

## Reply to Referee 1 Comments

Manuscript-No: acp-2017-503

**Denitrification, dehydration and ozone loss during the Arctic winter 2015/2016**

We thank reviewer 1 for the constructive, helpful criticism and the suggestion for revision. We followed the suggestions of reviewer 1 and revised the manuscript accordingly.

*General statement: This is a fine paper on an important topic that merits publication after revision. I do have several comments for the authors, delineated below. Important ones are marked with \*.*

*\*1) The question of how denitrification and dehydration as such, versus a longer duration of cold temperatures into later parts of the spring season, have not been examined quantitatively here. The authors should therefore avoid trying to make statements about how important denitrification and dehydration were (or would be) for the ozone loss. I suggest that the authors consider this point carefully in revision. I point out one place to make a change in text but I think there could well be others.*

We hope that with the changes we made in the frame of the revision all misleading sentences have been corrected.

*2) page 2, line 15. Please change ice to water ice here since some literature speaks of nitric acid ices. With this change, I don't think you need to say water ice later in the text; doing it once is sufficient.*

We have changed “ice” to “water ice” as suggested.

*\*3) page 2, line 27. This statement makes a lot of assumptions that I don't think are merited. First, it ignores the literature on “denoxification”, much of which suggests that denoxification later in the spring, when there is more sunlight, can be as important or more so in prolonging ozone loss provided temperatures are cold enough. Second (and related), I would argue that prolonging the ozone loss depends more on vortex stability and dynamics than it does on the degree of denitrification. Please add a discussion of these issues here, with appropriate references.*

The importance of denitrification for ozone loss was shown by e.g. Salawitch et al. 1993 and Rex et al. (1997). We added the missing references. For an additional discussion of denoxification and the importance of vortex stability we added the following paragraph in the introduction: *Another factor contributing to the severity of ozone destruction is the reduction of nitrogen ( $\text{NO}_x = \text{NO} + \text{NO}_2$ ) via the conversion of  $\text{NO}_x$  into  $\text{HNO}_3$  on the surfaces of PSCs, the so-called denoxification. Denoxification becomes important if*

temperatures are continuously low during the course of the winter as is the case in the Antarctic (e.g. Waibel et al. 1999). It has been shown that polar vortex stability, chlorine activation and ozone loss tend to be greater with lower vortex temperatures (e.g. von Hobe et al., 2013). Therefore, it is not surprising that the most severe ozone loss ever observed in the Arctic occurred in spring 2011, at the end of the most persistently cold Arctic winter in the stratosphere on record (Manney et al., 2011; Sinnhuber et al., 2011; Hommel et al., 2014)

4) page 4, line 28-29. *I don't think these accuracy claims are true for MLS below 100 mb. Please check.*

We have checked this. In Livesey et al. (2017) useful range of Aura-MLS O<sub>3</sub> for scientific studies is given from 261-0.02 hPa. As stated in Livesey et al. (2017) there had been a high MLS v2.2 bias at 215 hPa observed in some comparisons versus certain ozonesonde and satellite datasets. These high biases, however, were reduced in versions v3.3x and v3.4x, with additional smaller reductions in the ozone values in v4.2x, the version that has been used in the present study. In addition, substantial oscillations that were present in the ozone profiles in previous versions have been ameliorated in v4.2x.

5) page 5, line 2. *Missing a word. Lowest retrieval level?*

Thanks for pointing this out. It indeed should read “lowest retrieval levels”. This has been corrected.

6) page 5, line 30. *Reader needs a pointer ahead to indicate that you will define what you mean by unprecedented. Add leading to unprecedented formation of ice PSCs (defined quantitatively below). . .*

The sentence reads now: *Temperatures dropped during the first cold period (December to end of January) below the ice formation threshold temperatures (Manney et al., 2016) leading to unprecedented formation of ice PSCs as will be discussed in more detail below (see Fig. 2).*

7) page 7, line 10. *2CH<sub>4</sub>+H<sub>2</sub>O isn't quite total hydrogen. I don't think it matters much for your purposes, but please have a look at LeTexier et al. (QJRMS, 1988) on this.*

This is correct, total hydrogen is properly defined as 2CH<sub>4</sub>+H<sub>2</sub>O+H<sub>2</sub>, but in the lower and middle stratosphere H<sub>2</sub> is constant and thus total hydrogen can in the lower/middle stratosphere be derived from 2CH<sub>4</sub>+H<sub>2</sub>O. We changed the text as follows to be more precise: *Dehydration from the EMAC simulation is derived by using total “stratospheric” hydrogen (2CH<sub>4</sub>+H<sub>2</sub>O) as substitute for a passive H<sub>2</sub>O tracer (e.g., Rinsland et al., 1996; Schiller et al., 1996). Molecular hydrogen (H<sub>2</sub>) is nearly constant in the lower and middle stratosphere and can therefore be neglected in the calculation of total hy-*

drogen. The quantity  $2\text{CH}_4 + \text{H}_2\text{O}$  is generally constant in the stratosphere. However, slight deviations from this quasi-conserved quantity can be found at high latitudes during winter where transport of mesospheric air rich in molecular hydrogen and poor in water vapour and methane is brought into the upper stratosphere (e.g., Le Texier 1988, Engel et al. 1996).

\*8) page 7, line 18, 19. Need to be more careful here. You could say something like *The Arctic winter 2015/2016 had the greatest potential yet seen for record Arctic ozone loss if the vortex had remained stable (and temperatures had therefore remained cold) through late March.*

We refer here to the results by Manney and Lawrence (2016) and changed the paragraph as follows to make this more clear: *The Arctic winter 2015/2016 appeared to have the greatest potential yet seen for record Arctic ozone loss (Manney and Lawrence, 2016). Temperatures in the Arctic lower stratosphere were at record lows from December 2015 to early February 2016 (Manney and Lawrence, 2016; Matthias et al., 2016). As was shown by Manney et al. (2016) ozone destruction began earlier and proceeded more rapidly than in 2010/2011, the winter that so far has been the one with the strongest observed ozone loss in the Arctic (Manney et al., 2011). That lower-stratospheric ozone loss did not reach the extent of that in spring 2011 was primarily due to a major final stratospheric warming in early March 2016 that led to a vortex split and a full breakdown of the vortex by early April (Manney et al., 2016)*

\*9) page 9, line 30. Interesting can you say something more about which other ClOx species are likely to be holding too much active chlorine?  $\text{Cl}_2\text{O}_2$ ?  $\text{ClONO}_2$ ? Also, I don't think you can rule out that the activation is at the right time but just too weak? What is your justification for ruling that out? Please clarify this here, as well as in other places where it is mentioned.

It is correct that a possible explanation could also be that chlorine activation is just too weak. We unfortunately cannot rule out for sure what the cause of this discrepancy is. We know from other comparisons that there are also differences between the simulated and measured HCl and  $\text{ClONO}_2$ . Further, comparisons between different photolysis schemes performed by our colleagues at KIT (M. Sinnhuber and S. Versick) have revealed that the EMAC photolysis rates are too low at high solar zenith angles ( $>90^\circ$ ). The sentences have been changed as follows: *However, the enhancement of  $\text{ClO}_x$  ( $\text{ClO}_x = \text{Cl} + \text{HOCl} + 2 \cdot \text{Cl}_2 + 2 \cdot \text{Cl}_2\text{O}_2$ ) in the EMAC simulation is found at the same time as in the Aura/MLS ClO observation, thus indicating that the later increase in ClO is not necessarily caused by the activation of chlorine being too late in the model simulation but could also be caused by the partitioning between the active chlorine species. In EMAC the photolysis rates are calculated with the submodel JVAL (Section 2.1). JVAL is part of the standard configuration of EMAC that was also used in the EMAC*

simulations contributing to the Chemistry Climate Initiative (CCMI, Jöckel et al., 2016) (note a similar configuration is used here apart from the resolution). An intercomparison of several photolysis scheme has shown that JVAL provides lower photolysis rates at very high solar zenith angles ( $>90^\circ$ ) for e.g.  $\text{Cl}_2\text{O}_2$  than other schemes. Thus, the partitioning of chlorine containing species may be shifted for high solar zenith angles and thus could be the cause for the delay in the activation of ClO in the model simulation. However, to entirely rule out the cause for this difference further studies are necessary which however are beyond the scope of this study. The sentence in the conclusion has been changed as follows: *Since the enhancement in modelled  $\text{ClO}_x$  is found roughly at the same time as the increase in ClO observed by MLS, the disparity in the modelled and measured ClO may arise from chlorine activation being delayed in the model due to inaccuracies in the partitioning between chlorine species at high solar zenith angles.*



## Reply to Referee 2 Comments

Manuscript-No: acp-2017-503

### Denitrification, dehydration and ozone loss during the Arctic winter 2015/2016

We thank reviewer 2 for the constructive, helpful criticism and the suggestion for revision. We followed the suggestions of reviewer 2 and revised the manuscript accordingly.

*Khosrawi et al. present a detailed analysis of polar processes occurring at high northern latitudes during the Arctic winter 2015/16. In particular, they compare simulations carried out with a nudged version of the EMAC CCM with a range of satellite and aircraft observations. The analysis presented in the paper is of high standard and explores an important and relevant topic within the scope of ACP and as such merits publication following revision. I have several comments the authors should address before publication:*

#### *General Comments:*

*P5L25 The authors present their analysis averaged over a fixed latitude range (70-90N) rather than using a vortex following coordinate (e.g. by defining the edge of the vortex following Nash et al., 1996). Figure 12 in the manuscript shows the large zonal variation in temperature and chemical fields, and highlights that the vortex is neither centred on the pole nor circular. I wonder what effect using a fairly large area average has on the results compared to averaging only within the vortex. While I do not feel it necessary to redo the analysis in any way, I would like to see a discussion on how using a fixed latitudinal average may affect the results of the paper compared to only considering airmasses within the vortex.*

In our analyses the usage of equivalent latitude is not mandatory since the separation between dynamics and chemistry is done by using the difference between the active (chemistry+dynamics) and the passive (dynamics only) tracer. However, in the frame of our analyses we have calculated ozone loss within an equivalent latitude band as well as within a geographic latitude band in order to quantify the differences in estimated ozone loss between the two approaches. Figure 1 and 2 in this reply show ozone loss in mixing ratio and Dobson Units for both latitude and equivalent latitude. In terms of mixing ratios the result is almost the same (2.1 ppmv compared to 2.03 ppmv) while in Dobson Units the ozone loss on equivalent latitudes is approximately 10% lower (117 DU compared to 103 DU). Figure 3 shows that there are slight differences between the O<sub>3</sub> column time series between latitude and equivalent latitude, but that our result remain the same, namely that in contrast to the other recent Arctic winters very low O<sub>3</sub> values are found in 2010/2011. We added the following text in section 3.4: *Note that,*

rather than employing a vortex following coordinate as e.g. equivalent latitudes, we have chosen to perform our analyses on a fixed geographic latitude band. Such an approach is justified here because the use of a passive tracer allows dynamical and chemical processes to be separated, thus facilitating the quantification of chemical ozone loss. On equivalent latitudes the same amount of ozone loss in terms of mixing ratio is derived while in terms of column loss ozone loss is 10% less (103 DU). In the conclusion the following text has been added: Note that we did not use equivalent latitudes here since separation between chemical and dynamical processes is achieved via the passive  $O_3$  tracer. On equivalent latitudes the same amount of ozone loss in terms of mixing ratio is derived while in terms of column loss ozone loss is 10% less (103 DU)

*P3L22* While the authors have reference all the appropriate literature on the model configuration and description, and a detailed description of the EMAC model is not required, I would like to see further information on those parts of the model key to this paper. For example, section 2 should, in my mind, include a description of which PSC and aerosol types are included in the model, how sedimentation velocities are calculated, which heterogeneous reactions occur on aerosol surfaces, do uptake coefficients include temperature dependencies, etc. I feel this would significantly aid those not familiar with the EMAC CCM configuration.

We agree that it would be worthwhile to provide more information on the parts of the model that are key to this paper. We added the following text briefly describing the PSC scheme and referring to Kirner et al. for more details: The submodel MSBM simulates the number densities, mean radii and surface areas of sulphuric acid aerosols and liquid and solid polar stratospheric cloud particles. The formation of STS particles is calculated according to Carslaw et al. (1995) through the uptake of  $HNO_3$  and  $H_2O$  on the liquid binary sulphuric acid/water particles. Ice particles are assumed to form homogeneously at temperatures below  $T_{ice}$ . For the simulation of NAT particles the “kinetic growth NAT parameterisation” is used. The “kinetic” parameterisation is based on the growth and sedimentation algorithm given by Carslaw et al. (2002) and van den Broek et al. (2004). The vapour pressure over ice is calculated according to Marti and Mauersberger (1993) and the vapour pressure over NAT according to Hanson and Mauersberger (1988). NAT formation takes place as soon as a supercooling of 3 K below  $T_{NAT}$  is reached. The sedimentation velocity of ice particles is calculated according to Waibel et al. (1997) and for NAT particles according to Carslaw et al. (2002). Eleven heterogeneous reactions that occur on the surfaces of liquid and solid PSC particles are considered. A comprehensive description of the submodel MSBM can be found in Kirner et al. (2011).

*Specific Comments:*

*P1L3 There is no need to capitalize polar stratospheric clouds here, and it should appear instead as it does in the Introduction (P2L10). However, in the Introduction it should read PCSs within the brackets.*  
This has been corrected.

*P1L18 This is at odds with P7L32, where the authors state maximum ozone loss is 120 DU. While 2 ppmv is the maximum mixing ratio difference, 100 DU is more representative of the average loss over mid March, and does not represent the maximum column loss. This also applies to the conclusions (P11L19).*

Thanks a lot for pointing this out. It should of course be the same amount of ozone loss in Dobson Units in all places of the paper. The exact amount is 117 DU. This has been corrected throughout the paper.

*I feel as well that it would be good to combine figures 7 and 8 so that total column differences appear below the  $\Delta O_3$  plot in a single panel and the reader can compare the column loss with the altitudes at which this is occurring.*

We would prefer to not combine figures 7 and 8 since these figures show ozone loss in different units, namely DU and ppmv and combining these may be confusing for the reader. However, to make a comparison of these figures easier we adjusted the time axes of figure 8, so that both figures have the same time scale.

*P3L4 I feel that having defined  $T_{\text{NAT}}$  and PSC, these should be used consistently throughout the manuscript in place of NAT existence temperature and polar stratospheric clouds.*

We agree and now the abbreviations  $T_{\text{NAT}}$  and PSCs are used consistently throughout the manuscript.

*P7L12I feel  $\Delta H_2O$  should be defined in the text as  $\Delta NO_y$  and  $\Delta O_3$  are. In fact, I feel each should be specifically defined in the text and figure captions (i.e. state  $\Delta O_3 = O_3 - O_3^*$ ).*

We followed the suggestion and each of the deltas are specifically defined in the text and figure captions.

*P9L3 Is the Khosrawi et al. (2017) paper in prep, which it is in the reference list, or now published? If so this should be stated in the text. Further, if the paper is not yet available I do not feel that the reference should be included in this manuscript and reference to it removed (i.e. removed the sentence on P9L2-4. This also applies to the papers referenced on P10L27-28. Certainly they should say they are in prep if they are not yet published, and further if the findings of those studies are not key to this paper I do not feel they should be included.*

We agree and removed the sentences referring to Sinnhuber et al. (2017), Braun et al. (2017) and Johansson et al. (2017) since these studies are not key to this paper and it is not yet clear when these papers will be submitted and published. We would like to keep the Khosrawi et al. (2017) reference since this paper is ready for submission, but kept on hold due to the new MIPAS PSC product which is not published yet. We anticipate to submit this paper in autumn. Therefore, we changed the status in the reference list from “in preparation” to “to be submitted”. Contrary to other journals as e.g. JGR, in the Copernicus journals the papers not published yet are listed with all other references in the reference list.

