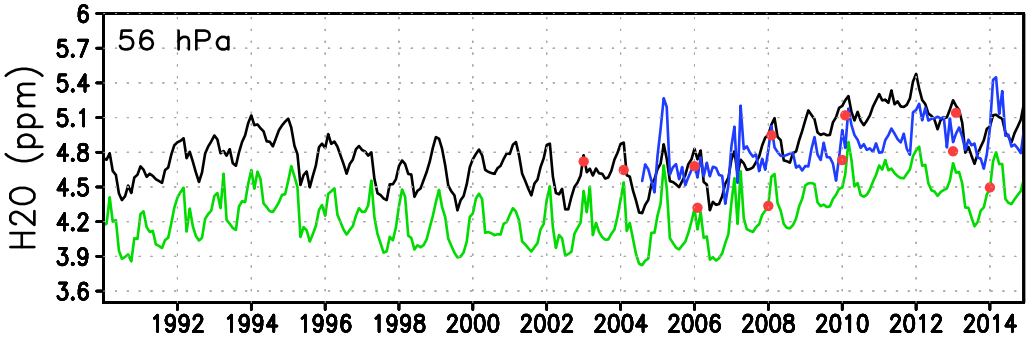

Figure 4. ~~**(a)** Sodankylä~~ Sodankylä monthly mean water vapour mixing ratio from FinROSE (black), MLS (~~orange~~blue), ECMWF ERA-Interim (green) and soundings (~~blue~~ red dots) at 56 hPa ~~. **(b)** Anomalies of water vapour (black), tracer describing transported water vapour (red), tracer describing water produced by methane oxidation (blue) from FinROSE and water vapour anomaly from ECMWF ERA-Interim (green) as ppm in 1994–2013 at latitudes~~ between ~~70–90° N at level 1 hPa~~1990–2014. ~~**(c–e)** Same as panel **(b)** , but levels 10, 56 and 100 hPa.~~

