Author's response

Case study of ozone anomalies over northern Russia in the 2015/2016 winter: Measurements and numerical modeling

By Yury M. Timofeyev, Sergei P. Smyshlyaev, Yana A. Virolainen, Alexander S. Garkusha, Alexander V. Polyakov, Maxim A. Motsakov, Ole Kirner

Abstract. Episodes of extremely low ozone columns were observed over the territory of Russia in the Arctic winter of 2015/2016 and the beginning of spring 2016. We compare total ozone columns (TOC) from different remote sensing techniques (satellite and ground-based observations) with results of numerical modelling over the territory of the Urals and Siberia for this period. We demonstrate that the provided monitoring systems (including the new Russian Infrared Fourier Spectrometer IKFS-2) and modern 3-dimensional atmospheric models can capture the observed TOC anomalies. However, the results of observations and modelling show differences of up to 20-30% in TOC measurements. Analysis of the role of chemical and dynamical processes demonstrates that the observed short-term TOC variability is not a result of local photochemical loss initiated by heterogeneous halogen activation on particles of polar stratospheric clouds that formed under low temperatures in the mid-winter.

Reply to Topical Editor

Dear Topical Editor,

Thank you for your comments on the paper and constructive recommendations. We have carefully checked the manuscript and fixed all typos found with an assistance of the English native speaker. Following we mention how the manuscript has been changed after corrections.

Thank you again for taking the time to review our manuscript.

With respect,

Yu.M.Timofeyev, S.P.Smyshlyaev, Ya.A.Virolainen, A.S.Garkusha, A.V.Polyakov, M.A. Motsakov, O.Kirner.

Reply to reviewer 1

Dear Referee,

Thank you for your comments on the paper and constructive recommendations. We have thoroughly checked the manuscript and tried to fix the potential typos and clarify the meanings. In particular, you are absolutely right regarding the sentence at section 3, page 4, lines 10-11. We tried to assess the differences between the CCM response and the CTM response. At the revised version we corrected this sentence. At the end of section 3, page 5, lines 20-24 we presented conclusion about this comparison.

"In general, the comparison of the EMAC and RSHU simulation, which both use the ERA-Interim reanalysis, and OMI, demonstrate that as well the interactive coupling between dynamical and chemical processes, as the different spatial resolutions do not have a principal influence on the quality of the representation of the short-term column ozone variability at local points. Both models show a good qualitative agreement with the OMI satellite observations, while for some local points and time periods the best agreement is shown by the EMAC CCM, and for others by the RSHU CTM".

Following we mention how the manuscript has been changed.

Thank you again for taking the time to review our manuscript.

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Yu.M.Timofeyev, S.P.Smyshlyaev, Ya.A.Virolainen, A.S.Garkusha, A.V.Polyakov, M.A. Motsakov, O.Kirner.

Reply to reviewer 2

Dear Referee,

Thank you for taking the time to review our manuscript and your positive decision.

With respect,

Yu.M.Timofeyev, S.P.Smyshlyaev, Ya.A.Virolainen, A.S.Garkusha, A.V.Polyakov, M.A. Motsakov, O.Kirner.

REVISED PAPER WITH CHANGES MARKED

Case study of ozone anomalies over northern Russia in the 2015/2016 winter: Measurements and numerical modeling

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Abstract. Episodes of extremely low ozone columns were observed over the territory of Russia in the Arctic winter of 2015/2016 and the beginning of spring 2016. We compare total ozone ~~column~~ columns (TOC) ~~obtained using~~ from different remote sensing techniques (satellite and ground-based observations) and results of numerical modelling over the territory of the Urals and Siberia for ~~the above~~ this period. We demonstrate that the provided monitoring systems (including the new Russian Infrared Fourier- spectrometer IKFS-2) and modern 3-dimensional atmospheric models ~~are able to~~ can capture the observed TOC anomalies. However, the results of observations and modelling show ~~discrepancies~~ differences of up to 20-30% in TOC measurements. Analysis of the role of chemical and dynamical processes demonstrates that observed short-term TOC variability is not a result of local photochemical loss initiated by heterogeneous halogen activation on particles of polar stratospheric clouds that formed under low temperatures in the mid-winter.

1 Introduction

~~Abnormally~~ Extremely low values of total ozone columns (TOC) were recorded in January-February 2016 in the polar region of the Northern Hemisphere (Zvyagintsev et al., 2016; Manney and Lawrence, 2016). Observed low values were recorded long before the beginning of spring, when chemical destruction of ozone occurs periodically in the Northern Hemisphere as a result of a strong vortex and the long existence of polar stratospheric clouds (PSCs) (Manney et al., 2011). Early TOC anomalies ~~in the TOC~~ during the winter 2015/2016 ~~winter make one wonder~~ leads to the question whether chemical ozone destruction ~~on the surface of polar stratospheric clouds~~, for which a long existence of PSCs is necessary, ~~to be~~ is completely responsible for the observed anomalies, or also other factors, especially dynamic ones, ~~would have a greater~~ have an important effect on the observed features. The analysis of the meteorological conditions during the winter 2015/2016 ~~winter~~ showed that during this period the lower polar stratosphere was extremely cold, which created a potential for a record ozone depletion in the spring of 2016, but a strong sudden stratospheric warming in early March 2016 destroyed the polar vortex and prevented formation of a spring ozone anomaly (Manney and Lawrence, 2016). Nevertheless, during the entire winter of 2015/2016 in the northern part of Russia, the ozone content was lower than in previous years, and the depth of short-term ozone anomalies in January and February 2016 was comparable to the depth of the ozone mini-holes of the spring of 2011.