*P9L14 The simulations presented in the study are described as nudged in section 2. Therefore, surely any difference in temperature between the model and observations is a result of the nudged dataset and not the model. I feel saying temperatures as simulated with EMAC tend to be slightly warmer than measured outside the polar vortex is misleading, as the temperature field is not being simulated freely. Presumably, in a free-running model the temperature biases would be significantly different.*

It is correct that the simulated temperatures in EMAC mainly reflect the temperature field of the meteorological analyses used for nudging the simulation. However, the EMAC temperatures and the temperatures from the ECMWF operational analyses, used in our analyses for nudging, are not 100% identical although they are very similar. The EMAC temperatures are not replaced by ECMWF operational temperatures, but the internally calculated EMAC temperatures are pushed toward the ECMWF operational analyses. Therefore, small differences between EMAC and ECMWF remain. We changed the sentence as follows: *Temperatures in EMAC (nudged towards ECMWF operational analyses) tend to be slightly warmer than measured outside the polar vortex.*

*P9L28 Without providing further information this a difficult conclusion to follow. Can the authors be sure that chlorine activation is not just too weak? The assertion in the manuscript reads as though the chlorine activation is correct, but petitioning between other active chlorine species is the cause of the low ClO values, indicating too high Cl, Cl<sub>2</sub>O<sub>2</sub> etc. Can this be demonstrated by showing that ClONO<sub>2</sub> and HCl are well simulated? Looking at these species should highlight the ability of the model to capture chlorine activation. Here also ClO<sub>x</sub> should be defined.*

It is correct that a possible explanation could also be that chlorine activation is just too weak. We know from other comparisons that there are also differences between the simulated and measured HCl and ClONO<sub>2</sub>. Further, comparisons between different photolysis schemes performed by our colleagues at KIT (M. Sinnhuber and S. Versick) have revealed that the EMAC photolysis rates are too low at high solar zenith angles ( $>90^\circ$ ). ClO<sub>x</sub> is now

defined in the text and the discussion on the differences between EMAC and MLS in ClO has been changed as follows: *However, the enhancement of  $\text{ClO}_x$  ( $\text{ClO}_x = \text{Cl} + \text{HOCl} + 2 \cdot \text{Cl}_2 + 2 \cdot \text{Cl}_2\text{O}_2$ ) in the EMAC simulation is found at the same time as in the Aura/MLS ClO observation, thus indicating that the later increase in ClO is not necessarily caused by the activation of chlorine being too late in the model simulation but could also be caused by the partitioning between the active chlorine species. In EMAC the photolysis rates are calculated with the submodel JVAL (Section 2.1). JVAL is part of the standard configuration of EMAC that was also used in the EMAC simulations contributing to the Chemistry-Climate Model Initiative (CCMI, Jöckel et al., 2016) (note a similar configuration is used here apart from the resolution). An intercomparison of several photolysis scheme has shown that JVAL provides lower photolysis rates at very high solar zenith angles ( $>90^\circ$ ) for e.g.  $\text{Cl}_2\text{O}_2$  than other schemes. Thus, the partitioning of chlorine containing species may be shifted for high solar zenith angles and thus could be the cause for the delay in the activation of ClO in the model simulation. However, to entirely rule out the cause for this difference further studies are necessary which however are beyond the scope of this study.*

*P11L4 The model simulations are nudged, and so is it still true that the EMAC model has weak downwards transport in this configuration? I would have thought that nudging the model ruled out dynamical factors as likely causes of any biases in chemical fields when compared with observations. Vertical winds are not nudged in EMAC, but divergence and vorticity are. In EMAC, the vertical wind is calculated with the help of these two parameters. Nevertheless, despite the nudging, the vertical transport is underestimated. The results are improved when a higher resolution is used, but the problem that the vertical transport is underestimated remains.*

*P11L9 A further complication here is surely that if the fine-scale features are not present in the ECMWF dataset used for nudging then the model could never accurately capture these features. Perhaps a discussion on this and to what extent will this limit the ability of your future T255 model to reproduce this structure is warranted.*

The following text has been added to the last paragraph of section 4.2 to discuss this: *However, it should be kept in mind that a good agreement between model simulations and observations can only be obtained if the model simulations are nudged towards meteorological analyses. It can be expected that comparison with free running model simulations would show larger differences. Further, the results are also limited by the accuracy of the meteorological analyses, e.g. resolving small-scale temperature fluctuations and mountain waves will still be problematic even when a T255 resolution is used.*

*P12L1-3 This is true only for nudged configurations where the dynamics is accurately captured, and would not be true of free-running models. I feel this is an important point which should be made to caveat the conclusion. To be more clear on this point we mention now at several places in the conclusions that a nudged EMAC simulation was used.*

*Technical Corrections:*

*P11L29  $\text{ClO}_x$  should have a subscript x. Similarly subscripts should be used for  $\text{NO}_y$  in Figure 4.*

Thanks for pointing this out. This has been corrected.

*Figure 1 I feel contours should be used consistently alongside the shading in the figures to aid with clarity, as is done in the top panel in Figure 1. This could be applied to all the pressure vs time plots.*

We have tried this, but found that the addition of extra contours make the Delta and PSC plots too cluttered and thus harder to interpret.

*Figure 13 It looks like there are zeros used for multiple contours in the top panels ( $\text{ClO}$ ) in Figure 13, indicating the contour label does not have enough decimal places. This should be corrected.*

Thanks for pointing this out. The figure has been corrected.

*In a number of locations the grammar and sentence structure could be improved - I would encourage the authors to undertake another proof-read of the manuscript. The sentence on P9L30-32 should certainly be edited for clarity.*

We have performed another proof-read of the manuscript and hope that everything is correct now.

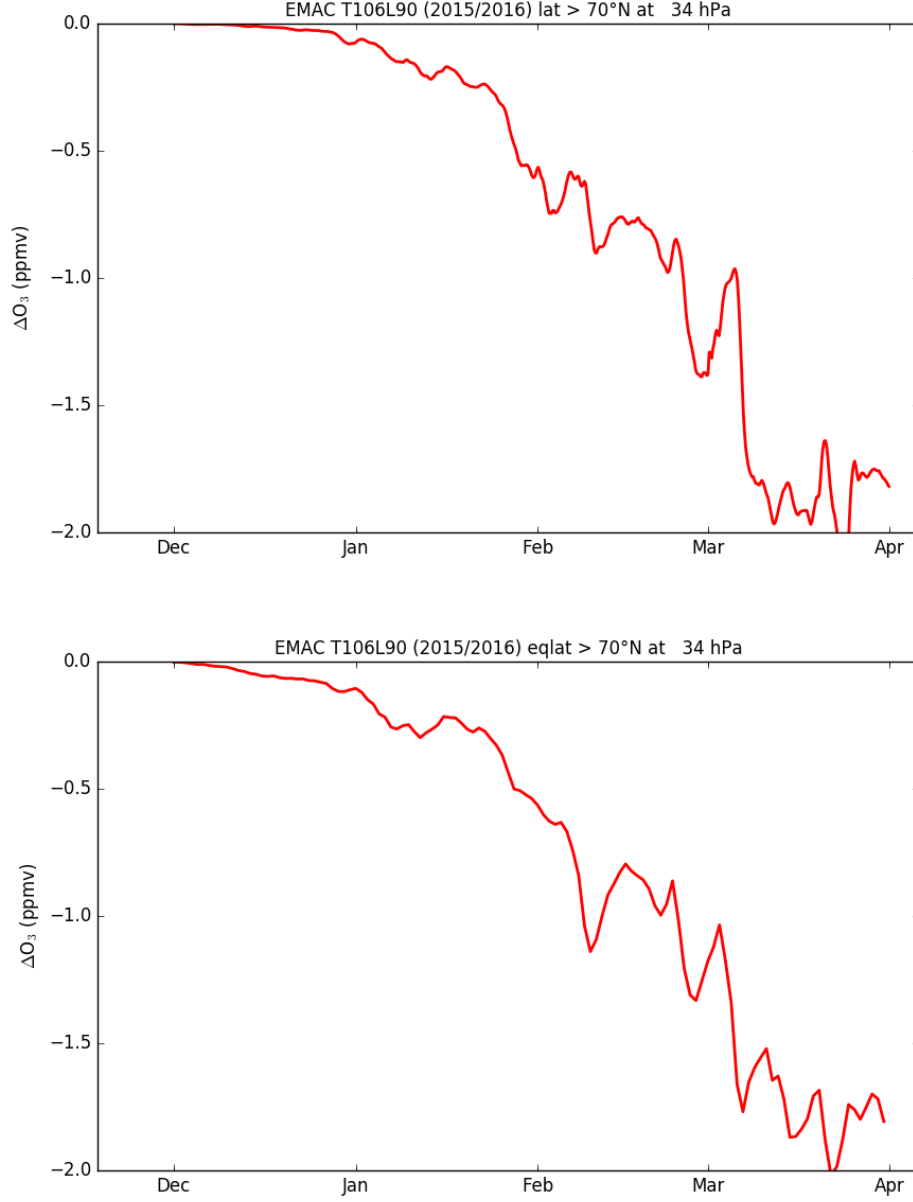


Figure 1: Ozone loss from EMAC T106L90 simulation at 34 hPa for the Arctic winter 2015/2016. Ozone loss has been derived from the difference between the active tracer  $O_3$  and the passive tracer  $O_3^*$  ( $\Delta O_3 = O_3 - O_3^*$ ). Top: average over 70-90°N latitude, bottom: average over 70-90°N equivalent latitude.

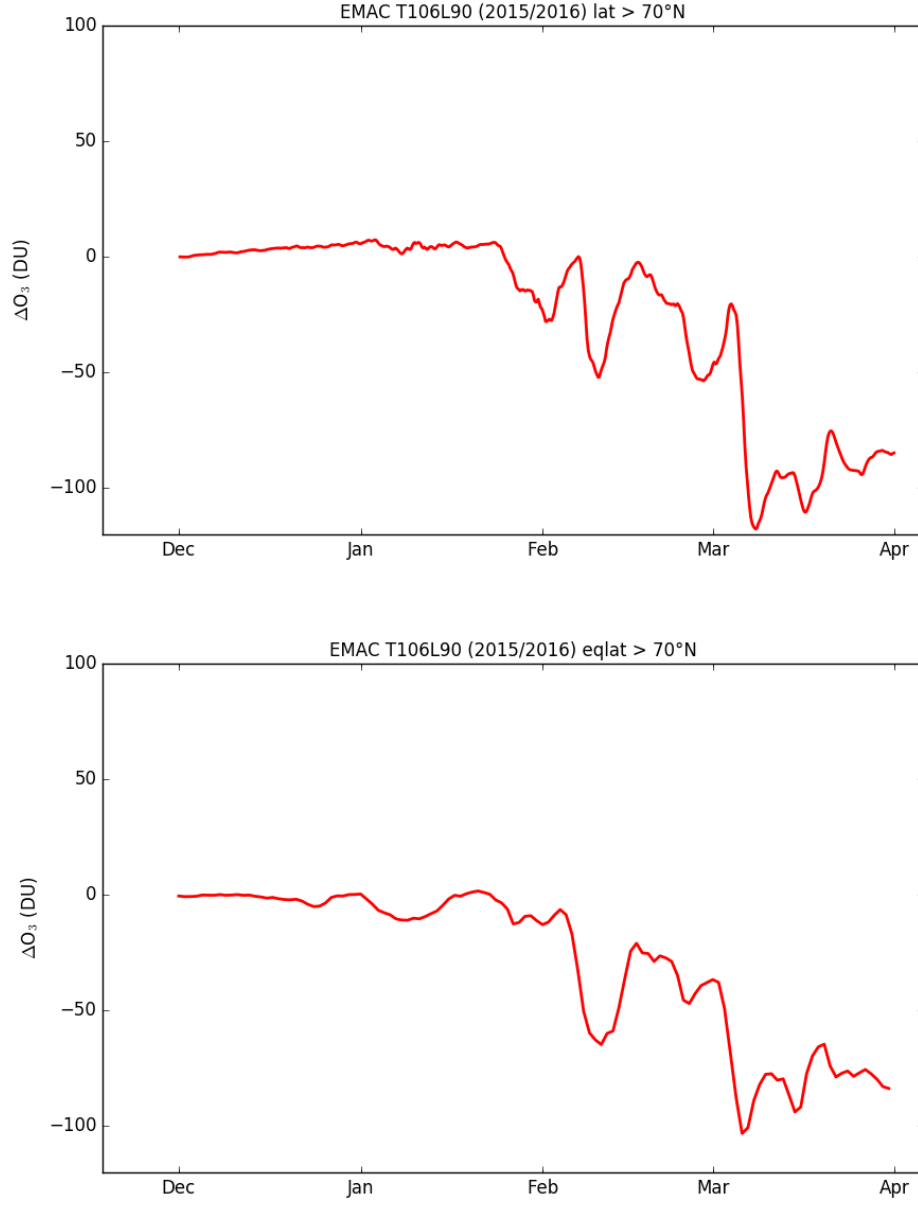


Figure 2: Total column ozone loss derived from the EMAC T106L90 simulation. Ozone loss has been derived from the difference between the active tracer  $O_3$  at the passive tracer  $O_3^*$  ( $\Delta O_3 = O_3 - O_3^*$ ). Top: average over 70-90°N latitude, bottom: average over 70-90°N equivalent latitude.



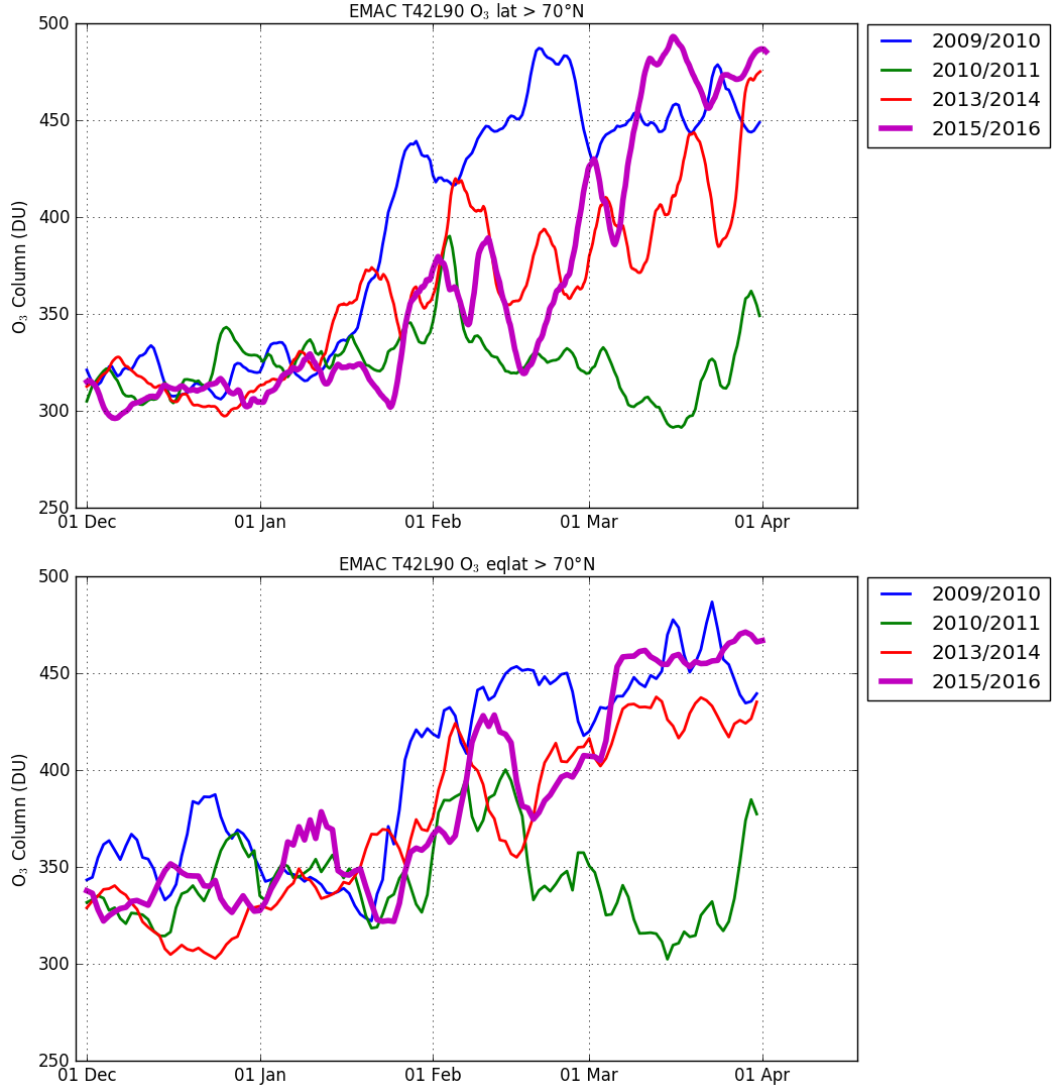


Figure 3: Ozone column time series for the Arctic winters 2009/2010 (blue), 2010/2011 (green), 2013/2014 (red) and 2015/2016 (magenta) averaged over 60-90°N latitude (top) and 60-90°N equivalent latitude (bottom). Results from the EMAC T42L90 simulation are shown.