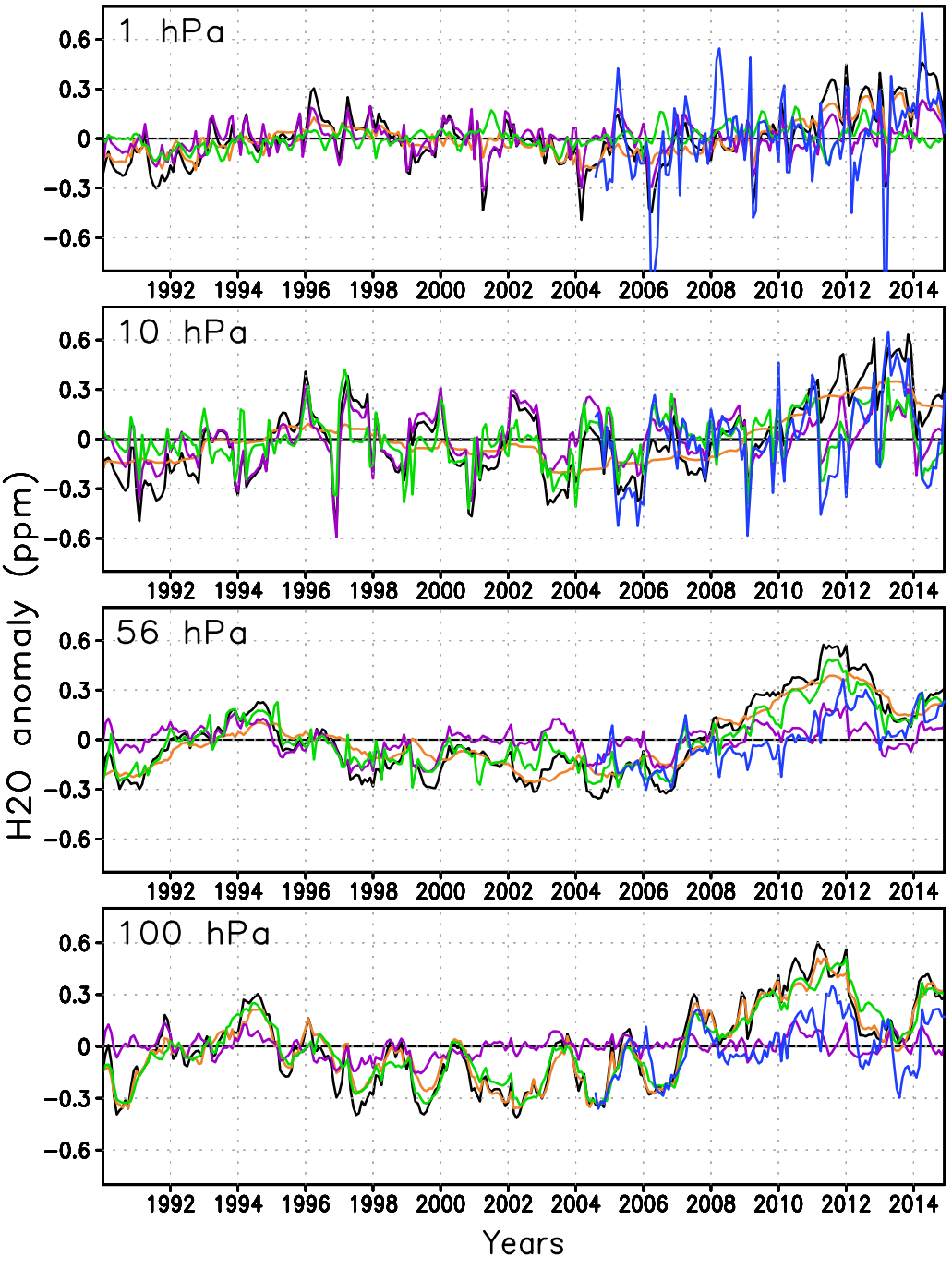

Figure 5. **(a)** Anomalies of water vapour (black), tracer describing transported water vapour (orange), tracer describing water produced by methane oxidation (purple) from FinROSE and water vapour anomaly from ECMWF ERA-Interim (green) as ppm in 1990–2014 and, water vapour anomaly from MLS (blue) in 2004–2014. Anomalies are calculated at latitudes between 70–90° N at the level of 1 hPa. **(b-d)** Same as panel **(a)**, but levels 10, 56 and 10 hPa .