Over recent decades, investigation of total ozone time-scale variations demonstrated regular occurrence of ~~the spring deep~~ a strong ozone depletion over the Antarctic region in spring. This phenomenon ~~was~~ is called the “ozone hole”. In the Northern Hemisphere, similar to the ~~southern hemisphere~~ Southern Hemisphere ~~polar column ozone loss~~ the ozone loss in polar spring usually has been observed on smaller spatial scales as well as over shorter time intervals~~, for example in 2011~~ (Manney et al., 2011; Balis, 2011). For episodes with extremely low TOCs (less than 220 Dobson units) such as in the spring of 2011 these phenomena were called “ozone mini-holes” (Millan and Manney, 2017). Observation and prediction of the occurrence of episodes with ~~abnormally~~ extremely low ozone ~~content~~ columns close to “mini-holes” is both crucial for the investigation of its nature and for the prediction of potential increase of UV-radiation on the Earth’s surface. Unusually sharp and repetitive TOC loss was observed over the territory of the Urals and Siberia in the first quarter of 2016. In some cases, the TOC loss reached 40-50% in comparison with climatic values (Zvyagintsev et al., 2016).

In this paper, we study the episodes of low TOCs over some Russian stations in January and February 2016 based on remote sensing observations and results of numerical modeling.

2 Total ozone column measurements over Russia during winter 2016

Monitoring of the total ozone level is provided by various ground-based remote sensing systems (Brewer and Dobson spectrophotometers, M-124 filter ozonometers, DOAS, Microwave and IR methods, lidar measurements) and by various satellite systems (https://disc.gsfc.nasa.gov/; Timofeyev and Vasiliev, 2008; Staehelin et al., 2001). According to regular extensive validation programs (Balis et al., 2007; Boynard et al. 2016; Garkusha et al., 2017), total ozone measurement errors can be from 1–2 to 10% depending on the method, device, time and place of the measurements.

We analyzed ~~the~~ total ozone data of the first quarter of 2016, obtained by the basic Russian ground-based ozonometer M-124 and the satellite instruments OMI and SBUV (recording outgoing solar reflected and scattered spectra of UV radiation), IASI and a new Russian instrument IKFS-2, (recording outgoing atmospheric thermal IR radiation). The features of ~~such~~ satellite instruments as OMI, SBUV and IASI and the Russian ground-based ozonometer M-124 are well-known (Balis et al. 2007; Bhartia et al., 2013; Kroon et al., 2008; Viatte et al., 2011; Boynard et al., 2016). Independent assessments of TOC measurement errors ~~(Virolainen et al., 2017)~~ showed values of 3.3–4.1 % for IASI, 2.0–3.5 % for M-124, and 1.9–2.1 % for OMI instruments (Virolainen et al., 2017). The infrared Fourier-transform spectrometer IKFS-2 on-board the satellite “Meteor-M N2” was launched in July 2014. IKFS-2 was preeminently designed for temperature-humidity sounding of the atmosphere and for measurement of ~~some climatically important~~ climate relevant gases, including ozone. Detailed description of the characteristics of IKFS-2 is given by Golovin et al. (2014). The advantage of the IKFS-2 and IASI instruments is its ability to conduct measurements in the absence of sunlight, which is especially important ~~for polar regions~~ in Polar Regions, where ~~the polar night exists for a long time,~~ during polar night ~~which the work of~~ solar radiation measurement ~~devices is~~ are impossible.

The description of the IKFS-2 measurement interpretation methodology, as well as ~~estimates~~ an estimation of the errors ~~in~~ of TOC measurements ~~of TOCs~~ for cloudless and cloudy atmosphere, are given in ~~the works (~~Garkusha et al., (2017); and Garkusha et al., (2018). The technique of interpretation, based on the method of artificial neural networks (ANN), is described in detail in ~~the paper (~~Garkusha et al., (2017). The approximation of the solving operator of the inverse problem by a three-layer perceptron is used~~,~~. The activation function of the neurons of the hidden layer is the hyperbolic tangent, ~~the output neuron~~ is linear. The main feature of the technique is the use as predictors of principle components (PC) of the spectra measured by IKFS-2. The set of predictors consists of 25 PC of the entire measured spectrum (660-2000 cm^{-1}), 50 PC only ~~of~~ for the ozone absorption band and the measurement zenith angle. For ANN training, the results of TOC measurements ~~using~~ of the OMI instrument ~~from~~ on the AURA satellite were used (McPeters et al, 2015). Estimates of the error in determining the TOCs with IKFS-2 are on ~~the~~ average in the range of 2-6%. The largest differences (up to 10%) are observed in the ~~southern~~ Southern polar latitudes in the presence of an ozone hole over Antarctica.

In the first quarter of 2016, three short-term periods with significantly lower daily TOCs compared to the climatologically average values for the period from 1979 to 2017, were registered over the territory of Russia. TOCs decreases reached: 39–52% (in 26.01–01.02 over the Northern regions of the Urals and Siberia), 30–50% (in 20.02–03.03 over Northern Siberia), 27-39% (in 09–19.03 over Central Siberia) of daily average values of column ozone (191–257, 227–321, 257–321 DU, for these three periods~~, respectively~~) (Zvyagintsev et al., 2016). Extremely low winter TOC values (episodically less than mini-hole threshold) were observed over the ~~northern~~ Northern regions of the Urals and Siberia for the first time. During January 27–31 TOCs smaller than 220 DU were recorded at Russian ozonometric network stations using M-124 measurements (Pechora, 65°N, 57°E; Khanty-Mansiysk, 61°N, 69°E; Turukhansk, 66°N, 88°E; Round, 64°N, 100°E) and by OMI devices on the board of Aura satellite.

Figure 1 taken from ~~(Garkusha et al 2018)~~ Garkusha et al. (2018) depicts the spatial distribution of TOCs in February 23-27, 2016, based on measurements of the two instruments of the same type - IKFS-2 and IASI. The figure shows good agreement between these two independent satellite measurements.

Figure 2 presents the evolution of TOCs measured at three ground-based observational stations: Khanty-Mansyisk (61°N, 69°E), Tura (61° N, 100° E), ~~Pechora, and Khanty-Mansyisk~~. and Pechora (65°N, 57°E). The comparison allows us to draw the following conclusions:

(a) All instruments and measurement methods generally provide a good description of the main features of TOC time variations, including observed short-term ozone loss. For the ~~whole~~ complete period ~~of comparison~~, the averaged differences ~~in the results obtained by~~ between different types of measurements ~~in most cases~~ are about 1–5%, with standard deviations of 3–8%.