# Denitrification, dehydration and ozone loss during the Arctic winter 2015/2016

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**Abstract.** The Arctic winter 2015/2016 was one of the coldest stratospheric winters in recent years. A stable vortex formed by early December and the early winter was exceptionally cold. Cold pool temperatures dropped below the Nitric Acid Tri-hydrate (NAT) existence temperature of about 195 K, thus allowing ~~Polar Stratospheric Clouds~~ polar stratospheric clouds (PSCs) to form. The low temperatures in the polar stratosphere persisted until early March allowing chlorine activation and catalytic ozone destruction. Satellite observations indicate that sedimentation of PSC particles led to denitrification as well as dehydration of stratospheric layers. Model simulations of the Arctic winter 2015/2016 nudged toward European Center for Medium-Range Weather Forecasts (ECMWF) analyses data were performed with the atmospheric chemistry-climate model ECHAM5/MESSy Atmospheric Chemistry (EMAC) for the Polar Stratosphere in a Changing Climate (POLSTRACC) campaign. POLSTRACC is a High Altitude and Long Range Research Aircraft (HALO) mission aimed at the investigation of the structure, composition and evolution of the Arctic Upper Troposphere and Lower Stratosphere (UTLS). The chemical and physical processes involved in Arctic stratospheric ozone depletion, transport and mixing processes in the UTLS at high latitudes, ~~polar stratospheric clouds~~ PSCs as well as cirrus clouds are investigated. In this study an overview of the chemistry and dynamics of the Arctic winter 2015/2016 as simulated with EMAC is given. Further, chemical-dynamical processes such as denitrification, dehydration and ozone loss during the Arctic winter 2015/2016 are investigated. Comparisons to satellite observations by the Aura Microwave Limb Sounder (Aura/MLS) as well as to airborne measurements with the Gimballed Limb Observer for Radiance Imaging of the Atmosphere (GLORIA) performed on board of HALO during the POLSTRACC campaign show that the EMAC simulations are in fairly good agreement with observations. We derive a maximum polar stratospheric O<sub>3</sub> loss of ~2 ppmv or ~~100~~ 117 DU in terms of column in mid March. The stratosphere was denitrified by about ~~84~~ 8 ppbv HNO<sub>3</sub> and dehydrated by about ~~10.6~~ 1 ppmv H<sub>2</sub>O in mid to end of February. While ozone loss was quite strong, but not as strong as in 2010/2011, denitrification and dehydration were so far the strongest observed in the Arctic stratosphere in ~~the~~ at least past 10 years.

## 1 Introduction

Since the early eighties, thus for more than 30 years, substantial ozone depletion has been observed each year during winter and spring in the Antarctic stratosphere (WMO, 2010). Polar ozone depletion is associated with enhanced chlorine from anthropogenic chlorofluorocarbons and heterogeneous chemistry under cold conditions. The deep Antarctic "hole" contrasts with the generally weaker ozone ~~depletions~~ depletion observed in the warmer Arctic (Solomon et al., 2014). Nevertheless, substantial ozone depletion has been observed for cold Arctic winters. Especially, in the past 15 years, ozone loss in the Arctic occasionally approached the degree of ozone loss in the Antarctic as ~~e.g. in-~~ e.g. in- winter 2004/2005 (e.g. Manney et al., 2006; Tilmes et al., 2006; Livesey et al., 2015, and references therein) and 2010/2011 (e.g., Manney et al., 2011; Sinnhuber et al., 2011; Hommel et al., 2014).

Polar stratospheric clouds (~~PSC~~ PSCs) play a key role in stratospheric ozone destruction in the polar regions (Solomon et al., 1986; Crutzen and Arnold, 1986). Heterogeneous reactions which take place on and within the PSC particles convert halogens from relatively inert reservoir species into forms which can destroy ozone in the polar spring (e.g., Peter, 1997; Solomon, 1999; Lowe and MacKenzie, 2008). PSCs form at altitudes between ~~15-30~~ 15-30 km and consist of liquid and/or solid particles. According to their composition and physical state they have been classified into three different types: (1) supercooled ternary solutions (STS), (2) Nitric Acid Trihydrate (NAT) and (3) water ice. Liquid PSC cloud particles (STS) form by the condensation of water vapour ( $H_2O$ ) and nitric acid ( $HNO_3$ ) on the liquid stratospheric background sulfate aerosol particles at temperatures 2–3 K below the NAT existence temperature  $T_{NAT}$  ( $\sim 195$  K at 50 hPa) while for the formation of solid cloud particles (NAT and ice) lower temperatures are required (slightly above or below the ice frost point  $T_{ice} \sim 188$  K at 50 hPa) (e.g. Carslaw et al., 1994; Koop et al., 1995).

Solid PSC particles can grow to larger sizes than liquid PSC particles and finally sediment out of the stratosphere (Fahey et al., 2001). The sedimentation of the solid particles can lead to dehydration and/or denitrification of the stratosphere. Solid  $HNO_3$  containing PSC particles leading to denitrification can either consist of NAT or ice depending on the prevailing formation mechanism. It has been shown that the nucleation of NAT on ice is quite efficient (e.g., Fueglistaler et al., 2002; Hoyle et al., 2013). The sedimentation of large  $HNO_3$  containing ice PSC particles can lead to greater denitrification than the sedimentation of (typically smaller) NAT or liquid PSC particles alone (Lowe and MacKenzie, 2008; Wohltmann et al., 2013; Manney and Lawrence, 2016).

Denitrification limits the deactivation process of the ozone destroying substances in springtime and thus leads to a prolongation of the ozone destroying cycles (e.g., Salawitch et al., 1993; Rex et al., 1997). Evidence of denitrification has been found in the Arctic and Antarctic from in situ and remote sensing observations (Fahey et al., 1990; Solomon, 1999; Waibel et al., 1999; Kondo et al., 2000; Santee et al., 2000; Manney et al., 2011). Denitrification is most intense over the Antarctic region, where large fractions of available  $NO_y$  are irreversibly removed from the stratosphere each winter.  $NO_y$  is the sum of principal reactive nitrogen species, of which  $HNO_3$ ,  $NO$ ,  $NO_2$ ,  $N_2O_5$ , and  $ClONO_2$  are important in the lower stratosphere (Fahey et al., 1989). Dehydration in the stratosphere is generally observed over the Antarctic (e.g., Kelly et al., 1989; Vömel et al.,

1995; Nedoluha et al., 2000) but only rarely in the Arctic (e.g., Fahey et al., 1990; Vömel et al., 1997; Pan et al., 2002; Schiller et al., 2002; Khaykin et al., 2013).

Another factor contributing to the severity of ozone destruction is the reduction of nitrogen ( $\text{NO}_x = \text{NO} + \text{NO}_2$ ) via the conversion of  $\text{NO}_x$  into  $\text{HNO}_3$  on the surfaces of PSCs, the so-called denoxification. Denoxification becomes important if temperatures are continuously low during the course of the winter as is the case in the Antarctic (e.g. Waibel et al., 1999). It has been shown that polar vortex stability, chlorine activation and ozone loss tend to be greater with lower vortex temperatures (e.g. von Hobe et al., 2013). Therefore, it is not surprising that the most severe ozone loss ever observed in the Arctic occurred in spring 2011, at the end of the most persistently cold Arctic winter in the stratosphere on record (Manney et al., 2011; Sinnhuber et al., 2011).

The Arctic winter 2015/2016 was one of the coldest stratospheric winters in recent years. ~~A stable vortex formed already in early December and the early winter was exceptionally cold.~~ The Arctic polar vortex in the early winter 2015/2016 was the strongest and coldest of the last 68 years (Matthias et al., 2016). Temperatures within the vortex dropped below the NAT existence temperature  $T_{\text{NAT}}$ , thus allowing PSCs to form. Tropospheric and stratospheric cloud structures were observed simultaneously over Svalbard. Synoptic-scale ~~polar-stratospheric-clouds~~ PSCs extended over a nearly 8 km deep layer (Dörnbrack et al., 2016). The low temperatures in the polar stratosphere persisted until early March allowing PSC formation, chlorine activation and catalytic ozone destruction. Satellite observations indicate that sedimentation of PSC particles led to denitrification as well as dehydration of stratospheric layers (Manney and Lawrence, 2016). Widespread persistent ice PSC layers were observed by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) (Voigt et al., 2016). Ozone destruction was strong, but not as strong as in 2010/2011, since a major final sudden stratospheric warming ended the Arctic winter 2015/2016 by early March (Manney and Lawrence, 2016).

Model simulations of the Arctic winter 2015/2016 nudged toward European Center for Medium-Range Weather Forecasts (ECMWF) analyses were performed with the atmospheric chemistry-climate model ECHAM5/MESSy Atmospheric Chemistry (EMAC) for the POLSTRACC (Polar Stratosphere in a Changing Climate) campaign. POLSTRACC was a HALO mission (High Altitude and Long Range Research Aircraft) aiming at the investigation of the structure, composition and evolution of the Arctic Upper Troposphere Lower Stratosphere (UTLS). The chemical and physical processes involved in Arctic stratospheric ozone depletion, transport and mixing processes in the UTLS at high latitudes, ~~polar-stratospheric-clouds~~ PSCs as well as cirrus clouds were investigated. In this study, an overview of the chemistry and dynamics of the Arctic winter 2015/2016 as simulated with EMAC is given. Chemical-dynamical processes such as denitrification, dehydration and ozone loss will be investigated and comparisons to satellite observations by the Aura Microwave Limb Sounder (Aura/MLS) as well as to airborne measurements with the Gimballed Limb Observer for Radiance Imaging of the Atmosphere (GLORIA) performed onboard of HALO will be shown.

## 2 Model simulations and observations

### 2.1 EMAC

The ECHAM5/MESSy Atmospheric Chemistry (EMAC) model is a numerical chemistry and climate simulation system that includes sub-models describing tropospheric and middle atmosphere processes and their interaction with oceans, land and human influences (Jöckel et al., 2010). It uses the second version of the Modular Earth Submodel System (MESSy2) to link multi-institutional computer codes. The core atmospheric model is the 5th generation European Centre Hamburg general circulation model (ECHAM5, Roeckner et al. (2006). For the present study we applied EMAC (ECHAM5 version 5.3.02, MESSy version 2.52) in T106L90MA and T42L90MA resolution, i.e., with a spherical truncation of T106 and T42 (corresponding to a quadratic Gaussian grid of approximately  $1.125^\circ \times 1.125^\circ$  and  $2.8^\circ \times 2.8^\circ$  degrees, respectively, in latitude and longitude) with 90 vertical hybrid pressure levels from the surface up to 0.01 hPa (approx. 80 km). A Newtonian relaxation technique of the prognostic variables temperature, vorticity, divergence and the (logarithm of the) surface pressure above the boundary layer and below 1 hPa towards ECMWF ERA-Interim reanalysis data (Dee et al., 2011) and ECMWF operational analysis was applied, respectively, in order to nudge the model dynamics towards the observed meteorology.

For the analyses of the Arctic winter 2015/2016 we use the EMAC data from a T106L90 simulation that was chemically initialised based on a former EMAC simulation. The T106L90 simulation was started on 1 July 2015 and continued until 30 April 2016, applying a nudging toward ECMWF operational analysis. For the comparisons to recent winters we performed an EMAC T42L90 simulation covering the time period 1 January 2008 to 30 April 2016. The T42L90 simulation was nudged toward ECMWF ERA-interim analysis data until 30 June 2015 and toward ECMWF operational analysis data thereafter. In both simulations (T106L90 and T42L90) a comprehensive chemistry setup for the stratosphere and troposphere is included. Reaction rate coefficients for gas phase reactions and absorption cross sections for photolysis are taken from Atkinson et al. (2007) and Sander et al. (2011b). The applied model setup comprised among others the submodels: MECCA for the gas-phase chemistry (Sander et al., 2011a), JVAL for the calculation of photolysis rates (Sander et al., 2014), MSBM (Multi-phase Stratospheric Box Model) for the processes related to ~~polar stratospheric clouds~~ PSCs (Kirner et al., 2011), TROPOP for diagnosing the tropopause and boundary layer height, SORBIT for sampling model data along sun-synchronous satellite orbits (Jöckel et al., 2010) as well as H<sub>2</sub>O for stratospheric water vapor.

The submodel MSBM simulates the number densities, mean radii and surface areas of sulphuric acid aerosols and liquid and solid PSC particles. The formation of STS particles is calculated according to Carslaw et al. (1995) through the uptake of HNO<sub>3</sub> and H<sub>2</sub>O on the liquid binary sulphuric acid/water particles. Ice particles are assumed to form homogeneously at temperatures below T<sub>ice</sub>. For the simulation of NAT particles the “kinetic growth NAT parameterisation” is used. The “kinetic” parameterisation is based on the growth and sedimentation algorithm given by Carslaw et al. (2002) and van den Broek et al. (2004). The vapour pressure over ice is calculated according to Marti and Mauersberger (1993) and the vapour pressure over NAT according to Hanson and Mauersberger (1988). NAT formation takes place as soon as a supercooling of 3 K below T<sub>NAT</sub> is reached. The sedimentation of ice particles is calculated according to Waibel et al. (1999) and for NAT particles according

to Carslaw et al. (2002). Eleven heterogeneous reactions that occur on the surfaces of liquid and solid PSC particles are considered. A comprehensive description of the submodel MSBM can be found in Kirner et al. (2011).

## 2.2 Aura/MLS

The Microwave Limb Sounder (MLS) on the Earth Observing System Aura Satellite was launched in July 2004. The Aura/MLS instrument is an advanced successor to the MLS instrument on the Upper Atmosphere Research satellite (UARS). MLS is a limb sounding instrument that measures the thermal emission at millimetre and submillimetre wavelengths using seven radiometers to cover five broad spectral regions (Waters et al., 2006). Measurements are performed from the surface to 90 km with a global latitude coverage from 82° S to 82° N. Vertical profiles are measured every 165 km along the suborbital track with a horizontal resolution of  $\sim 200\text{--}500$  km along track and a footprint of  $\sim 3\text{--}9$  km across-track. Here, we use Aura/MLS version v4.2 HNO<sub>3</sub>, O<sub>3</sub> and ClO data. The data screening criteria given by Livesey et al. (2017) have been applied to the data.

A detailed assessment of the quality and reliability of the Aura/MLS v2.2 HNO<sub>3</sub> measurements can be found in Santee et al. (2007). The HNO<sub>3</sub> in v3.3 was significantly improved compared to v2.2. In particular, the low bias in the stratosphere was largely eliminated. Measurements of v4.2 HNO<sub>3</sub> are performed with a horizontal resolution of 400–500 km and a vertical resolution of 3–4 km over most of the vertical range. In the lower stratosphere, the precision has been estimated to be 0.6 ppbv

and the systematic uncertainty for HNO<sub>3</sub> is estimated to be 0.5–2 ppbv (2- $\sigma$  estimates).