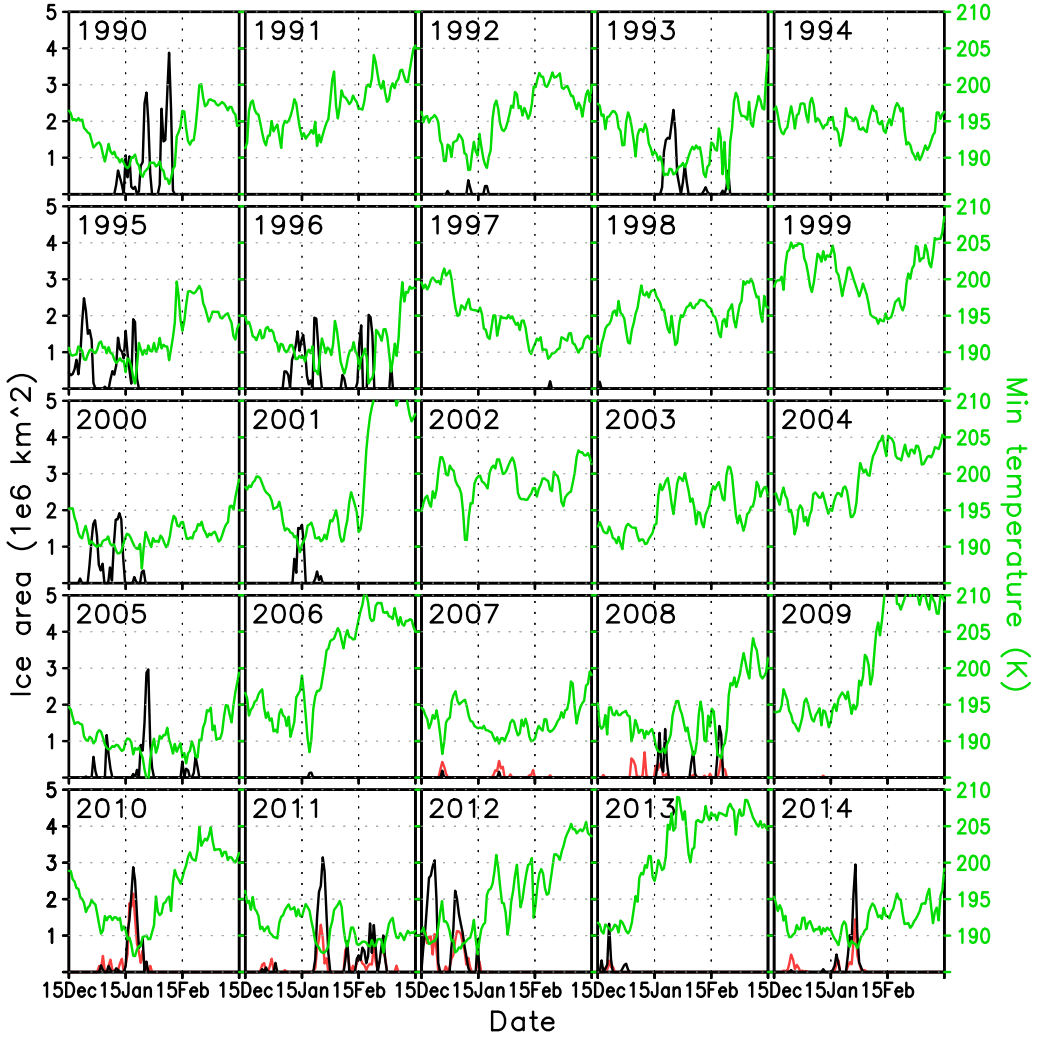

Figure 6. The area ~~of the air mass~~ where ~~ICE and NAT~~ ice PSCs formed in the FinROSE simulation (black) and was observed by CALIPSO (red) and the minimum temperature between 50–90° N from ERA-Interim (green, right *y* axis) for winters between 1990 and ~~2013~~ 2014 at 56 hPa. ~~FinROSE ICE area is in black and CALIPSO ICE area is red (left *y* axis). FinROSE NAT area is in green and CALIPSO NAT area in blue (right *y* axis).~~