(b) The only exception ~~is~~ are the IASI measurements in Khanty-Mansiysk and Tura, for which the standard deviations of the differences with ground-based measurements ~~in the first quarter of 2016~~ of M-124 reach 12% in the first quarter of 2016. In addition, ~~at the Tura station,~~ IASI data overstates the M-124 measurements by 11% on average at the Tura station.

(c) All satellite data overestimate the values of TOC in comparison with ground-based measurements of M-124 during the short-term periods of ozone loss. This is~~, possibly,~~ probably ~~due to the fact that~~ because the optimal retrieved solution is not constructed ~~not~~ only from atmospheric radiation spectra that have been measured, but ~~it~~ also ~~employs~~ applies *a priori* information ~~about~~ for the calculation of TOCs. This *a priori* information does not account for a particular ozone profile and may cause distortions in the estimation of the local TOC. To exclude this effect, it is necessary to improve the *a priori* information by making it dependent on the type of ozone profile, characteristic for the season and the region and observations.

3 Comparison of total ozone column measurements and numerical modeling

~~Also relevant to this issue is the comparison of observational data~~ In order to evaluate the observational data, we compare them with ~~the~~ results of numerical modeling. Values of TOC were calculated by two three-dimensional atmospheric chemistry models, which take into account observed variations of meteorological parameters ~~based on re-analysis of the measurement results~~ through using reanalysis for the prognostic variables temperature, vorticity, divergence and surface pressure, in two different ways. We performed simulations with the chemistry-climate model (CCM) ~~EMAC (~~ECHAM/MESSy Atmospheric Chemistry model~~)~~ (EMAC, Jöckel et al., 2006) applying a nudging technique using the ERA-Interim reanalysis (Dee et al., 2011), and with the Russian State Hydrometeorological university chemistry-transport model (RSHU CTM) using directly the meteorological fields of the ERA-Interim or MERRA reanalysis (Smyshlyaev et al., 2017). The motivation for using two different models is to ~~try to~~ assess on the one hand the impact of the interactive coupling between ~~physical~~ dynamical and chemical processes available in the CCM ~~relatively~~, and on the other hand the impact of the given offline meteorological ~~data using~~ reanalysis fields linked to chemical and transport processes used in the CTM. In addition, the models have different spatial resolution, which makes it possible to estimate the effect of model resolution on the comparison with the observations related to the local points.

The EMAC model is a numerical chemistry and climate simulation system that includes tropospheric and middle atmosphere processes (Jöckel et al., 2010). It uses the second version of the Modular Earth Submodel System (MESSy2). The core atmospheric model is the 5th generation European Centre Hamburg general circulation model (ECHAM5, Roeckner et al. 2006). The core model~~,~~ ECHAM5~~,~~ uses a spectral transform technique, the so-called T-value indicating the degree of triangular spectral truncation. For the present study, we applied EMAC (ECHAM5 version 5.3.02, MESSy version 2.52) in T42 resolution; i.e., with a spherical truncation of T42 (corresponding to a quadratic grid of 2.8 x 2.8 degrees, respectively, in latitude and longitude). Vertically, the model resolves the troposphere, stratosphere and lower mesosphere (39 hybrid levels from the surface up to 0.01 hPa, about 80 km). As mentioned ~~We~~ we applied a Newtonian relaxation technique

(Nudging) to our model simulation with the help of the ERA-INTERIM reanalysis data set (Dee et al., 2011) to improve consistence between the simulated and observed temperature and wind fields responsible for the dynamical impact on ozone distribution. A detailed description of the EMAC model and its applications can be found in (Righi et al., 2015, Virolainen et al., 2016) Jöckel et al. (2010), Righi et al. (2015), or Virolainen et al. (2016).

The global RSHU CTM is based on the Institute of Numerical Mathematics and Russian State Hydrometeorological University (INM RAS – RSHU) CCM (Galin et al., 2007), but meteorological fields are not calculated but specified from the ERA-INTERIM or Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al., 2011) reanalyzes. The use of different reanalysis data made it possible to compare their effect on the observed short-period variability of the ozone content at the observation stations under in this study. The RSHU CTM has 5 x 4 degrees horizontal resolution in longitude by latitude and 31 vertical sigma levels from the surface up to approximately 60 km. The distribution of the oxygen, hydrogen, nitrogen, chlorine, bromine and carbon gases are calculated in the manner described by Smyshlyaev et al. (1998). PSCs formation and evolution is taken into account according to Smyshlyaev et al. (2010).

The analysis of comparison between modeling and experimental (OMI, version TOMS) leads to the following conclusions (Fig.3) In Fig. 3. the comparison between OMI measurements (version TOMS) with the simulation results of EMAC and RSHU (first simulation uses the MERRA, second simulation the ERA-Interim reanalysis) is illustrated. Following conclusions can be drawn::

- Both models sufficiently describe time variations of the total ozone content. On average, the RSHU model provides 1–2% smaller values of the TOC than those observed by OMI. EMAC, conversely, exceeds the OMI measurements by 7–9%. The standard deviations for both models are 6–7%. This approaches the standard deviations between different types of measurements of the total ozone content during the examined period.

- EMAC better describes the TOC variations during some ozone loss periods than the RSHU CTM model: . For example, at the Khanty-Mansiysk station standard deviation stood stands at 4–5% for EMAC model whereas the RSHU model ranged between 6 and 8%. At the Tura station during the January minima, on the contrary, the RSHU model is in better agreement with OMI measurements (3% vs. 7%). Neither model of the both models describes the observed January mini-holes at the Pechora station (standard deviations reach 12–15%).

- On certain days, the differences between measurements and modeling can be up to 20–30%. Models The both models often overestimate the total ozone content measured by the OMI instrument (especially the EMAC model).