Detailed validation of the MLS O<sub>3</sub> v2.2 product and comparisons with other data sets can be found in Jiang et al. (2007), Froidevaux et al. (2008) and Livesey et al. (2008). In the stratosphere and above, v4.2 ozone profiles are very similar to the v2.2 and v3.3x/v3.4x profiles. Comparisons have indicated general agreement within 5–10 % with stratospheric profiles from satellite, balloon, aircraft, and ground-based data (Livesey et al., 2017).

The quality and reliability of the v2.2 MLS ClO measurements were assessed in detail by Santee et al. (2008). The ClO product was significantly improved in v3.3 and v3.4 (Livesey et al., 2013). In particular, the substantial ( $\sim 0.1\text{--}0.4$  ppbv) negative bias present in the v2.2 ClO values at pressures larger than 22 hPa was mitigated to a large extent, primarily through retrieval of CH<sub>3</sub>Cl, which was a new MLS product in v3.3 and v3.4. The ClO retrieval is largely unchanged over much of the profile in v4.2. Measurements of ClO are performed with a horizontal resolution of 300–600 km and a vertical resolution of 3–4.5 km. The precision lies generally within  $\pm 0.1$  ppbv (Livesey et al., 2017). Although the negative bias at the lowest retrieval levels has not been entirely eliminated, we make no attempt to correct for it in this analyses.

## 2.3 GLORIA

The Gimbalbed Limb Observer for Radiance Imaging of the Atmosphere (GLORIA) combines a classical Fourier transform spectrometer with a 2-D detector array. The instrument takes limb images of the atmosphere from the flight altitude of HALO or M55-Geophysica down to 4 km. This results in vertical sampling steps of about 150 m at 8 km tangent height from a typical HALO flight level of 14 km. Individual images contain 128 pixels (spectra) in the vertical dimension and 48 pixels in the horizontal dimension. The spectra associated with the pixel rows are binned to reduce uncertainties. The spectral range of the observations currently extends from about 780 to 1400 cm<sup>-1</sup> (Riese et al., 2014). The list of species with signatures in

this spectral range includes temperature,  $\text{H}_2\text{O}$ ,  $\text{HDO}$ ,  $\text{O}_3$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ ,  $\text{CFC-11}$ ,  $\text{CFC-12}$ ,  $\text{HCFC-12}$ ,  $\text{SF}_6$ ,  $\text{HNO}_3$ ,  $\text{N}_2\text{O}_5$ ,  $\text{ClONO}_2$ ,  $\text{HO}_2\text{NO}_2$ ,  $\text{PAN}$ ,  $\text{C}_2\text{H}_6$ ,  $\text{H}_2\text{CO}$ ,  $\text{NH}_3$ . Details on the instrument design and calibration are given in Friedl-Vallon et al. (2014) and Kleinert et al. (2014). GLORIA is operated in a high-spectral, medium-spatial sampling (“chemistry”) mode and a medium-spectral, high-spatial sampling (“dynamics”) mode. The spectral samplings are  $0.0625\text{ cm}^{-1}$  for the chemistry mode and  $0.625\text{ cm}^{-1}$  for the dynamics mode (Riese et al., 2014). In this study, trace gas retrievals from measurements in the chemistry mode are used. A first validation of the retrieval results in the chemistry mode can be found in Woiwode et al. (2015).

### 3 Arctic winter 2015/2016

#### 3.1 Overview

In the Arctic winter 2015/2016, temperatures were at record lows from December 2015 to early February 2016 with an unprecedented period of temperatures below the ice formation threshold (Manney and Lawrence, 2016). The extraordinarily strong and cold polar vortex in early winter (November-December 2015) was caused by very low planetary wave activity in the stratosphere (Matthias et al., 2016). The Arctic winter ended in early March by a major final sudden stratospheric warming. By mid-March, the vortex had been displaced far off the pole and split. The offspring vortices decayed rapidly, resulting in a full breakup of the vortex by early April (Manney and Lawrence, 2016).

In ~~FigureFig.~~ 1 the temporal evolution of temperature and PSC surface area density at high latitudes ( $70\text{--}90^\circ\text{N}$ ) as function of pressure for ~~the Arctic winter 2015/2016~~ (December 2015 to March 2016) as simulated with EMAC is shown. Temperatures below  $195\text{ K}$  are found between  $70$  and  $10\text{ hPa}$  from early December to end of January. Zonal mean temperatures remained cold afterwards, but not as cold as during December and January. Temperatures dropped during the first cold period (December to end of January) below the ice formation threshold temperatures (Manney and Lawrence, 2016) leading to unprecedented formation of ice PSCs as will be discussed in more detail below (see Fig. 2). The simulated temperatures are in good agreement with observations from Aura/MLS (see Fig. 12 and Sect. 4.1).

The extensive formation of PSCs as simulated with EMAC can be seen in ~~FigureFig.~~ 1 (bottom). Here, the total surface area density (liquid + solid) is shown. The first PSCs are found in the beginning of December and PSC formation maximises throughout January (between  $80$  and  $20\text{ hPa}$ ). During the second cold phase in February PSCs are still present but to a lesser extent. In ~~FigureFig.~~ 2 the surface area densities of STS, NAT and ice as a function of pressure are shown ( $70\text{--}90^\circ\text{N}$ ). Since the liquid particles have the largest surface area density,  $A_{\text{STS}}$  is almost identical to  $A_{\text{PSC}}$ . PSCs consisting of NAT are found between  $150$  and  $20\text{ hPa}$  throughout December and January, and consisting of ice between  $80$  and  $30\text{ hPa}$  in January. Compared to other extreme Arctic winters, e.g. the 2010/2011 winter, much larger amounts of PSCs are simulated accordance with the preceding low temperatures for the Arctic winter 2015/2016. Furthermore, ~~also~~ the largest surface area density for ice is simulated for the Arctic winter 2015/2016 compared to previous Arctic winters e.g. the 2010/2011 Arctic winter, which has been the most extreme in that respective so far (e.g., Manney et al., 2011; Sinnhuber et al., 2011; Hommel et al., 2014). Ice



PSC persisted in 2015/2016 over a much longer time period than in e.g. the Arctic winter 2010/2011 as can be seen in the EMAC results for the Arctic winter 2010/2011 shown in Khosrawi et al. (2017).

### 3.2 Denitrification

Solid  $\text{HNO}_3$  containing PSC particles can sediment out of the stratosphere and thus lead to an irreversible removal of  $\text{HNO}_3$  (denitrification). Severe denitrification was observed by Aura/MLS in the Arctic winter 2015/2016. Figure 3 shows the  $\text{HNO}_3$  gas phase distribution as simulated with EMAC for certain dates between 24 December 2015 and 12 February 2016 at 52 hPa. Strong gas phase removal of  $\text{HNO}_3$  is evident throughout the entire period considered here. Gas phase  $\text{HNO}_3$  is extremely low within the Arctic vortex in December and January, but mixing ratios increase somewhat (but still remain quite low) in February. That this gas phase removal of  $\text{HNO}_3$  led to a permanent removal and thus to a denitrification of the stratosphere can be seen from the redistribution of  $\text{NO}_y$  in the model (Figure Fig. 4).

In model simulations, denitrification can be quantified by applying a passive  $\text{NO}_y^*$  tracer. Figure 4 shows the simulated  $\text{NO}_y$  change ( $\Delta\text{NO}_y$ ) averaged over 70-90°N as function of pressure and time. The unperturbed  $\text{NO}_y^*$  was simulated by a passive tracer that was initialized according to the  $\text{NO}_y$  distribution on 1 December 2015. The passive tracer is transported as all other chemical species but does not undergo any chemical changes or sedimentation. The difference of  $\text{NO}_y$  and  $\text{NO}_y^*$  gives the amount of  $\text{NO}_y$  that has been denitrified/re-nitrified ( $\Delta\text{NO}_y = \text{NO}_y - \text{NO}_y^*$ ).

Figure 4 shows that strong denitrification is also simulated with EMAC for the Arctic winter 2015/2016. The maximum denitrification-sequestration is reached at the end of January (about 8 ppbv). Below the denitrified layers this layer re-nitrification (about 4 ppbv) due to the evaporation of the sedimenting PSC particles at lower pressure levels higher pressure levels (lower altitudes) is clearly visible. Thus, the amount of  $\text{HNO}_3$  that has been permanently removed (denitrified) is between 4-8 ppbv. Diabatic descent within the polar vortex causes the downward shift of the denitrified/re-nitrified areas. The mixing ratio increase at the re-nitrification altitudes is lower than the mixing ratio decrease at the denitrification altitudes, because the total mass of sedimented should be conserved and the pressure increases at decreasing altitude (Groß et al., 2005).

### 3.3 Dehydration

The long period of temperatures below the ice formation threshold led to much greater dehydration than previously seen in the Arctic (Manney and Lawrence, 2016). Large areas of ice PSC throughout January were observed with CALIPSO that also were the greatest observed in the Arctic in the 8 years of the CALIPSO data record (Voigt et al., 2016). In the EMAC simulation large areas of ice PSCs are simulated throughout January (Figure Fig. 2 bottom). Dehydration peaks in the EMAC simulation towards the end of January and is also the strongest simulated compared to other cold winters as e.g. the Arctic winter 2010/2011. The simulated dehydration in EMAC is also in agreement with observations. Trace gas measurements from Aura/MLS show that exceptional dehydration occurred during the Arctic winter 2015/2016 (Manney and Lawrence, 2016).

Figure 5 shows the EMAC  $\text{H}_2\text{O}$  distribution at certain dates during the winter 2015/2016 at 52 hPa. On 24 December 2015 the  $\text{H}_2\text{O}$  distribution shows the usual background  $\text{H}_2\text{O}$  mixing ratios in the Arctic region. From January onwards, mixing ratios drop and an area with mixing ratios below 5 ppmv is found north of Scandinavia. Mixing ratios decrease further throughout



January and the area of dehydration increases. From February onwards  $\text{H}_2\text{O}$  mixing ratios start to increase again, but still remain lower than the pre-winter values.

Dehydration from the EMAC simulation is derived by using total ~~stratospheric~~ “stratospheric” hydrogen ( $2\text{CH}_4 + \text{H}_2\text{O}$ ) as substitute for a passive  $\text{H}_2\text{O}$  tracer (e.g., Rinsland et al., 1996; Schiller et al., 1996). Molecular hydrogen ( $\text{H}_2$ ) is nearly constant in the lower and middle stratosphere and can therefore be neglected in the calculation of total hydrogen. The quantity  $2\text{CH}_4 + \text{H}_2\text{O}$  is generally constant in the stratosphere. However, slight deviations from this quasi-conserved quantity can be found at high latitudes during winter where transport of mesospheric air rich in molecular hydrogen and poor in water vapour and methane is brought into the upper stratosphere (e.g., LeTexier et al., 1988; Engel et al., 1996).

The change in  $\text{H}_2\text{O}$  ( $\Delta\text{H}_2\text{O}$ ) is calculated by taking the difference of total hydrogen at time  $t$  and total hydrogen at time  $t_0$  ( $\Delta\text{H}_2\text{O} = (2\text{CH}_4 + \text{H}_2\text{O})(t) - (2\text{CH}_4 + \text{H}_2\text{O})(t_0)$ , with  $t_0 = 1$  December). The exceptional dehydration during the Arctic winter 2015/2016 can be seen in the temporal evolution of  $\Delta\text{H}_2\text{O}$  as function of pressure averaged over  $70\text{--}90^\circ\text{N}$  (~~Figure~~Fig. 6). The decrease of  $\Delta\text{H}_2\text{O}$  throughout January and February shows ~~dehydration of the lower stratosphere a~~  $\text{H}_2\text{O}$  decrease of around 1 ppmv extending between 60 and 30 hPa. ~~Dehydration-Sequestration into PSC particles~~ reaches its maximum in mid January ( $\Delta\text{H}_2\text{O}$  of up to 2 ppmv). Below the ~~dehydrated-depleted~~ areas re-hydration (up to 0.6 ppmv) due to the evaporation of the sedimenting PSC particles at ~~larger-higher~~ pressure levels (lower altitudes) is clearly visible. Thus, the amount of  $\text{H}_2\text{O}$  that has been permanently removed (dehydrated) is between 0.6-1 ppmv.

### 3.4 Ozone loss

The Arctic winter 2015/2016 ~~had appeared to have~~ the greatest potential yet seen for record Arctic ozone loss ~~since temperatures~~ (Manney and Lawrence, 2016). Temperatures in the Arctic lower stratosphere were at record lows from December 2015 to early February 2016 (Manney and Lawrence, 2016; Matthias et al., 2016). ~~Ozone~~ As was shown by Manney and Lawrence (2016) ozone destruction began earlier and proceeded more rapidly than in 2010/2011, the winter that so far has been the one with the strongest observed ozone loss in the Arctic (Manney et al., 2011). ~~However, That lower-stratospheric ozone loss did not reach the extent of that in spring 2011 was primarily due to~~ a major final stratospheric warming in early March 2016 ~~lead that led~~ to a vortex split and a full breakdown of the vortex by early April (Manney and Lawrence, 2016).

In the following the EMAC simulation is used to investigate ozone depletion during the Arctic winter 2015/2016 and compare the results with previous Arctic winters. Ozone depletion ( $\Delta\text{O}_3$ ) from the model simulation is determined by the difference between the modelled ozone ( $\text{O}_3$ ) ~~and an artificial and a~~ passive ozone tracer ( $\text{O}_3^*$ ) ( $\Delta\text{O}_3 = \text{O}_3 - \text{O}_3^*$ ). The passive ozone tracer was initialised on 1 December 2015 according to the ozone distribution on that day and was then advected and mixed as all other chemical species but did not undergo any chemical changes. The simulated ozone depletion (averaged over  $70\text{--}90^\circ\text{N}$ ) is shown in ~~Figure~~Fig. 7. From mid January onwards ozone depletion is visible in the EMAC simulation and a maximum depletion of about 2.1 ppmv is reached at about 30 hPa in mid March.

The simulated total column ozone loss time series from 1 December to 31 March averaged over  $70\text{--}90^\circ\text{N}$  is shown in ~~Figure~~Fig. 8. Changes in the total column become visible from the end of January onwards. The absolute maximum in total column ozone loss of about ~~+20 DU~~ -117 DU is reached on 7 March. Note that, rather than employing a vortex following

coordinate as e. g. equivalent latitude, we haven chosen to perform our analyses on a fixed geographic latitude band. Such an approach is justified here because the use of a passive ozone tracer allows dynamical and chemical processes to be separated, thus facilitating the quantification of chemical ozone loss. On equivalent latitudes the same amount of ozone loss in terms of mixing ratio is derived while in terms of column loss ozone loss is 10% less (103 DU).

### 5 3.5 Comparison to recent Arctic winters

~~For the comparison of the EMAC simulation of the Arctic winter 2015/2016 to previous Arctic winters the EMAC T42L90 simulation is used.~~ The results from both simulations, T42L90 and T106L90, are quite similar as can be seen from the time series comparison shown in Section 4 where the EMAC simulations are compared to Aura/MLS observations. The agreement with the Aura/MLS measurements is slightly better for the T106L90 simulation.

10 Although considerable ozone loss occurred during the Arctic winter 2015/2016, ozone loss was not as strong as in 2010/2011 as can be seen from ~~FigureFig.~~ 9 and ~~FigureFig.~~ 10. In ~~FigureFig.~~ 9 the March mean  $O_3$  column is shown for the years 2010 to 2016. Very low  $O_3$  column values are found in March 2011. Column values reach 250 DU. In March 2016, however, the  $O_3$  column remains quite high.