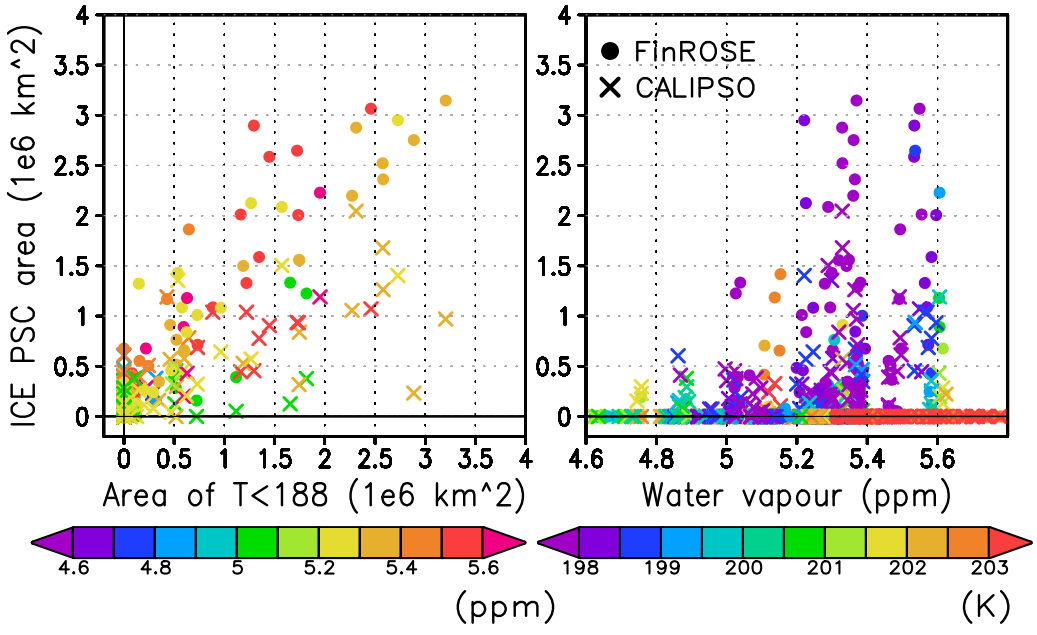

Figure 7. **(a)** ~~Relation~~ Scatter plot of ~~January ICE~~ December–February ice PSC area ~~and~~ versus the area of colder than ~~190~~188 K in the ~~Northern Hemisphere~~ northern hemisphere from FinROSE ~~(points)~~ and CALIPSO ~~(crosses)~~ at 56 hPa ~~level~~. The colour denotes the vortex ~~average~~ mean water vapour content (ppm). **(b)** Scatter plot of the December–February ice PSC area versus the vortex mean water vapour content (ppm) from FinROSE and CALIPSO at 56 hPa. The colour denotes the vortex average temperature (K). FinROSE is shown with dots and CALIPSO is shown with crosses.

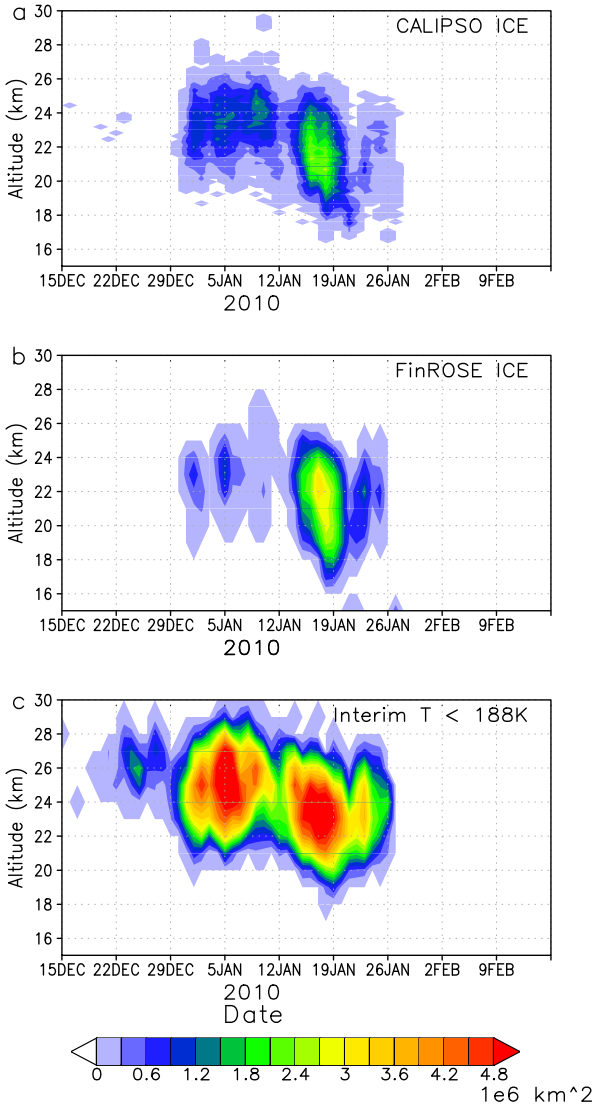

Figure 8. **(a)** ~~ICE~~ Ice PSC area from ~~FinROSE and~~ CALIPSO, **(b)** ~~NAT~~ Ice PSC area from FinROSE and ~~CALIPSO and~~ **(c)** ~~temperature~~ area of colder than 188 K from ECMWF ERA-Interim ~~and CALIPSO near Sodankylä~~ in winter 2009/2010.