In general, the comparison of calculations with two different models of the EMAC and RSHU simulation, which both use ERA-INTERIM reanalysis by different manner, , and OMI, demonstrated that both as well the interactive coupling between physical dynamical and chemical processes and higher as the different spatial resolutions do not have a principal influence on the quality of reproduction the representation of the short-term column ozone variability at local points. Both models demonstrated not bad show a good qualitative agreement with the OMI satellite observations, while for some local points and time periods the best correspondence was agreement is shown by the EMAC CCM, and for others - by RSHU CTM. Comparison of the results of the calculations with the RSHU CNVl with various the both RSHU CTM simulation, using different reanalysis data sets, show~~ed~~ that for MERRA data, the column ozone is systematically lower than ~~when using~~ for EPA-INTERIM data.

4. Analysis of the processes that ~~define~~ responsible for the observed ozone variability over Russia during the Arctic winter of 2015/2016

The role of chemical and dynamic processes in the observed TOC variability over Russia ~~was~~ is assessed based on the RSHU CTM calculations. Two days with the lowermost TOCs registered at all stations were selected for extended analysis. These days are January 27, 2016 (day 27) and February 19, 2016 (day 50) (Fig.3). Results of RSHU CTM simulations for these days are presented in Fig.4 for column ozone ~~(top figures)~~ together with the MERRA temperature data averaged for the lower stratosphere (14–25 km) ~~(bottom figures)~~. The regions with low TOCs are consistent with the low stratospheric temperatures. This is a result of dynamical isolation, which leads to stratospheric cooling and ~~potentially~~ may cause ozone depletion ~~as a result of~~ due to heterogeneous chemical reactions on PSCs particles leading to chlorine activation.

The surface area of the PSCs for the days with low stratospheric temperature and low column ozone episodes are presented in Fig. 5 ~~(top panel)~~. Enhanced PSCs surface area is located at the same regions where low stratospheric temperatures were registered. This is an obvious consequence of stratospheric cooling and may lead to heterogeneous chlorine and bromine activation followed by ozone depletion similar to the Antarctic ozone hole formation (Solomon, 1999). In order to evaluate local ozone destruction significance for the observed TOC loss, the photochemical ozone loss coefficient (s^{-1}) ~~(Jacobson, 2005)~~ (rate of ozone loss divided by the ozone concentration: $\Lambda_{O3} = L_{O3} / N_{O3}$, where L_{O3} - is photochemical ozone loss (mol/s/cm^3) and N_{O3} is ozone concentration (mol/cm^3), Jacobson (2005)), calculated with the RSHU CTM, is presented in the bottom panel of Fig.5.

The location of ~~zones~~ regions with enhanced ozone destruction is close to the regions with estimated low ~~TOCs~~ TOC on January 27 and February 19, but is not fully consistent. In addition, the minimum local photochemical ozone lifetime, estimated as a reciprocal of the ozone destruction coefficient, is about 200 days under these days' conditions. Such a long photochemical lifetime of ozone ~~may~~ can be treated as a sign of the unlikeliness that the observed short-term ozone variability ~~may be~~ is a result of local photochemical destruction initiated by heterogeneous chlorine and bromine activation on the particles of PSCs that formed in these regions. On the other hand, simultaneous low stratospheric cooling and low column ozone at the same locations may be caused by dynamic divergence that leads to heat and mass deficit, similar to polar vortex isolation (Solomon, 1999). Another confirmation of the prevalent dynamical nature of the observed episodes with low ozone concentration is their formation during polar night recorded during December 2015 and first part of January 2016 when photochemical destruction is negligible.

In order to check the conclusion about the dominant role of the dynamical processes in the observed short-term ozone loss two additional numerical experiments were carried out with RSHU CTM : the first simulation did not take into account the formation of polar stratospheric clouds in the Arctic ~~zone~~ region, and the second simulation did not take into account the chemical destruction of ozone to the North to the Northern polar circle. A comparison of the three model experiments for the three stations considered in this ~~paper~~ study is shown in Fig. 6. The results of model experiments have shown that the main features of the short-term ozone loss are reproduced even without ~~taking into account~~ considering chemical destruction within the polar ~~zone (red curve)~~ region. At the same time, difference between results of the model experiments with and without polar chemical ozone destruction ~~(claret curve) depicts~~ shows that the influence of chemical processes becomes noticeable at the end of February, especially for Pechora station.

5. Summary

Data analysis and numerical model experiments have been used to analyze the low TOCs recorded over Russia during the winter 2015/2016 ~~winter~~. Ozone anomalies were observed over the territory of the Urals and Siberia in winter and the beginning of spring 2016. In this ~~paper~~ study, we compare TOCs obtained ~~using~~ by different measuring methods (satellite and ground-based observations) and results of numerical modeling (for the stations Khanty-Mansiysk, Tura, and Pechora) for the ~~above~~ mentioned period. It is shown that ~~existed~~ current monitoring systems (including the new Russian Infrared Fourier- spectrometer IKFS-2) and modern 3-dimensional atmospheric models provide a good ~~description~~ representation of the occurrence of the TOC anomalies. However, results of observations and ~~modeling~~ simulations diverge on ~~particular~~ certain days by ~~as much as~~ up to 20-30%. Analysis of the role of chemical and dynamical processes in the observed ozone variability over the Russian Federation was based on the RSHU CTM calculations. This analysis demonstrated that it is unlikely that local photochemical ozone destruction, initiated by heterogeneous halogen activation on the particles of PSCs that formed under ~~registered~~ observed low temperatures ~~may be~~, is responsible for the short-term local ~~ozone destruction~~ minimum ozone values. The prevalent reason for the observed low TOCs may be dynamical flux divergence out of regions with observed low ozone content (Smyshlyaev et al., 2017).