Figure 10 shows the Arctic mean column  $O_3$  time series (averaged over  $60^\circ$  to  $90^\circ$ N) from 1 December to 30 April for the  
 15 four Arctic winters 2009/2010, 2010/2011, 2013/2014 and 2015/2016. The EMAC Arctic mean column shows considerable interannual variability. In contrast to the other Arctic winters very low  $O_3$  is found in 2010/2011. The extreme low  $O_3$  column that we find in the EMAC simulation for the winter 2010/2011 is in agreement with the results from Strahan et al. (2013) and Manney et al. (2011) using observations and model simulations. In 2015/2016 the  $O_3$  column was comparably low in  
 20 early winter, but from February onwards the  $O_3$  column started to increase significantly due to the disturbances of the Arctic stratosphere by sudden stratospheric warmings. In fact, winters with above average stratospheric wave activity have a warm, disturbed vortex, while winters with weak wave driving have a cold, long lasting vortex, with well-known impacts on Arctic March temperatures and  $O_3$  column (Strahan et al. (2013) and references therein). Manney and Lawrence (2016) found from MLS observations that ozone continued to decrease in the vortex at a rate slightly faster than that in 2011 until the beginning of March 2016. However, around mid-March ozone increased for the rest of the winter so that the ozone values always remained  
 25 higher than in 2011. This is also seen in the EMAC simulation. Therefore, our model simulations are in agreement with the results by Manney and Lawrence (2016) who showed that in the Arctic winter 2015/2016 the stratosphere ~~had appeared to have~~ the greatest potential yet seen for a massive Arctic ozone loss due to record low temperatures, but was disrupted by the final sudden warming in early March. In other words, massive Arctic ozone loss likely would have occurred in the Arctic winter 2015/2016 if the vortex had remained stable and temperatures remained low through late March.

30 On the other hand, although ozone loss was not stronger than in 2010/2011, denitrification and dehydration were the strongest observed so far (Manney and Lawrence, 2016). From the EMAC simulation the same result as from the observations is derived. Figure 11 shows the time series of  $HNO_3$  and  $H_2O$  for the same four Arctic winters as shown in ~~FigureFig.~~ 10. At 48 hPa several ppbv lower  $HNO_3$  mixing ratios than in previous cold Arctic winters is found from December to February. Pre-winter  $HNO_3$  mixing ratios were around 11 ppbv and drop to 4 ppbv in mid January. How much lower the  $H_2O$  mixing ratios drop

due to the dehydration during the Arctic winter 2015/2016 compared to other Arctic winters can be seen in the H<sub>2</sub>O time series at 48 hPa (Figure Fig. 11 bottom). In early December, H<sub>2</sub>O mixing ratios are as high as 5.8 ppmv and decrease to 5.2 ppmv, but decrease for a short period towards the end of January to even lower values (4.7 ppmv). From the end of January the H<sub>2</sub>O mixing ratios increase slowly, but still remain lower than the pre-winter values. The H<sub>2</sub>O mixing ratios are in addition  
5 ~1-1.5 ppmv lower in January and February than in previous cold Arctic winters.

## 4 Comparison to observations

In this study, we compare the EMAC simulations for the Arctic winter 2015/2016 to Aura/MLS observations. In another study Khosrawi et al. (2017) the EMAC simulations of HNO<sub>3</sub>, temperature and PSC volume density were compared for the Arctic winters 2009/2010 and 2010/2011 with satellite observations (Envisat/MIPAS and Aura/MLS). Here, we consider in addition  
10 to temperature and HNO<sub>3</sub> other trace gases such as O<sub>3</sub>, ClO (section 4.1) as well as H<sub>2</sub>O and compare the simulations to Aura/MLS observations. Additionally, the EMAC simulations are compared to remote sensing observations from GLORIA performed during the POLSTRACC measurement campaign (section 4.2). For the comparisons to Aura/MLS the EMAC SORBIT ~~output~~-output is used (Jöckel et al., 2010) while for the comparison to GLORIA the EMAC global ~~field~~ output is interpolated to the GLORIA measurement geolocations.

### 4.1 Comparison to Aura/MLS

Figure 12 shows a comparison of the temperature, HNO<sub>3</sub>, and O<sub>3</sub> distribution measured by Aura/MLS with the ones simulated with EMAC at about 50 hPa on 15 January 2016. For temperature as well as for HNO<sub>3</sub> and O<sub>3</sub> the simulations are in general agreement with the Aura/MLS observations. Nevertheless, some differences are found between model simulations and obser-  
20 vations. Temperatures as simulated with EMAC (nudged towards ECMWF operational analyses) tend to be slightly warmer higher than measured outside the polar vortex. The trace gas distributions of HNO<sub>3</sub> and O<sub>3</sub> simulated with EMAC show more fine-scale structures which may be related to the higher horizontal resolution ( $1.125^\circ \times 1.125^\circ \sim 125 \text{ km} \times 125 \text{ km}$  or less dependent on latitude) of the EMAC simulation compared to Aura/MLS (measurements every  $1.5^\circ \sim 165 \text{ km}$  and resolution of 200-500 km along track). Generally, the simulated HNO<sub>3</sub> mixing ratios are slightly lower than the ones measured with Aura/MLS while the simulated O<sub>3</sub> mixing ratios are quite similar to the observed O<sub>3</sub>.

25 The temporal development of ClO, HNO<sub>3</sub> and O<sub>3</sub> averaged over 70-90°N during the Arctic winter 2015/2016 as function of pressure as simulated with EMAC and observed by Aura/MLS is shown in Figure Fig. 13. Here, the EMAC SORBIT output is used (Jöckel et al., 2010) where EMAC is sampled along the sun-synchronous orbit of Aura/MLS. The use of the SORBIT output improves the agreement between observations and simulations of trace gases with a diurnal cycle as e. g. ClO significantly, but has a rather minor impact on the comparison between observations and simulations for other trace gases as  
30 e. g. O<sub>3</sub>. Generally, the temporal evolution of the trace gas distributions is realistically reproduced in the EMAC simulation. Nevertheless, there are some differences found between measurement and model simulations. In the observations, increased ClO mixing ratios are already found in December whereas in the model simulation the increase of ClO occurs somewhat later.

However, the enhancement of  $\text{ClO}_x$  ( $\text{ClO}_x = \text{Cl} + \text{HOCl} + 2 \cdot \text{Cl}_2 + 2 \cdot \text{Cl}_2\text{O}_2$ ) in the EMAC simulation is found at the same time as in the Aura/MLS ~~ClO~~  $\text{ClO}$  observation, thus indicating that the later increase in  $\text{ClO}$  ~~is probably not~~ is not necessarily caused by the activation of chlorine being too late in the model simulation but ~~rather of~~ could also be caused by the partitioning between the active chlorine species. In EMAC the photolyses rates are calculated with the submodel JVAL (Section 2.1). JVAL is part of the standard configuration of EMAC that was also used in the EMAC simulations contributing to the Chemistry-Climate Model Initiative (CCMI, (Jöckel et al., 2016)) (note a similar configuration is used here apart from the resolution). An intercomparison of several photolyses scheme has shown that JVAL provides lower photolysis rates at very high solar zenith angles ( $>90^\circ$ ) for e.g.  $\text{Cl}_2\text{O}_2$  than other schemes. Thus, the partitioning of chlorine containing species may be shifted for high solar zenith angles and thus could be the cause for the delay in the activation of  $\text{ClO}$  in the model simulation. However, to entirely rule out the cause for this difference further studies are necessary which however are beyond the scope of this study. The  $\text{ClO}$  mixing ratios are maximum in February in both the observations and model simulations, ~~but~~ However, at the maximum higher mixing ratios are found and these extend over a larger vertical range in the EMAC simulation than in Aura/MLS observations.

The temporal evolution of the  $\text{HNO}_3$  distribution as a function of pressure shows that the model simulation captures the general features well. In early December  $\text{HNO}_3$  mixing ratios are slightly underestimated by EMAC ( $\sim 1$  ppbv). Gas phase removal of  $\text{HNO}_3$  due to uptake in PSCs is more strongly simulated at higher pressure levels (Dec to Jan at around 100 hPa) while underestimated at lower pressure levels (January to February at around 50 hPa). PSCs composed of NAT form in EMAC as soon as temperatures drop below  $T_{\text{NAT}} - 3$  K which ~~results often~~ results in a too early formation of NAT particles. Among other things, this has also an impact on the denitrification as was found in another study comparing EMAC simulations for the Arctic winter 2009/2010 and 2010/2011 with Envisat/MIPAS and Aura/MLS observations (Khosrawi et al., 2017). Because NAT is calculated before STS in the model, the NAT formation occurs at the expense of STS since the available  $\text{HNO}_3$  is first consumed by the NAT clouds (e.g., Wohltmann et al., 2013). Since in reality STS and NAT clouds are often observed at the same time (e.g., Pitts et al., 2011; Peter and Groöb, 2012), this could be one explanation for the deviations in the  $\text{HNO}_3$  distribution.

The temporal evolution of EMAC  $\text{O}_3$  (~~FigureFig.~~ 13 bottom panel) is quite similar to that observed by Aura/MLS, especially in the lower stratosphere. In the upper stratosphere more  $\text{O}_3$  is brought down leading to higher  $\text{O}_3$  in the EMAC simulation above 20 hPa in March compared to Aura/MLS.

Figure 14 shows the time series of  $\text{HNO}_3$  and  $\text{O}_3$  at 50 hPa for Aura/MLS and the EMAC T42 and T106 simulation. In the EMAC simulation the  $\text{HNO}_3$  is slightly underestimated in the beginning of December (by about 1 ppbv). Larger differences at 50 hPa are found in the time period of denitrification (end of December to end of January). At this time, the EMAC simulations underestimate denitrification at 50 hPa by about 2-3 ppbv. The simulated  $\text{O}_3$  is in good agreement with Aura/MLS measurements during December and January. From February onwards the simulated  $\text{O}_3$  is up to 0.25 ppmv higher than the observed  $\text{O}_3$ . For both species the T106L90 simulation agrees slightly better with the Aura/MLS observations. ~~How important the resolution of the model simulation is and that especially along the HALO flight tracks a better agreement with measurements is derived with the EMAC T106L90 resolution is shown in Sinnhuber et al. (2017).~~

## 4.2 Comparison to GLORIA

The EMAC simulations were performed in support of the POLSTRACC campaign. This allows us to evaluate the model performance in the lower stratosphere by comparison to high resolved measurements performed onboard HALO. Here, we show a comparison of EMAC  $\text{HNO}_3$  and  $\text{O}_3$  to the remote sensing instrument GLORIA. ~~Further comparisons of EMAC to GLORIA for several trace gases will be shown in Johansson et al. (2017) and Braun et al. (2017) and comparison to in-situ instruments onboard HALO are shown in Sinnhuber et al. (2017).~~

The comparison shown here is for the POLSTRACC flight 21 on 18 March 2016. EMAC output has been taken along the times and location of GLORIA measurements (Figure Fig. 15). The GLORIA measurements in chemistry mode of flight 21 used in this comparison were performed over Scandinavia. By mid-March the polar vortex had been displaced off the pole and split. The colder offspring vortex was centered over Northern Russia and during flight 21 air masses at the border of this offspring vortex have been probed.

EMAC  $\text{HNO}_3$  and  $\text{O}_3$  compares generally well to GLORIA in terms of the distribution and mixing ratios. However, at 12-14 km, the area where the polar vortex has been probed,  $\text{O}_3$  mixing ratios from EMAC are slightly lower than the ones observed by GLORIA. The same holds for  $\text{HNO}_3$ , but differences between EMAC and GLORIA are larger. The underestimation of polar vortex  $\text{O}_3$  in the EMAC simulation could be either caused by a too weak downward transport or a too strong ozone destruction in the model. The former reason, however, is more likely, since a well known feature in EMAC is that the downward transport is underestimated in the lower parts of the polar vortices (Brühl et al., 2007). Further, ozone loss in EMAC is rather underestimated than overestimated as was found in the evaluation study by Khosrawi et al. (2009).

Another difference between EMAC and GLORIA is that less fine-scale structure is simulated with EMAC than observed by GLORIA, which is probably due to the rather coarse horizontal resolution of EMAC (T106 corresponding to  $1.125^\circ \times 1.125^\circ$ ) compared to GLORIA. Nevertheless, ~~this comparison and the ones presented in (Johansson et al., 2017)~~ these results show that EMAC simulations can be used for comparisons to aircraft measurements. In the future simulations with EMAC with an even higher horizontal resolution (T255) are anticipated which are expected to result in even better agreement with observations derived onboard aircraft. However, it should be kept in mind that a good agreement between model simulations and observations can only be obtained if the model simulations are nudged towards meteorological analyses. It can be expected that comparison with free running model simulations would show larger differences. Further, the results are also limited by the accuracy of the meteorological analyses, e.g. resolving small-scale temperature fluctuations and mountain waves will still be problematic even when a T255 resolution is used.

## 5 Conclusions

In this study, an overview of the chemistry and dynamics of the Arctic winter 2015/2016 as simulated with EMAC was given. The EMAC simulations were performed with a T106L90 resolution and nudged toward ECMWF operational analyses. Chemical-dynamical processes such as denitrification, dehydration and ozone loss were investigated and comparisons to satel-

lite observations by the Aura/MLS as well as to airborne measurements with GLORIA performed onboard of HALO were shown.

From the EMAC simulation we derive a maximum polar stratospheric O<sub>3</sub> loss of ~2 ppmv or ~~100~~117 DU in terms of column in mid March (averaged over 70-90°N). Note that we did not use equivalent latitudes here since separation between chemical and dynamical processes is achieved via the passive O<sub>3</sub> tracer. On equivalent latitudes the same amount of ozone loss in terms of mixing ratio is derived while in terms of column loss ozone loss is 10% less (103 DU). The stratosphere was denitrified by about ~~84.8~~ ppbv HNO<sub>3</sub> and dehydrated by about ~~40.6-1~~ ppmv H<sub>2</sub>O in mid to end of February. In agreement with the analyses of Aura/MLS observations by Manney and Lawrence (2016) we find that ozone loss was quite strong in 2015/2016, but not as strong as in 2010/2011. Denitrification and dehydration on the other hand were so far the strongest observed in the Arctic stratosphere.

Comparison of trace gas distributions of HNO<sub>3</sub>, ClO and O<sub>3</sub> shows that the EMAC simulations nudged toward ECMWF operational analyses generally reproduce well the Aura/MLS observations during the Arctic winter 2015/2016. However, there are some differences between the EMAC simulations and observations which need sensitivity studies in the future to improve the agreement between the model simulations and observations. In the EMAC simulation ~~the~~ HNO<sub>3</sub> is slightly underestimated (by about 1 ppbv). Larger differences are found in the area of denitrification which could be related to the partitioning between STS and NAT in the model. The observed increase in ~~ClO~~ ClO at the beginning of the winter is simulated later with EMAC. ~~Considering ClO<sub>x</sub> we found that activation of chlorine occurs in EMAC. Since the enhancement in modelled ClO<sub>x</sub> is found roughly at the same time as in the observations and that the difference the increase in ClO is therefore probably rather caused by the partitioning of the chlorine species than by a too late activation of chlorine observed by MLS, the disparity in the behaviour of modelled and measured ClO may arise from chlorine activation being delayed in the model due to inaccuracies in the partitioning between chlorine species at high solar zenith angles.~~

The comparison to GLORIA measurements shows that EMAC simulations nudged toward ECMWF operational analyses can reproduce the observations. Further, this comparison shows that, though EMAC is a climate model, EMAC simulations can be applied in support of aircraft campaigns and that these simulations provide a valuable data set not only for flight analyses but also for measurement - model intercomparisons.