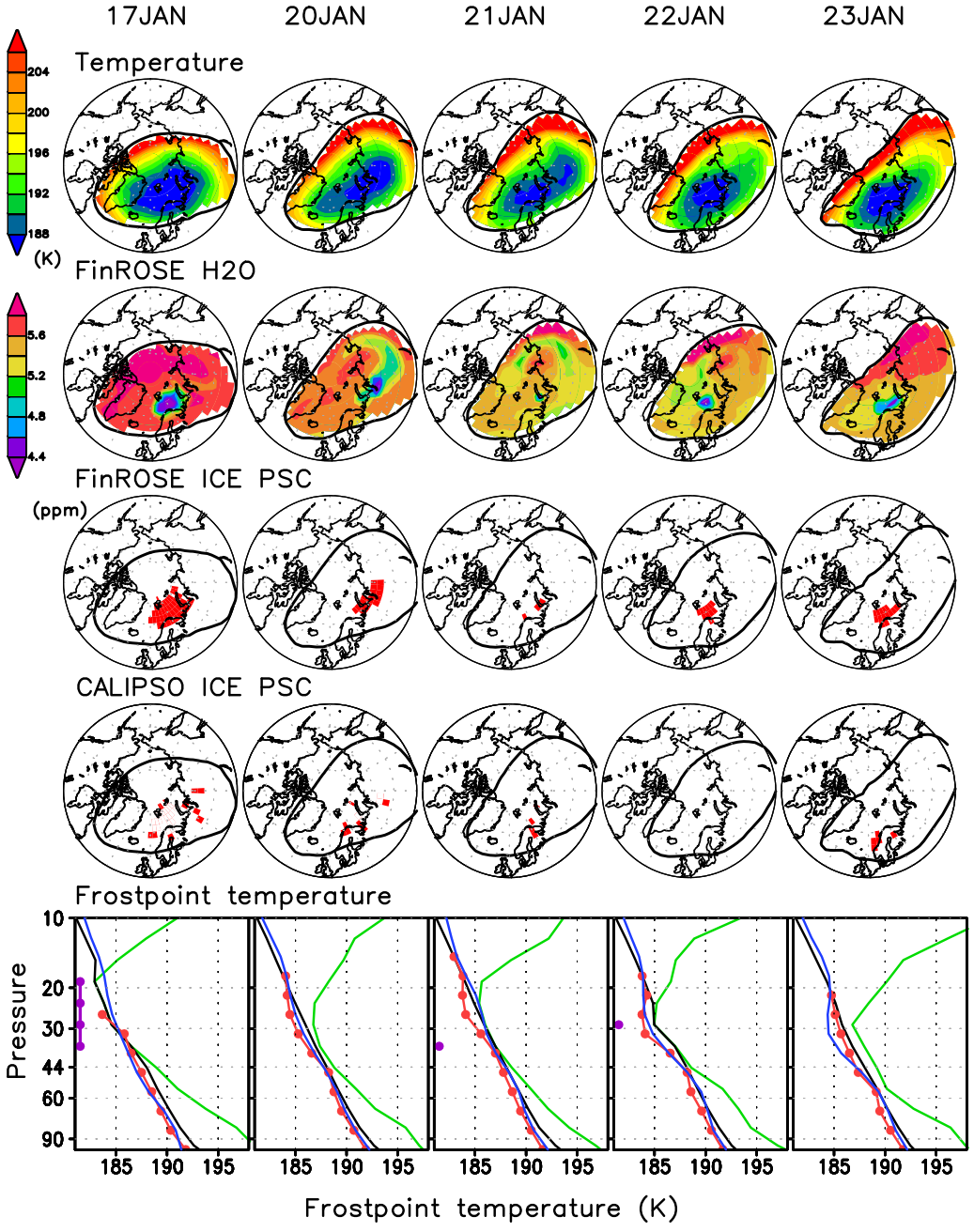

Figure 9. ~~Temperature, frost point (K)~~Upper four rows: temperature, water vapour (ppm)and ~~ICE~~ ice PSC occurrencefrom FinROSE ~~, MLS frost point temperature (K)~~and ~~CALIPSO ICE~~ice PSC occurrence from CALIPSO during the extreme cold period of winter ~~2010 (between 17 and 23 January).~~2010.The black contour ~~is~~ marks the border of the vortex defined as modified PV $>$ 36. All ~~the~~ maps are ~~from 56~~at the 35 hPa ~~altitude~~pressure level. Lowest row: ERA-Interim temperature (green), ~~frost point~~ frostpoint temperature from ~~Sodankylä water vapour~~ Sodankylä soundings (~~blue~~ red dots), from MLS (~~red~~blue) and from ~~FinROSE ctm~~ FinROSE (black). Purple dots shows the altitudes where FinROSE simulated ice PSC.