Acknowledgments

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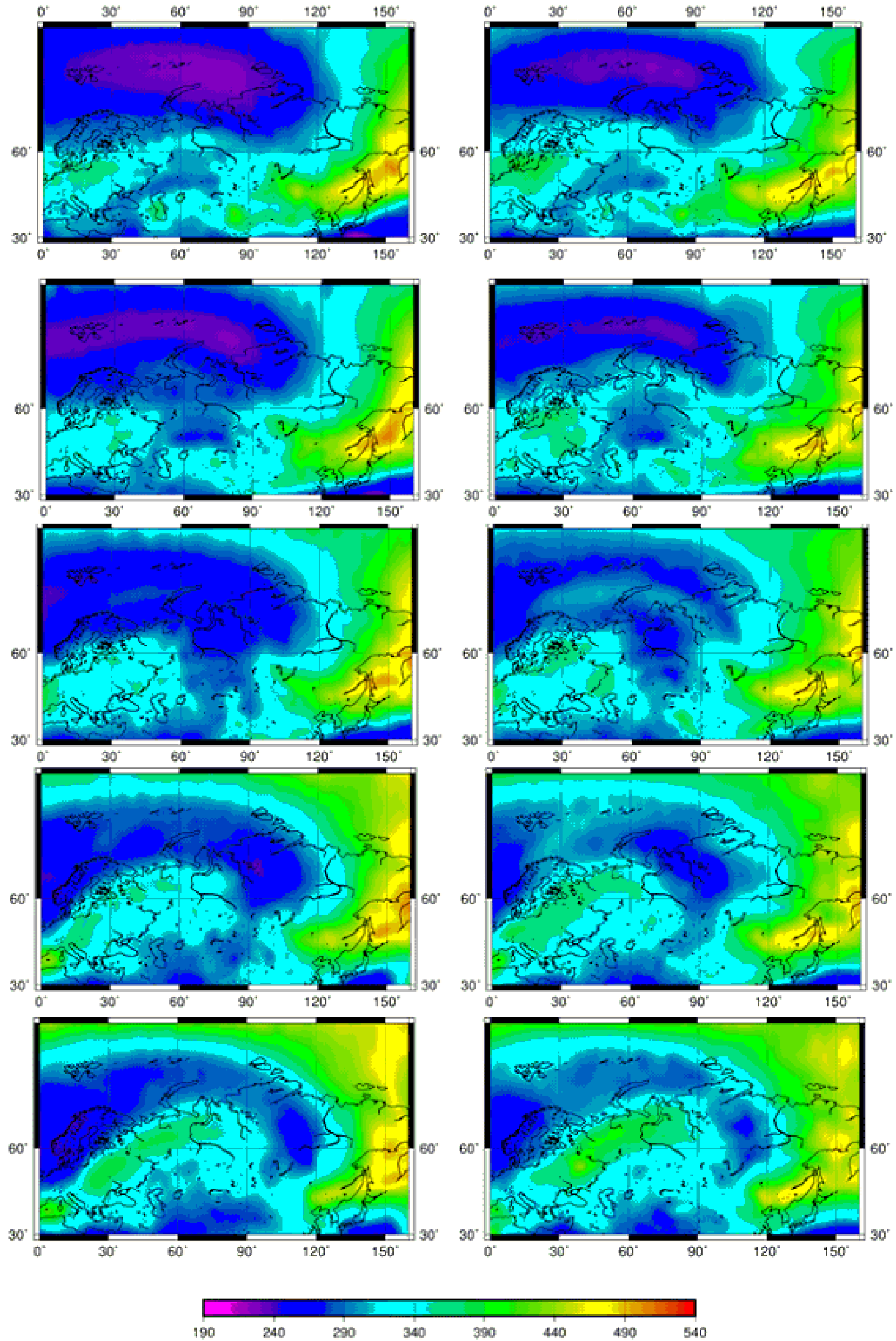

Figure 1. Spatial distributions of ~~the~~ total ozone columns in February 23 - 27, 2016, based on measurements of two instruments of the same type - IKFS-2 (left) and IASI (right). (Garkusha et al, 2018).