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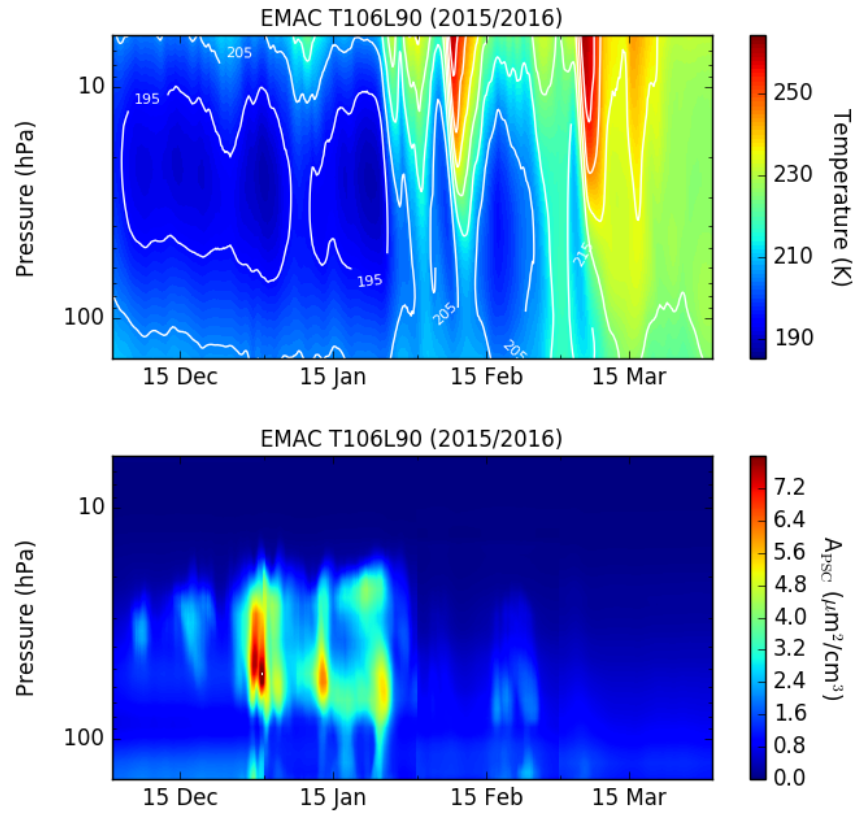
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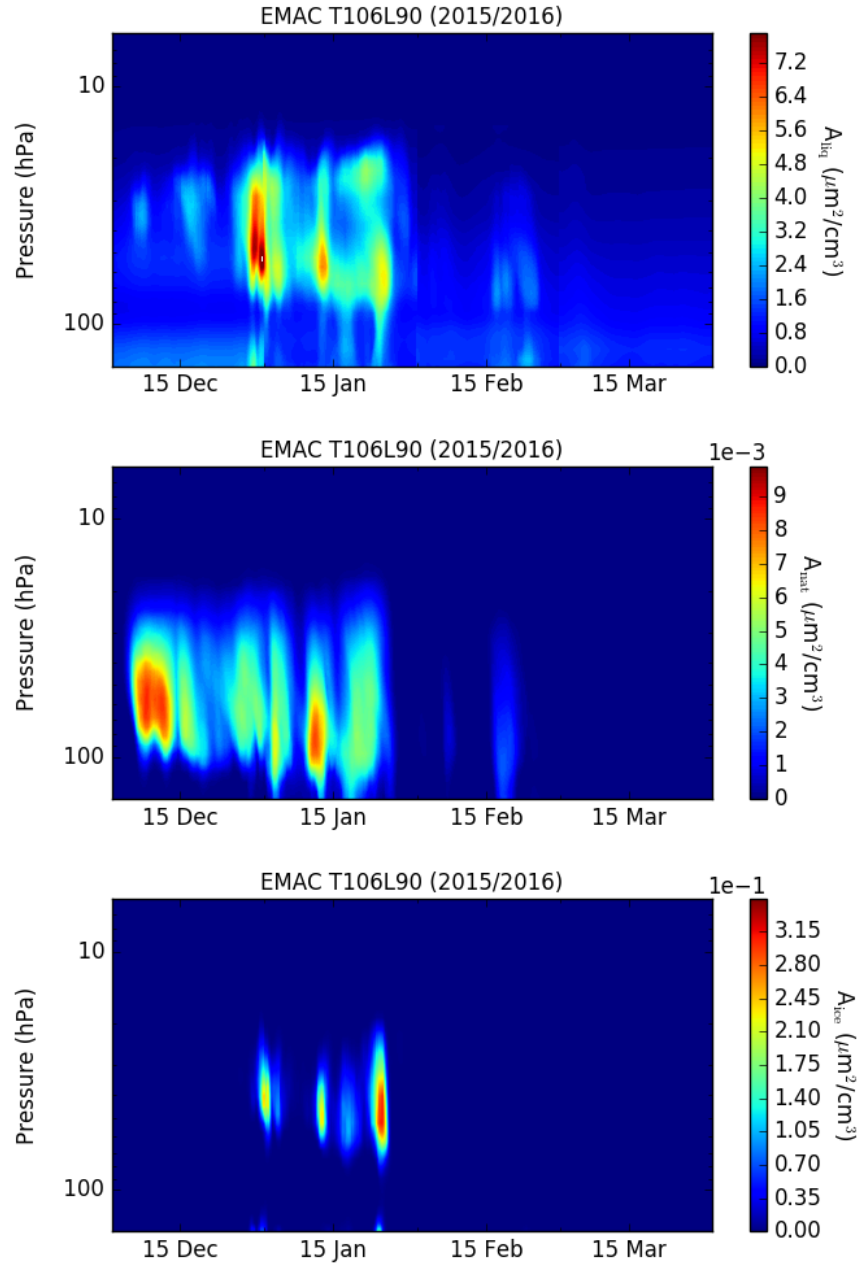
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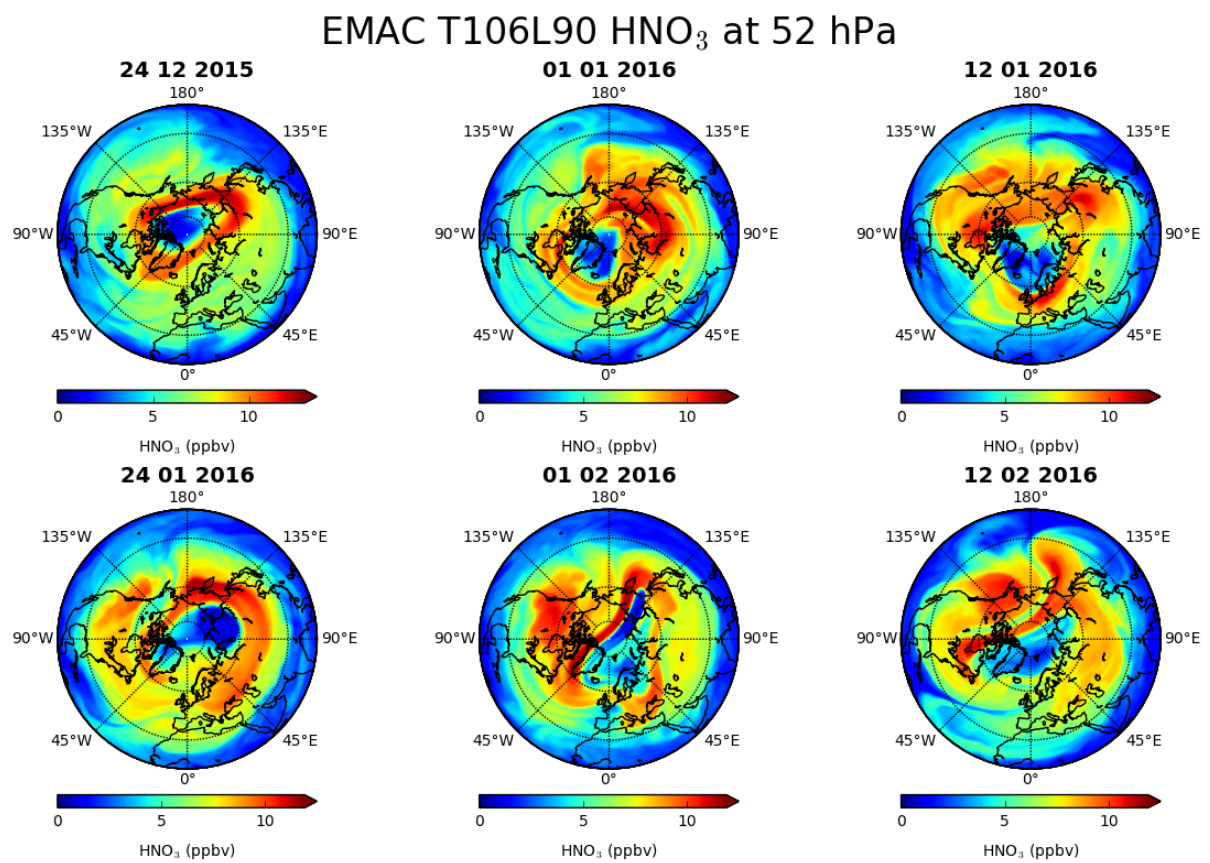
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**Figure 1.** Temporal evolution of temperature and surface area density of PSC particles (liquid + solid) at northern high latitudes (70-90°N) as function of pressure during the Arctic winter 2015/2016 as simulated with EMAC T106L90.

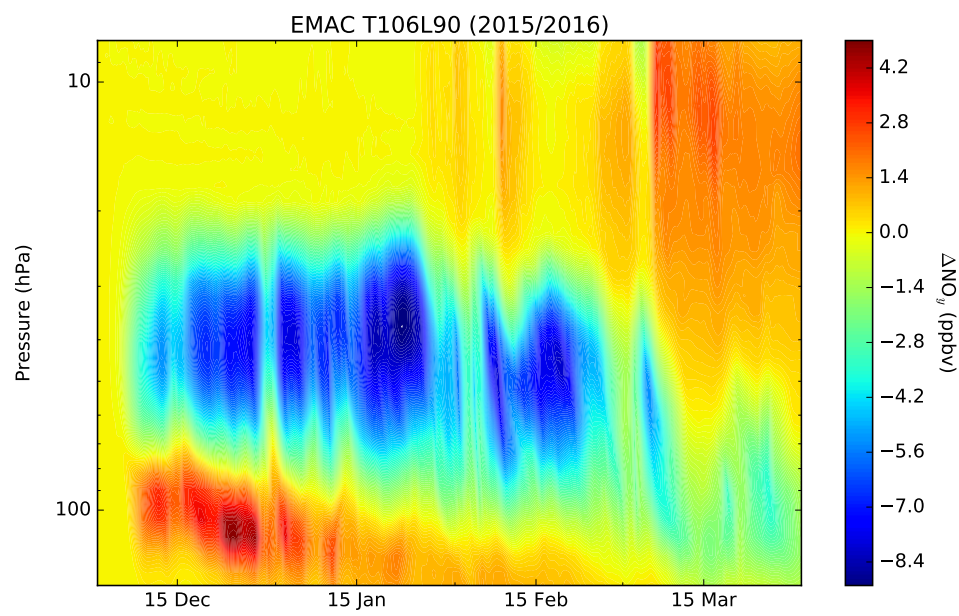


**Figure 2.** Temporal evolution of surface area density of STS (top), NAT (middle) and ice (bottom) particles at northern high latitudes (70-90°N) as function of pressure during the Arctic winter 2015/2016 as simulated with EMAC T106L90. Note the differences in the color bar for  $A_{\text{liq}} (\mu\text{m}^2/\text{cm}^3)$ ,  $A_{\text{NAT}} (10^{-3} \mu\text{m}^2/\text{cm}^3)$  and  $A_{\text{ice}} (10^{-1} \mu\text{m}^2/\text{cm}^3)$ .



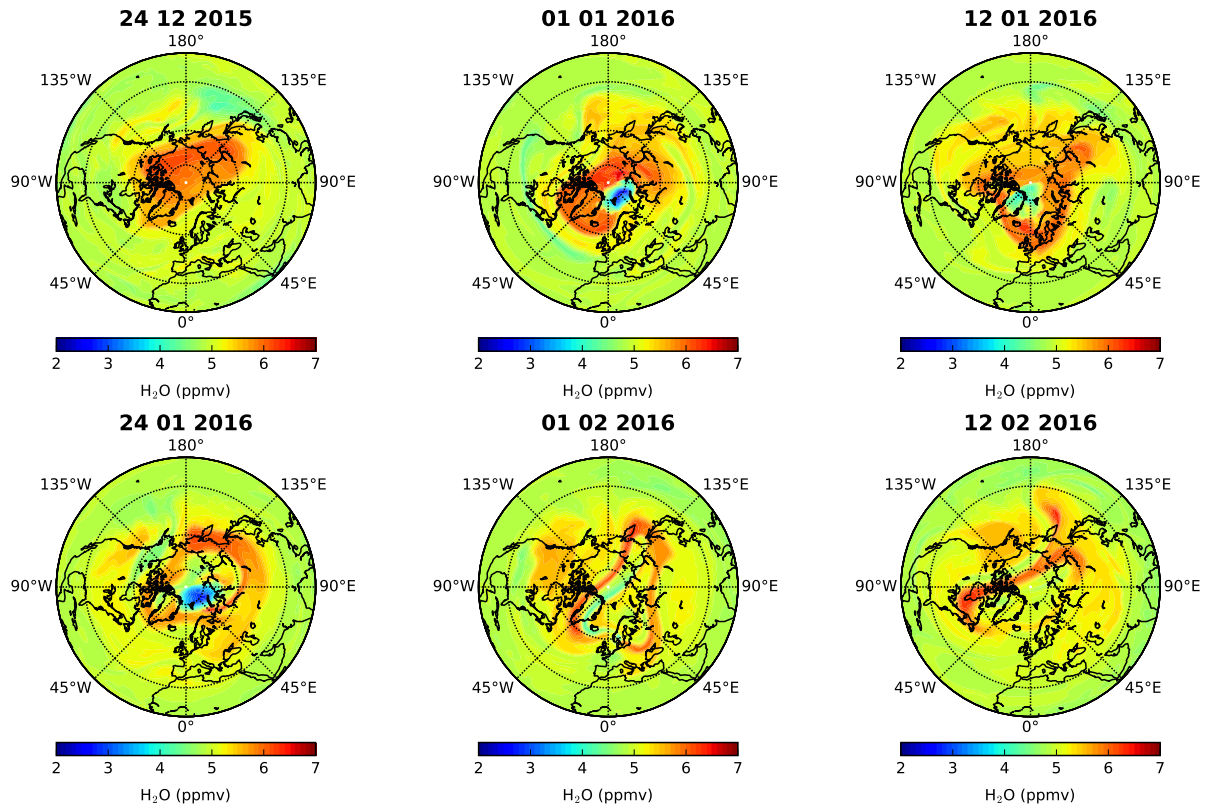
**Figure 3.** Distribution of HNO<sub>3</sub> as simulated with EMAC T106L90 at 52 hPa on certain dates between 24 December 2015 and 12 February 2016.



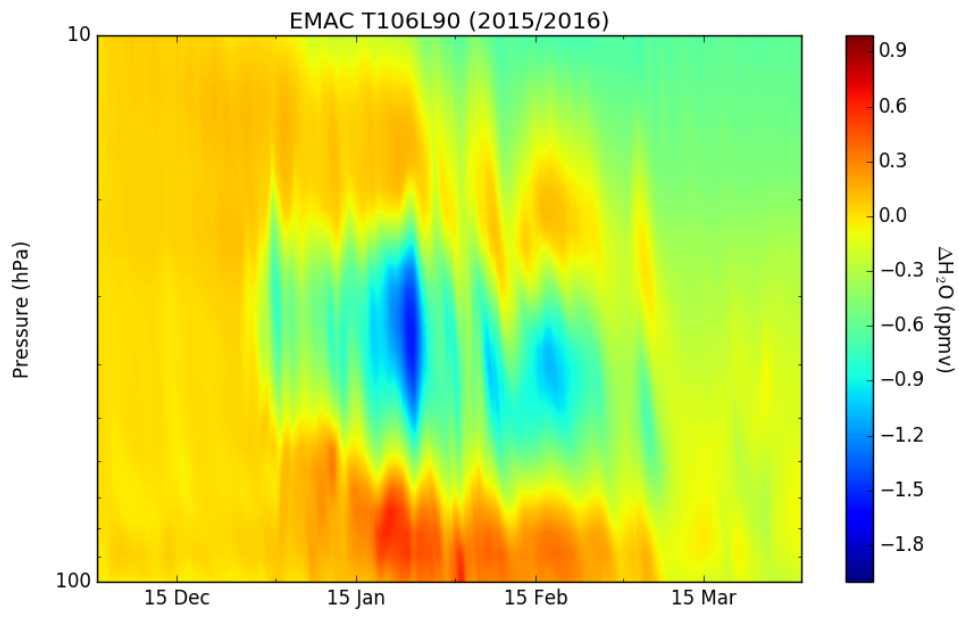


**Figure 4.** Redistribution of  $\text{NO}_y\text{-NO}_y$  ( $\Delta\text{NO}_y$ ) simulated with EMAC T106L90 (difference of  $\text{NO}_y\text{-NO}_y$  and the passive tracer  $\text{NO}_y^*$  ( $\Delta\text{NO}_y = \text{NO}_y - \text{NO}_y^*$ ), averaged over 70-90°N).