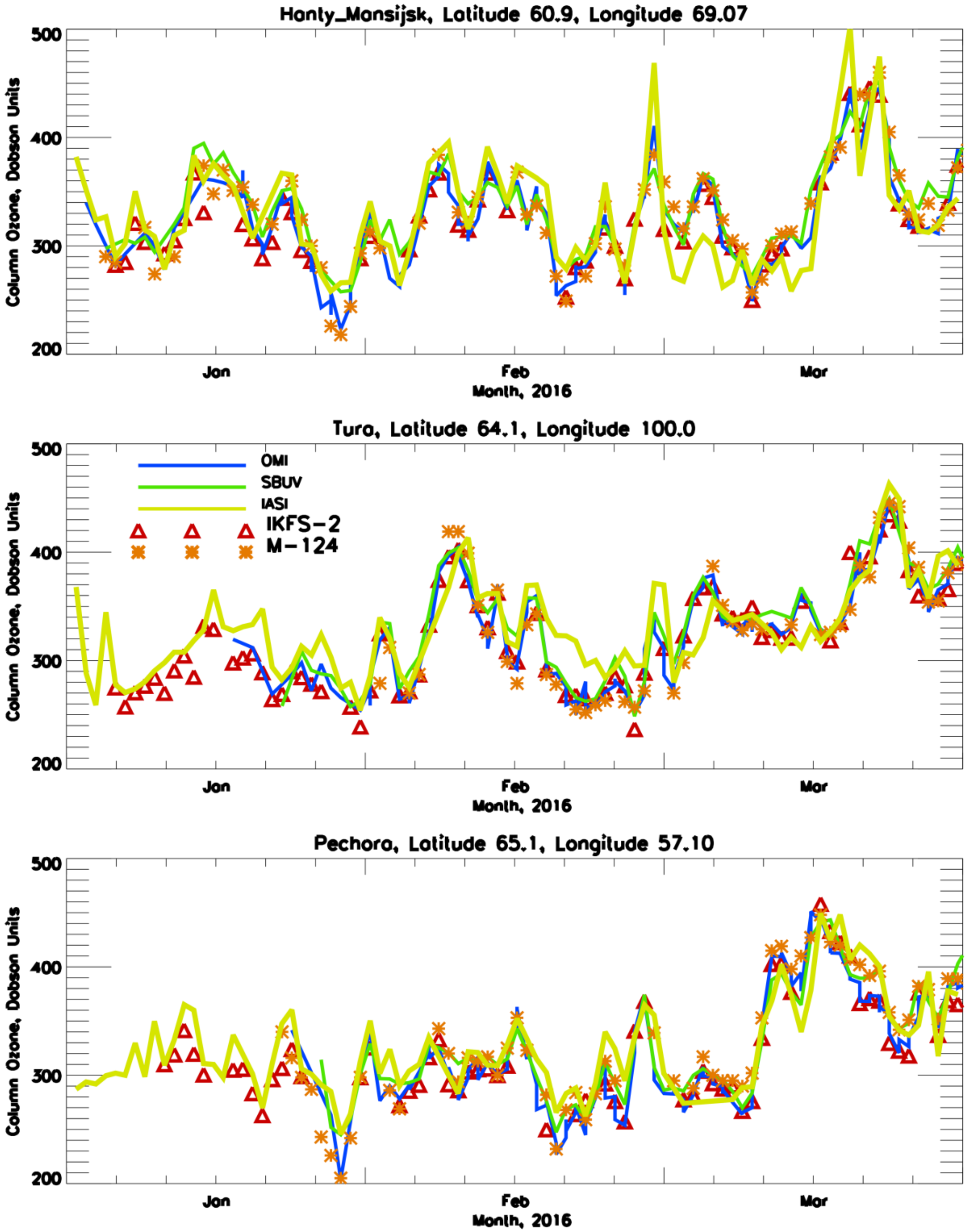

Figure 2: Total ozone measurements provided by ~~the~~ OMI, M-124, IKFS-2, IASI, and SBUV for the stations Khanty-Mansiysk, Tura, and Pechora ~~stations~~.

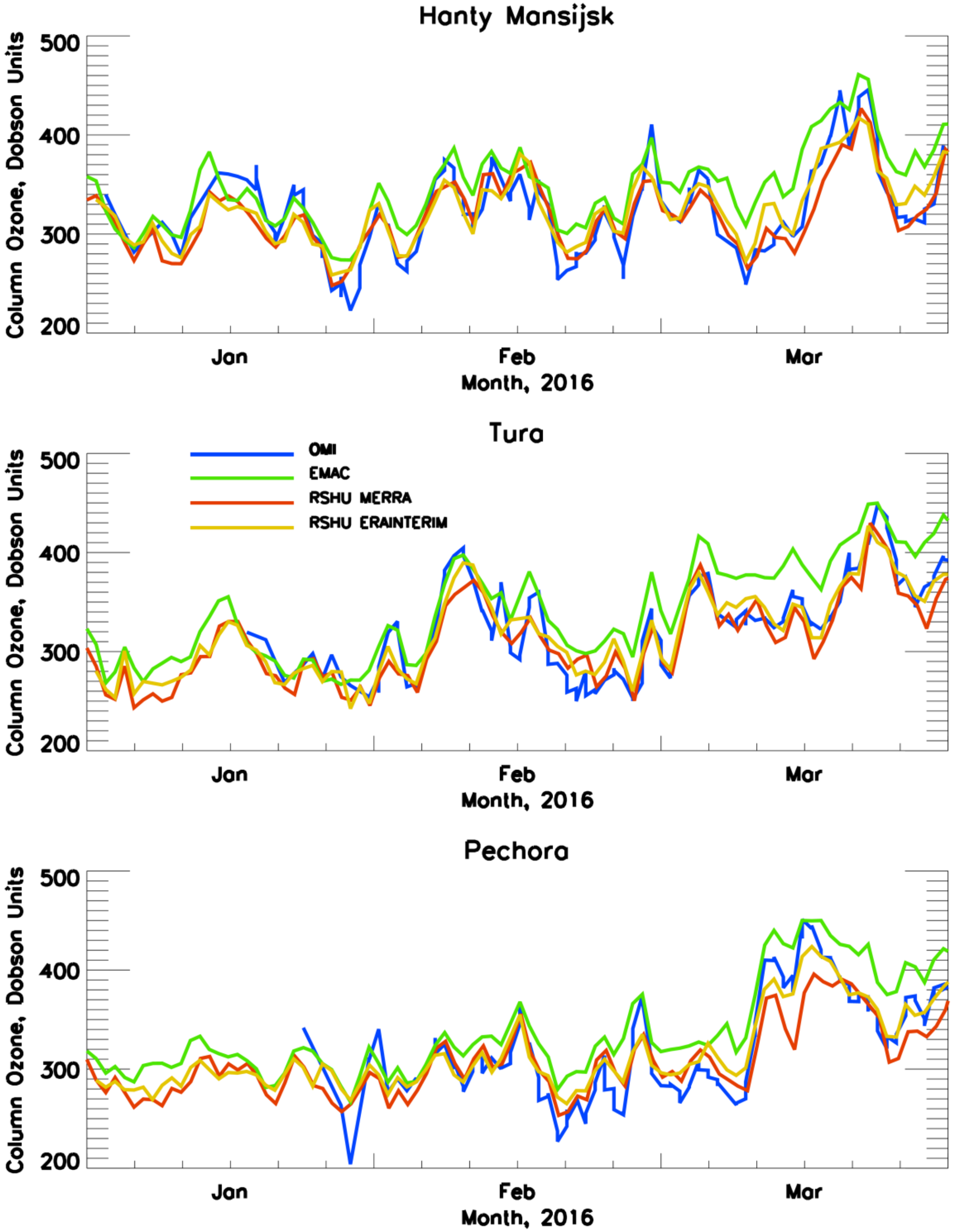

Figure 3: Total ozone measurements provided by OMI and ~~modeling~~ simulation results from EMAC and RSHU for the stations Khanty-Mansiysk, Tura, and Pechora.

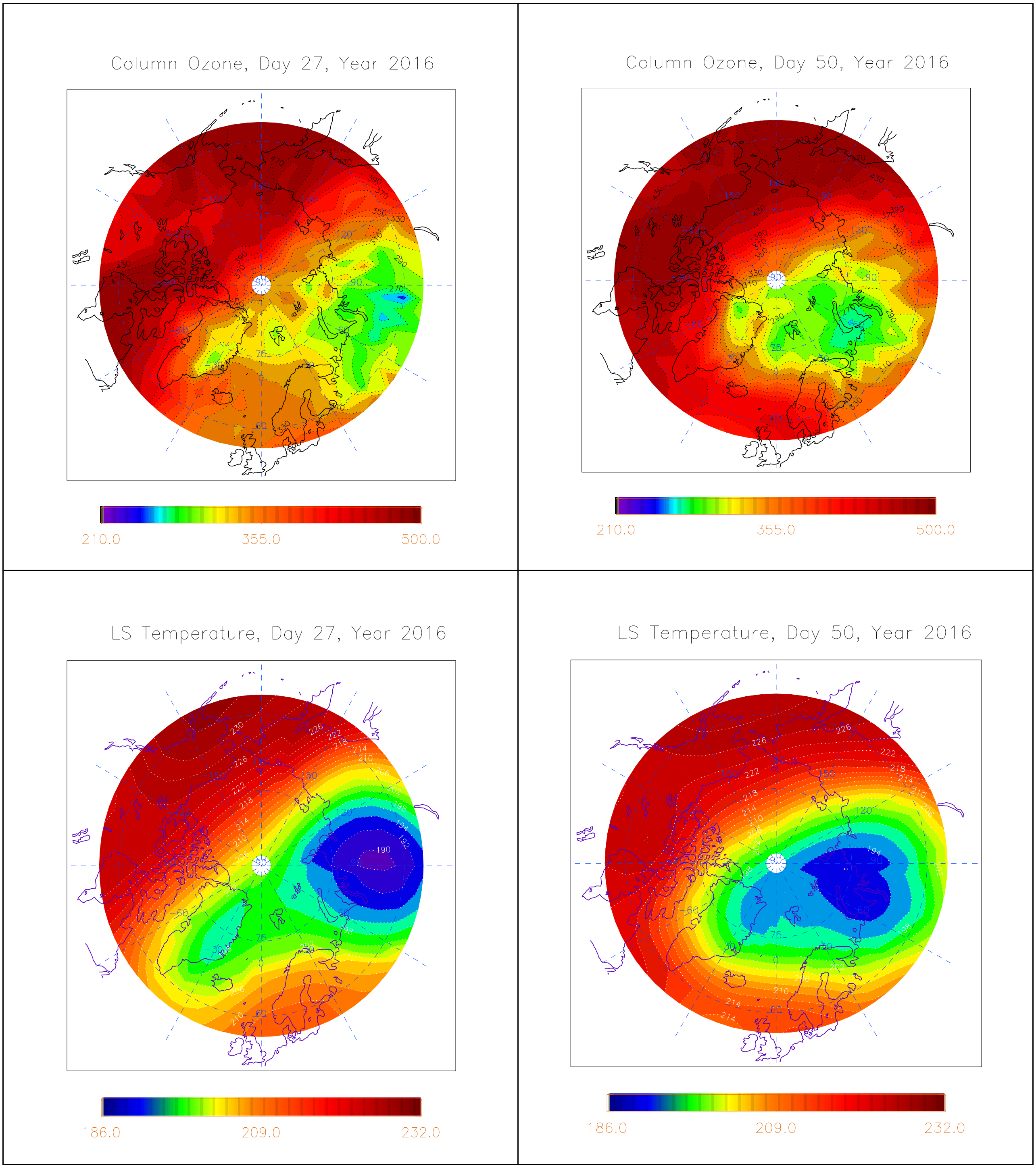

Figure 4: Column ozone (~~Dobson units~~ DU) for the days with minimum local registered values (January, 27 (*left*) and February, 19 (*right*)), simulated with the RSHU model (*top*) and temperature of the lower stratosphere (K) from MERRA reanalysis (*bottom*).