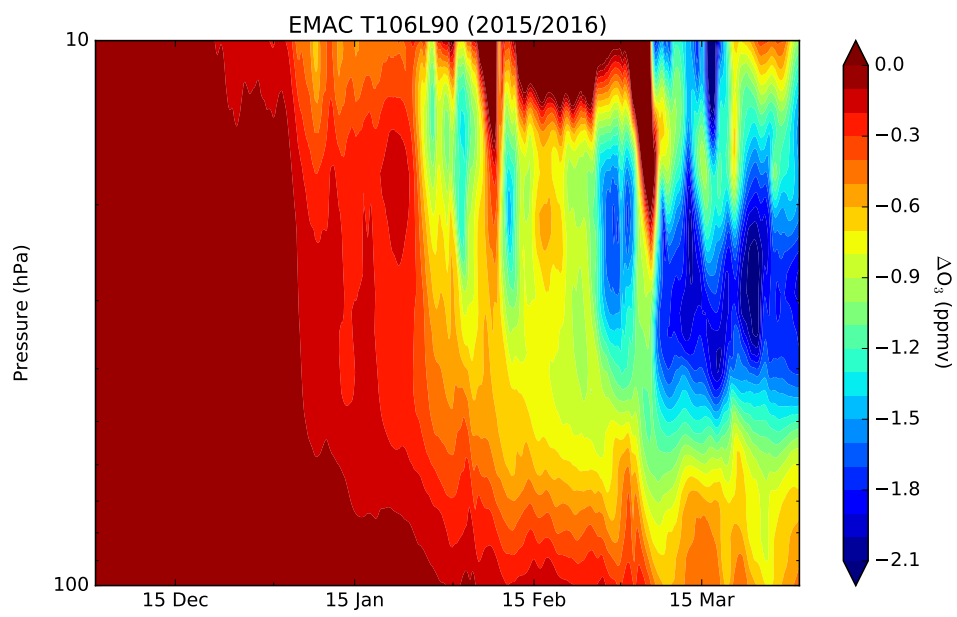
## EMAC T106L90 H<sub>2</sub>O at 52 hPa



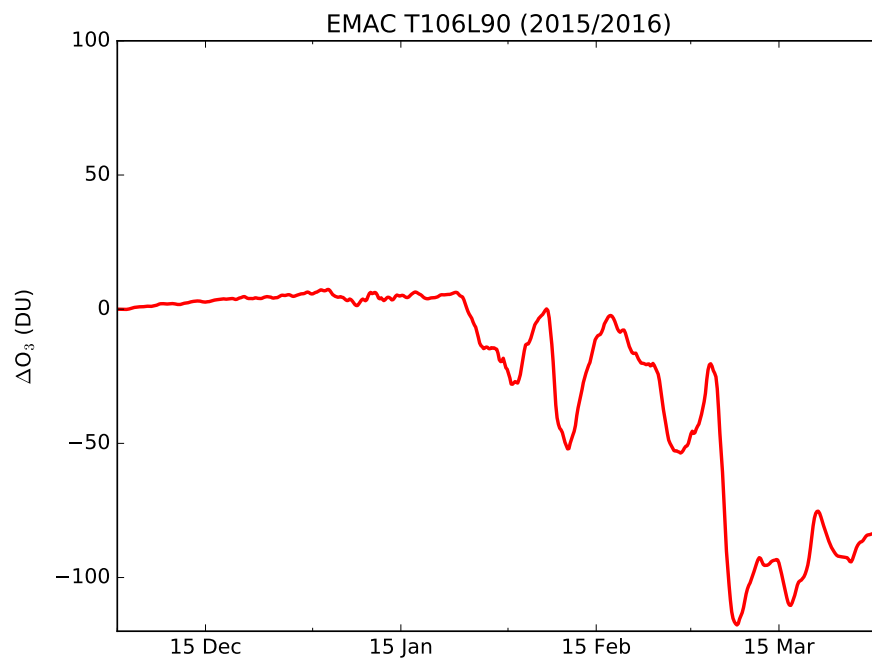
**Figure 5.** Distribution of H<sub>2</sub>O as simulated with EMAC T106L90 at 52hPa on certain dates between 24 December 2015 and 12 February 2016.



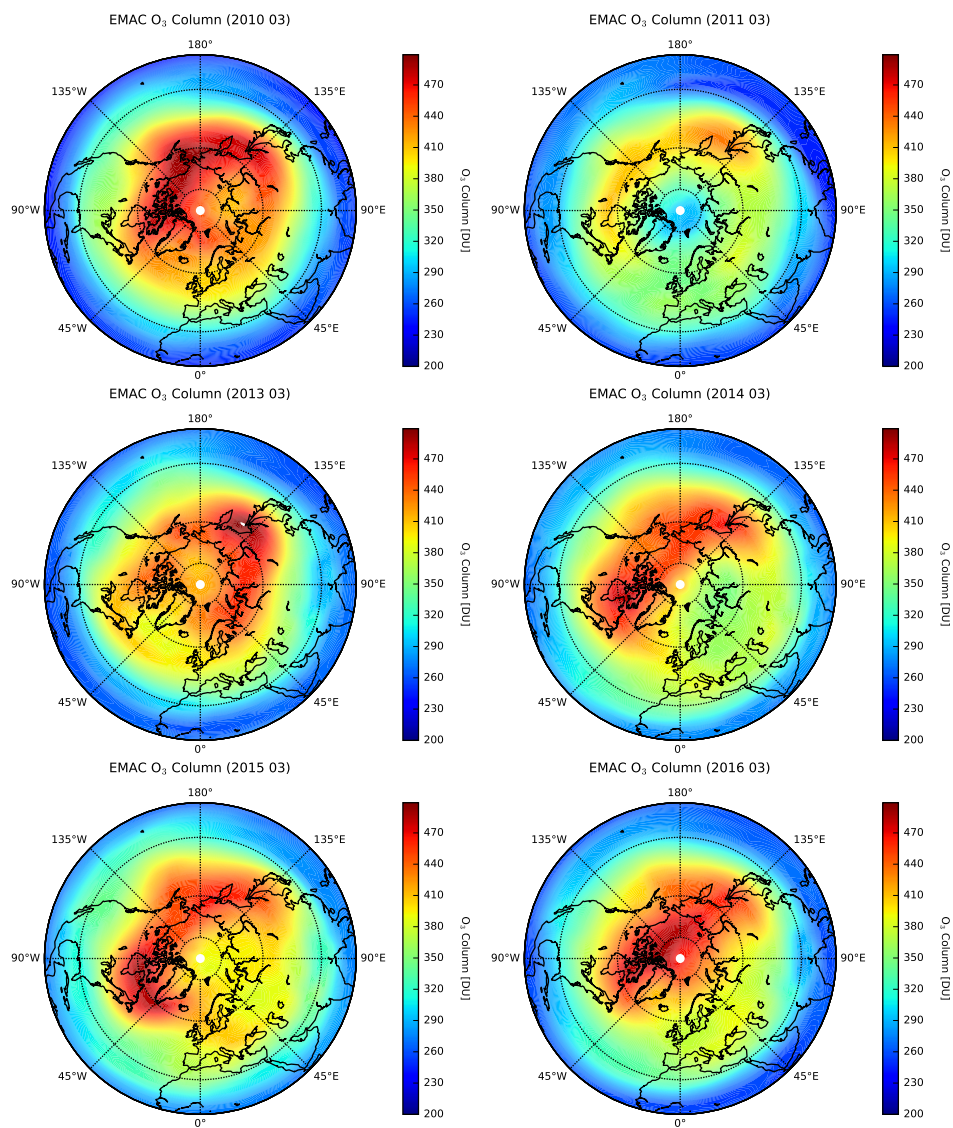
**Figure 6.** Redistribution of  $\text{H}_2\text{O}$  ( $\Delta\text{H}_2\text{O}$ ) as simulated with EMAC T106L90 at northern high latitudes ( $70\text{--}90^\circ\text{N}$ ) as function of pressure during the Arctic winter 2015/2016 (difference of total hydrogen ( $2\text{CH}_4 + \text{H}_2\text{O}$ ) at time  $t$  and total hydrogen at time  $t_0$  ( $t_0 = 1$  December) ( $\Delta\text{H}_2\text{O} = (2\text{CH}_4 + \text{H}_2\text{O})(t) - (2\text{CH}_4 + \text{H}_2\text{O})(t_0)$ )).



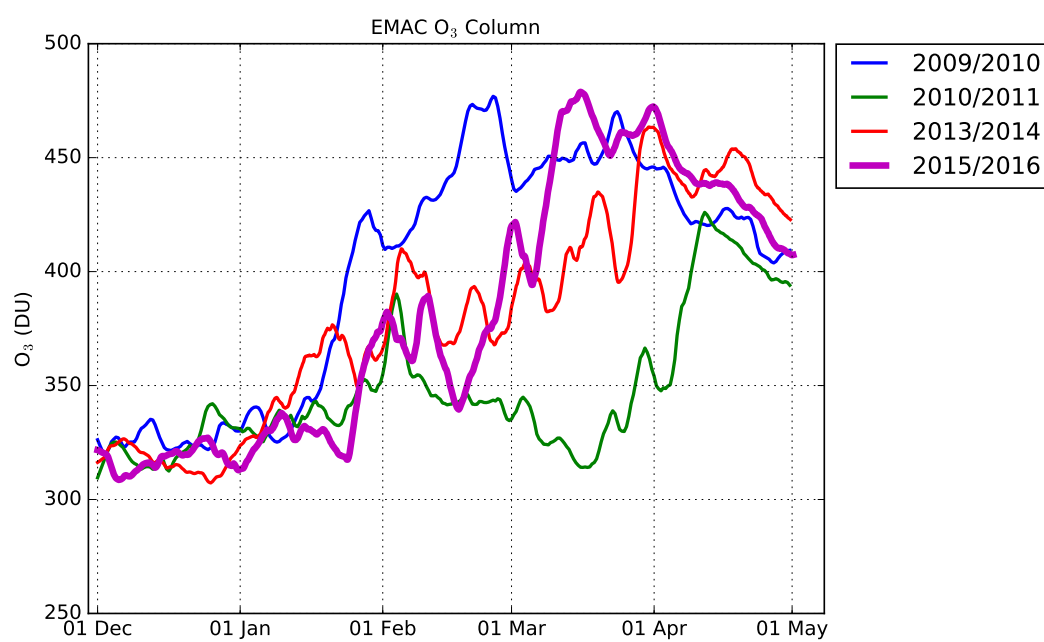
**Figure 7.** Ozone loss ( $\Delta O_3$ ) as simulated with EMAC T106L90 (difference of  $O_3$  and the passive tracer  $O_3^*$  ( $\Delta O_3 = O_3 - O_3^*$ ), averaged over 70-90°N) as function of time and pressure for the Arctic winter 2015/2016.



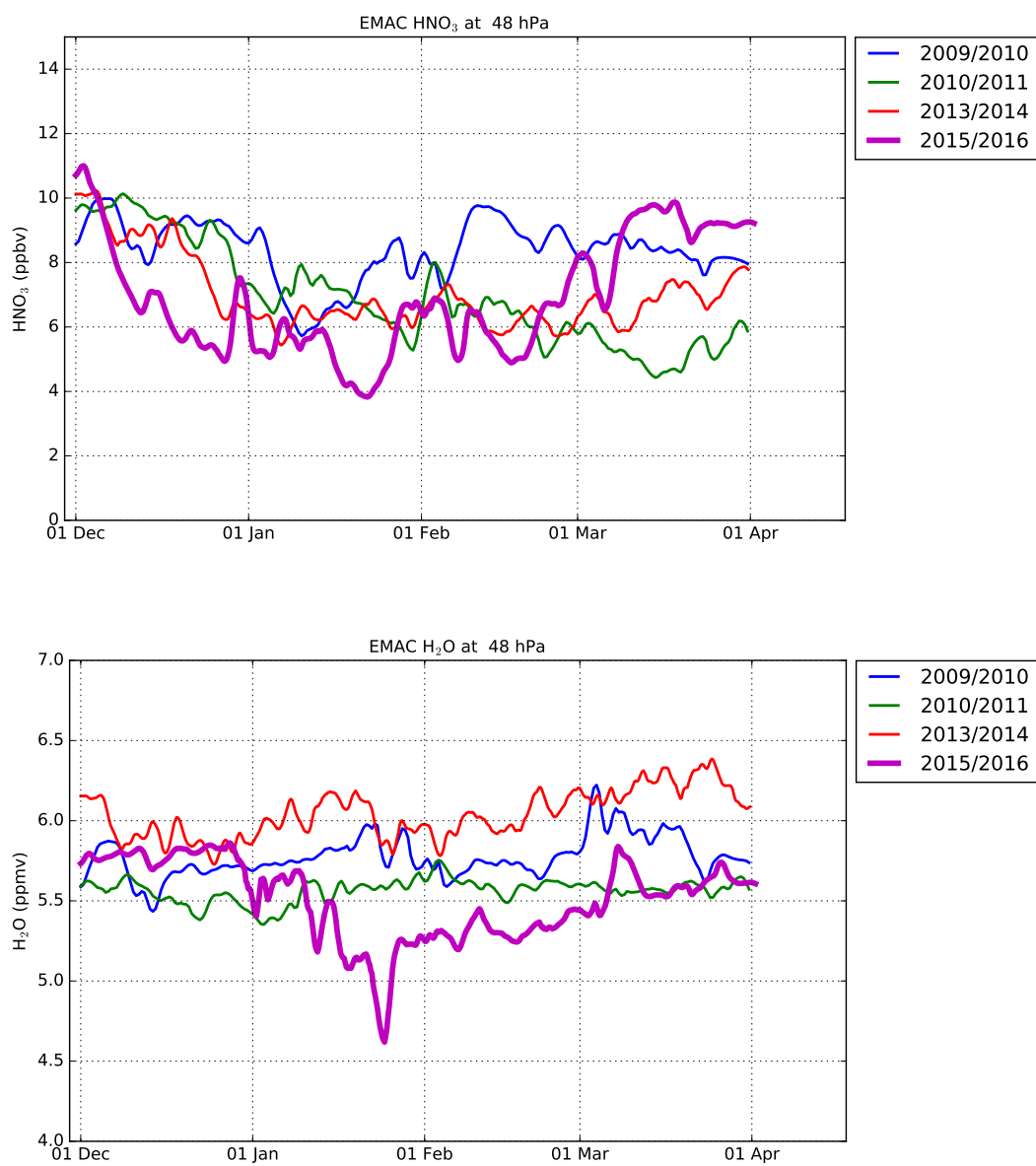
**Figure 8.** Total column ozone loss ( $\Delta O_3$ ) from EMAC T106L90 (70-90°N) for the Arctic winter 2015/2016. Total column loss has been derived from the difference between the active tracer  $O_3$  and the passive tracer  $O_3^*$  ( $\Delta O_3 = O_3 - O_3^*$ ).



**Figure 9.** Total ozone column (March monthly mean) from EMAC for the years 2010-2016 (Results from the EMAC T42L90 Simulation are shown here).