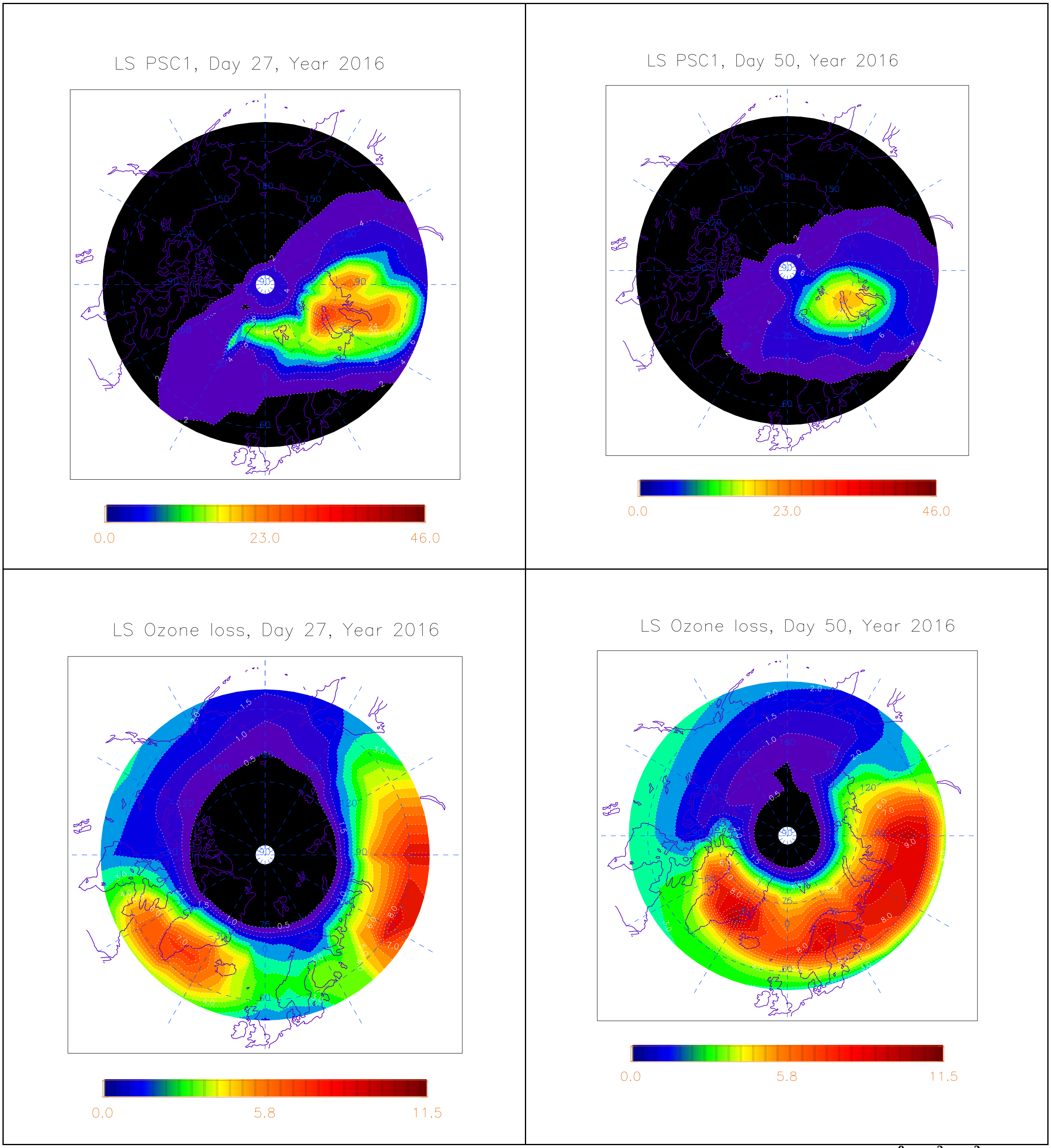

Figure 5: ~~Calculated with RSHU CTM low stratospheric p~~Polar stratospheric clouds surface area (10^8 cm^2/cm^3) for days with minimum local registered column ozone values ~~(*top panel*)~~ (January, 27 (*left*) and February, 19 (*right*)), simulated with the RSHU model (*top*) and averaged ~~for the low stratosphere~~ ozone loss coefficient ($10^8 s^{-1}$) of the lower stratosphere for the same days (*bottom* ~~*panel*~~).

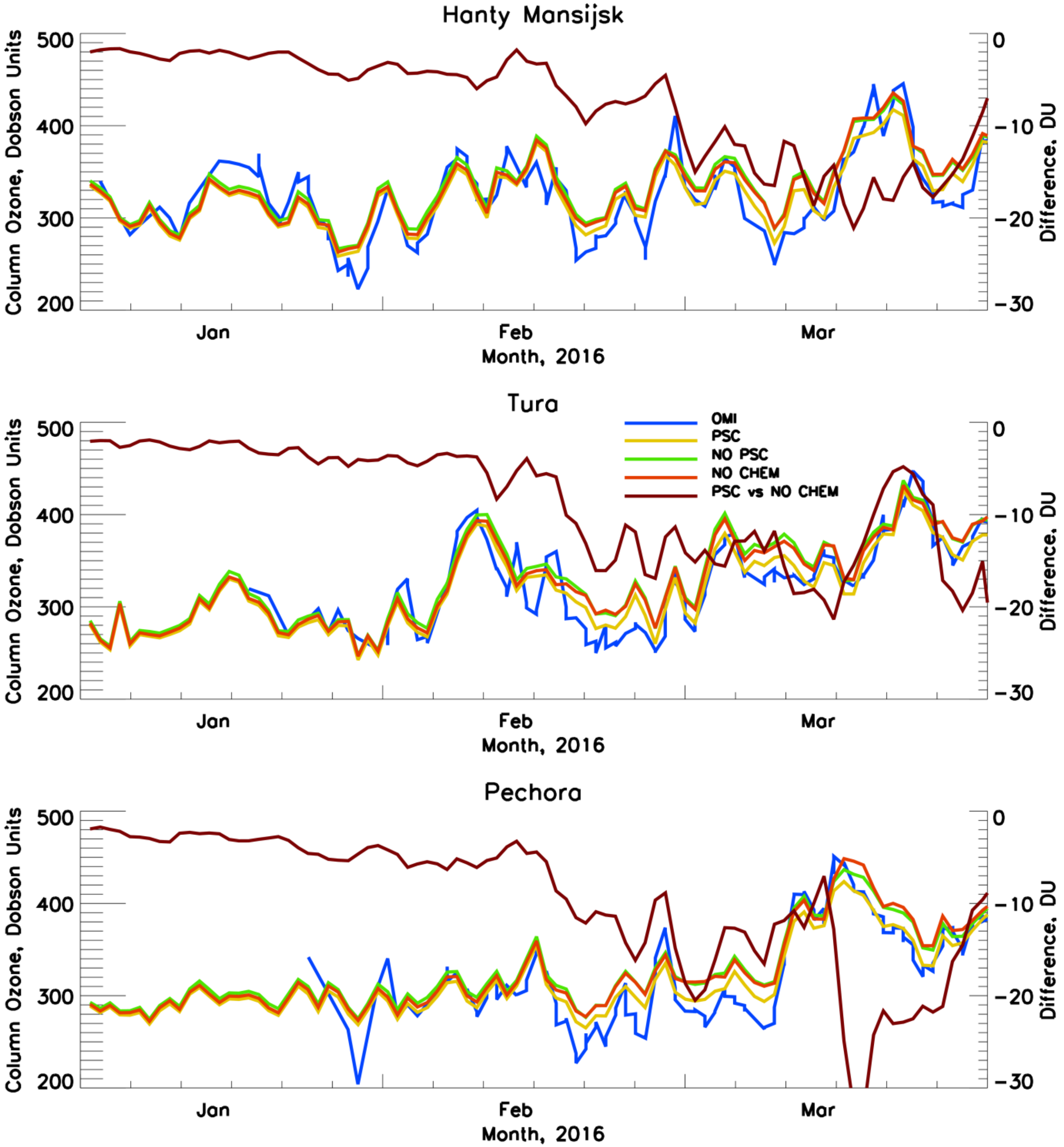

Figure 6: Column ozone variability ~~modeled~~ simulated with RSHU CTM for different scenarios for the stations Khanty-Mansiysk, Tura, and Pechora and difference between scenarios with no polar chemistry and full PSC processing included.