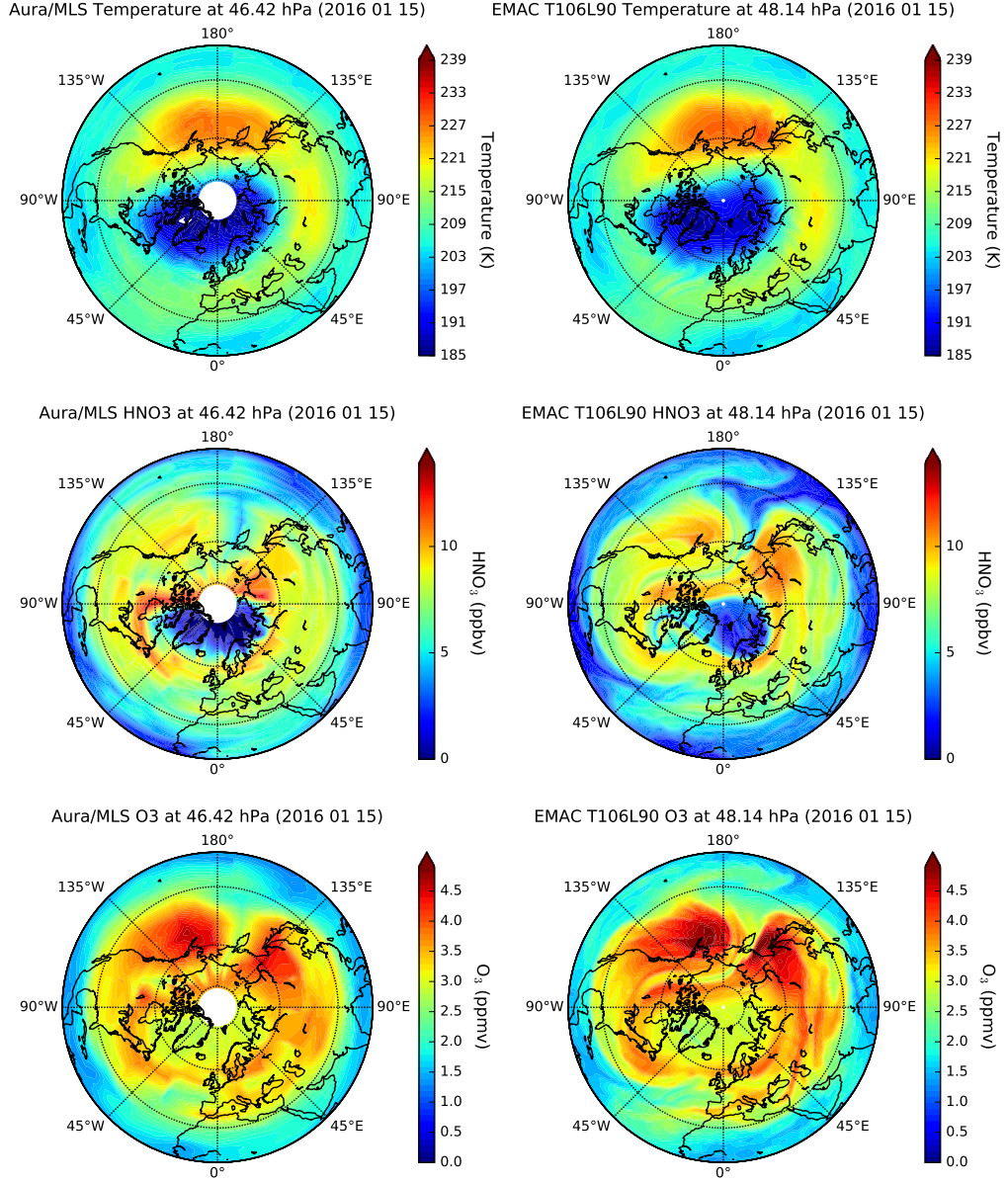


**Figure 10.** Ozone (O<sub>3</sub>) column time series for the Arctic winters 2009/2010 (blue), 2010/2011 (green), 2013/2014 (red) and 2015/2016 (magenta) averaged over 60-90°N (Results from the EMAC T42L90 Simulation are shown here).

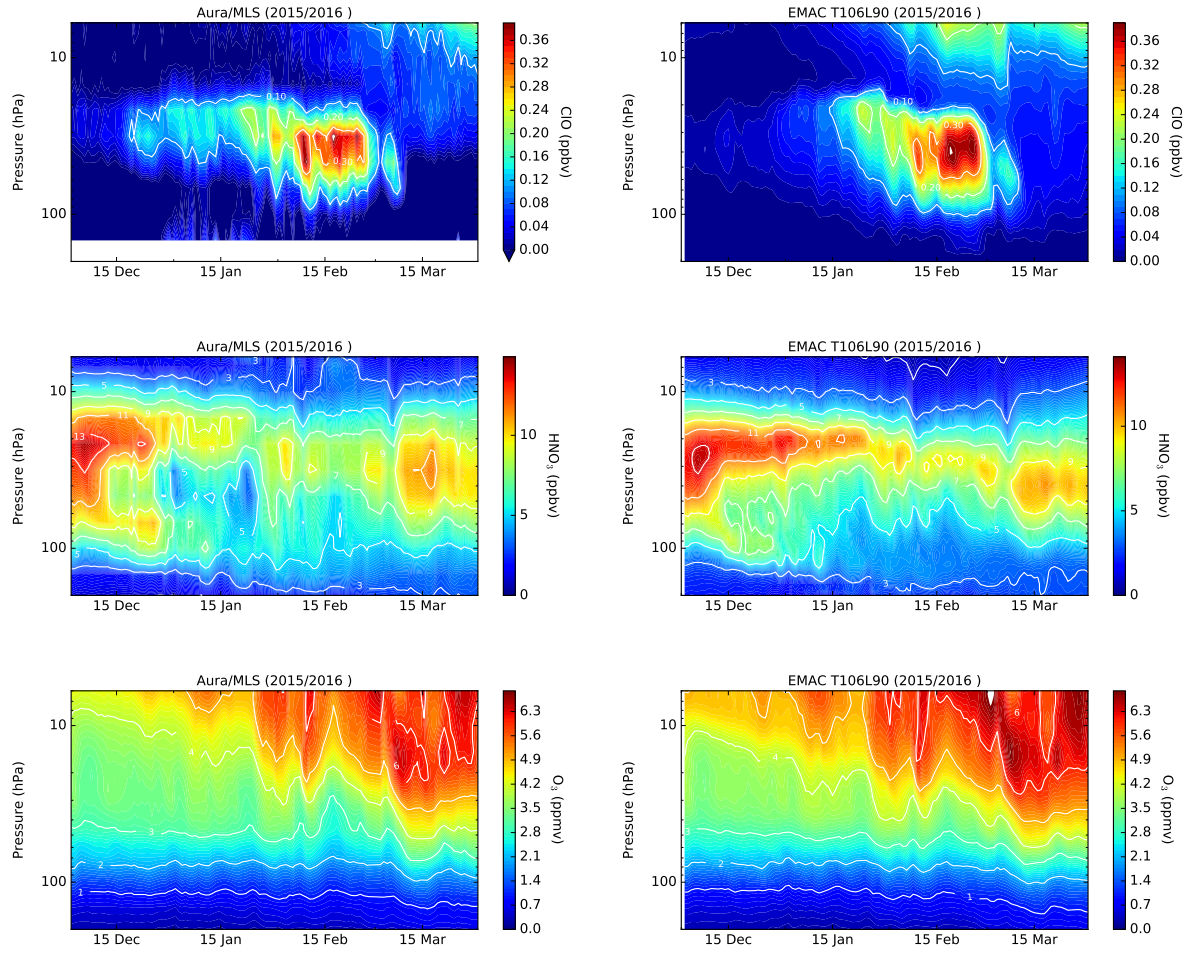


**Figure 11.** Tracer time series of HNO<sub>3</sub> and H<sub>2</sub>O for the Arctic winters 2009/2010 (blue), 2010/2011 (green), 2013/2014 (red) and 2015/2016 (magenta) at 48 hPa averaged over 70-90°N (Result from the T42L90 Simulation are shown here).

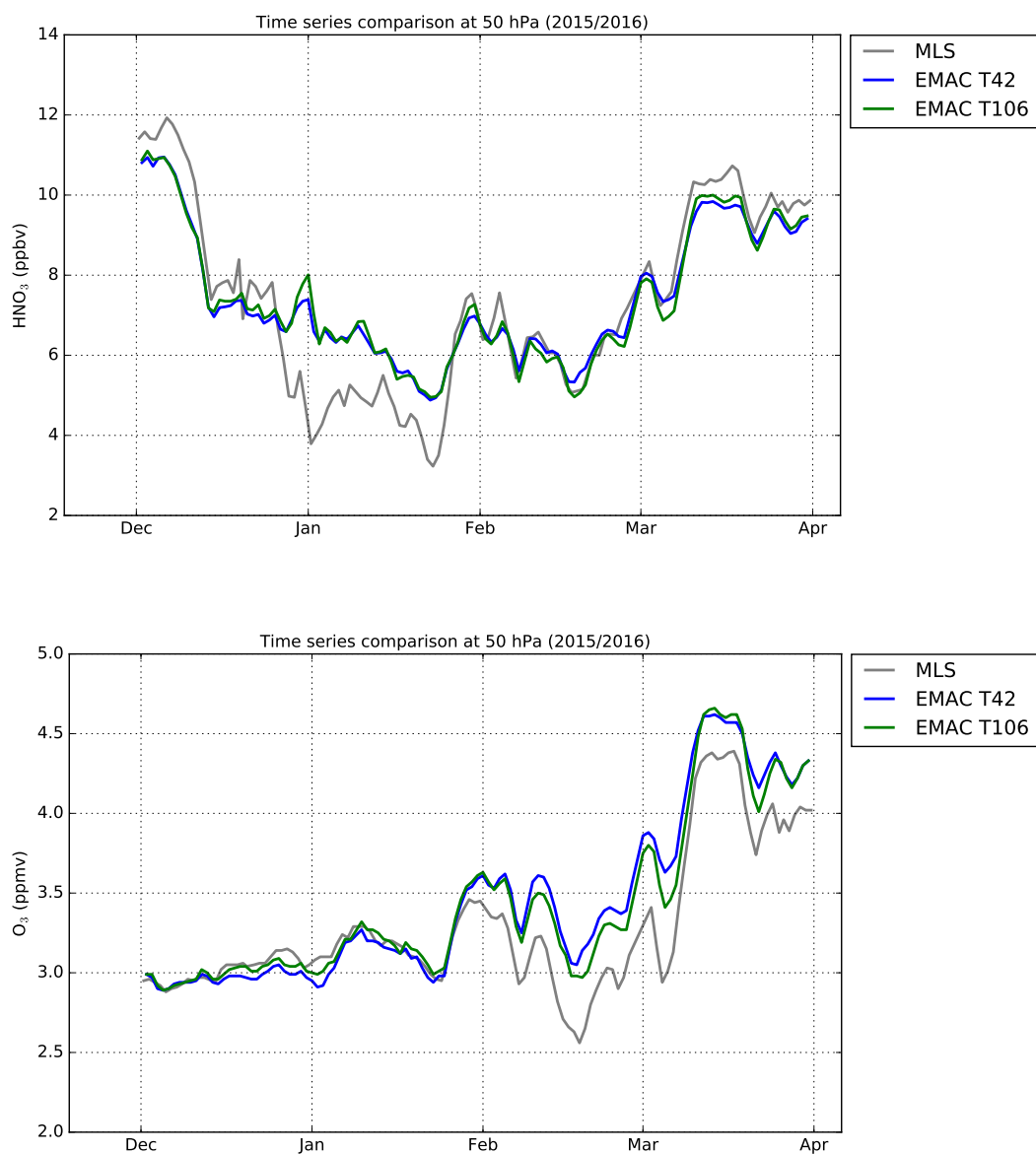




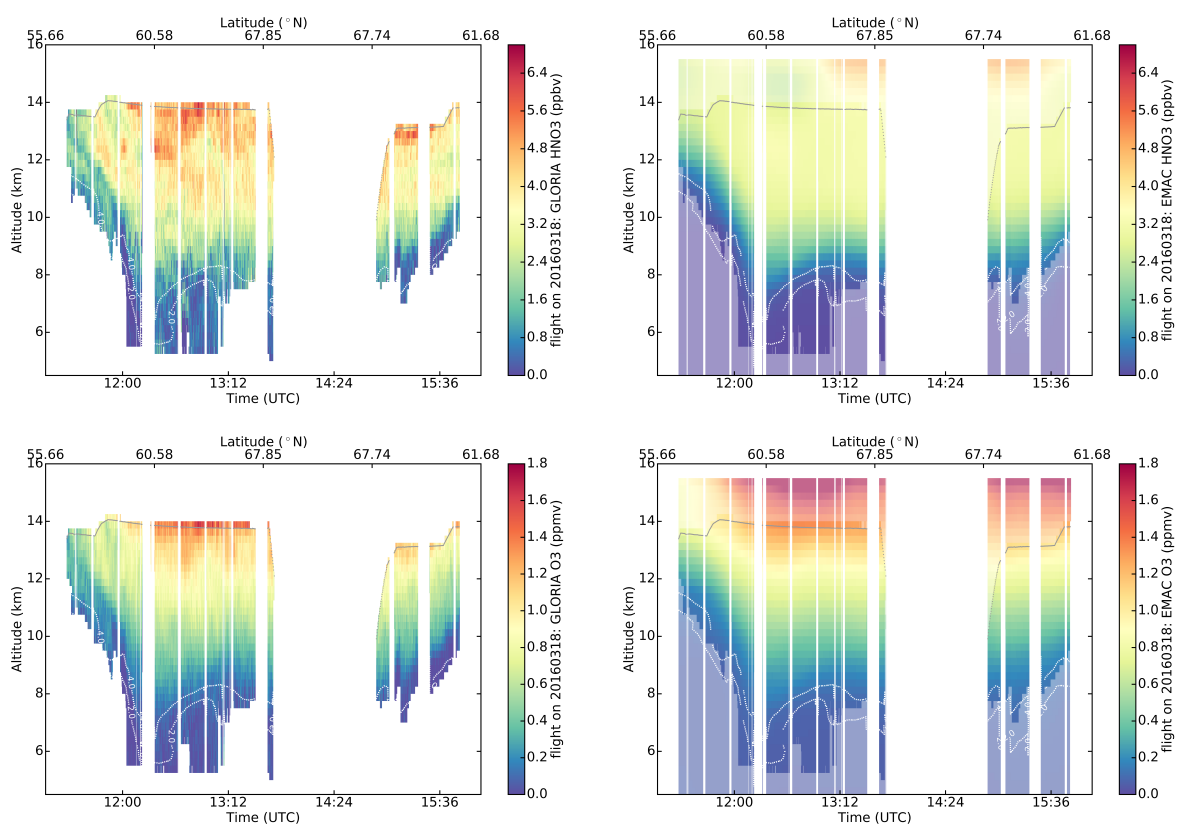
**Figure 12.** Temperature, HNO<sub>3</sub>, O<sub>3</sub> distribution measured by Aura/MLS (left) and simulated by EMAC T106L90 (right) at ~50 hPa on 15 January 2016.



**Figure 13.** Temporal evolution of daily mean  $\text{ClO}$ ,  $\text{HNO}_3$  and  $\text{O}_3$  at northern high latitudes (averaged over  $70\text{--}90^\circ\text{N}$ ) as function of pressure as observed by Aura/MLS (left) and simulated by EMAC T106L90 (right) for the Arctic winter 2015/2016 (EMAC SORBIT output used).



**Figure 14.** Time series of  $\text{HNO}_3$  and  $\text{O}_3$  from Aura/MLS measurements (grey) and from the EMAC T42L90 (blue), EMAC T106L90 (green) at  $\sim 50$  hPa averaged over  $70\text{--}90^\circ\text{N}$  (EMAC SORBIT output used).



**Figure 15.** GLORIA HNO<sub>3</sub> and O<sub>3</sub> observations during flight 21 on 18 March 2016 (left) and EMAC T106L90 output along the flight track (right).