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Influence of Wave Activity on the Composition of the Polar Stratosphere

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Abstract—The planetary wave impact on the polar vortex stability, polar stratosphere temperature, and content of ozone and other gases was simulated with the global chemical–climatic model of the lower and middle atmosphere. It was found that the planetary waves propagating from the troposphere into the stratosphere differently affect the gas content of the Arctic and Antarctic stratosphere. In the Arctic region, the degree of wave activity critically affects the polar vortex formation, the appearance of polar stratospheric clouds, the halogen activation on their surface, and ozone anomaly formation. Ozone anomalies in the Arctic region as a rule are not formed at high wave activity and can be registered at low activity. In the Antarctic Regions, wave activity affects the stability of polar vortex and the depth of ozone holes, which are formed at almost any wave activity, and the minimal ozone values depend on the strong or weak wave activity that is registered in specific years.

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1. INTRODUCTION

Interannual differences and intraseasonal variations in the composition and structure of the polar stratosphere are characterized by specific features that are not observed in other regions of the globe. The formation of the polar vortex (Harvey et al., 2002) and polar stratospheric clouds (PSCs) (Hamil and Toon, 1991), heterogeneous activation of chlorine and bromine gases on the PSC surface (Solomon et al., 1986), polar atmosphere denitrification and dehydration (Peter and Groob, 2012), and the formation of regions with low ozone content (called “ozone holes”) (Solomon, 1999) are among such specific features. The formation and development of ozone anomalies in the Antarctic and Arctic regions substantially differ: Antarctic ozone holes have been registered every year beginning from the mid-1980s (*WMO*, 2014); in the Arctic Regions, ozone considerably decreased only in individual years and did not reach such a depth as in the Antarctic Regions (Strahan et al., 2013).

The observed differences in the formation of ozone polar anomalies between the Northern and Southern Hemispheres are mainly caused by the stability of the polar vortex. In the Antarctic region, this vortex is formed at the beginning of winter and is stable for several months, occupying almost the entire extratropical region (Nash et al., 1996). In the Arctic region, the polar cyclone most often breaks during winter as a result of the nonlinear interaction with planetary waves during sudden stratospheric warmings (Holton, 1980; McIntyre, 1982; Pogoreltsev et al., 2014; Chipperfield and Jones, 1999).

The different stability of the polar vortex in the Northern and Southern Hemispheres may be caused by the different wave activity at the boundary between polar and middle latitudes (Haynes et al., 1991). Orographic stationary planetary waves propagating from the troposphere into the stratosphere are weaker in the Antarctic Regions than in Arctic, since the boundary between polar and middle latitudes is mainly occupied by oceans in the Southern Hemisphere and by continents in the Northern Hemisphere (Shindell et al., 2001). Therefore, planetary waves in the Southern Hemisphere have small amplitudes and slightly affect the mean flow. As a result, the zonal velocity insignificantly varies in time in the stratosphere, mass and heat are mainly transported around the pole, and there is no exchange between middle and polar latitudes (Newman et al., 2001). When wave activity is high, which is typical for winter in the Northern Hemisphere, planetary waves propagating from the troposphere affect the mean flow in the stratosphere and disturb the zonal transport stability around the pole, resulting in a breaking or splitting of the polar vortex (Vargin, 2013).

Meanwhile, considerable interannual differences in the ozone anomaly depth and in the area of the zone occupied by an ozone hole are observed in the Antarctic and Arctic Regions (Huck et al., 2005). The observations indicate that the variations in the average total ozone for the polar zone in the first spring months (Fig. 1) can reach 100 DU from year to year (Stolarski and Frith, 2006; Chehade et al., 2014). The content of chlorine and bromine trace gases (which mainly

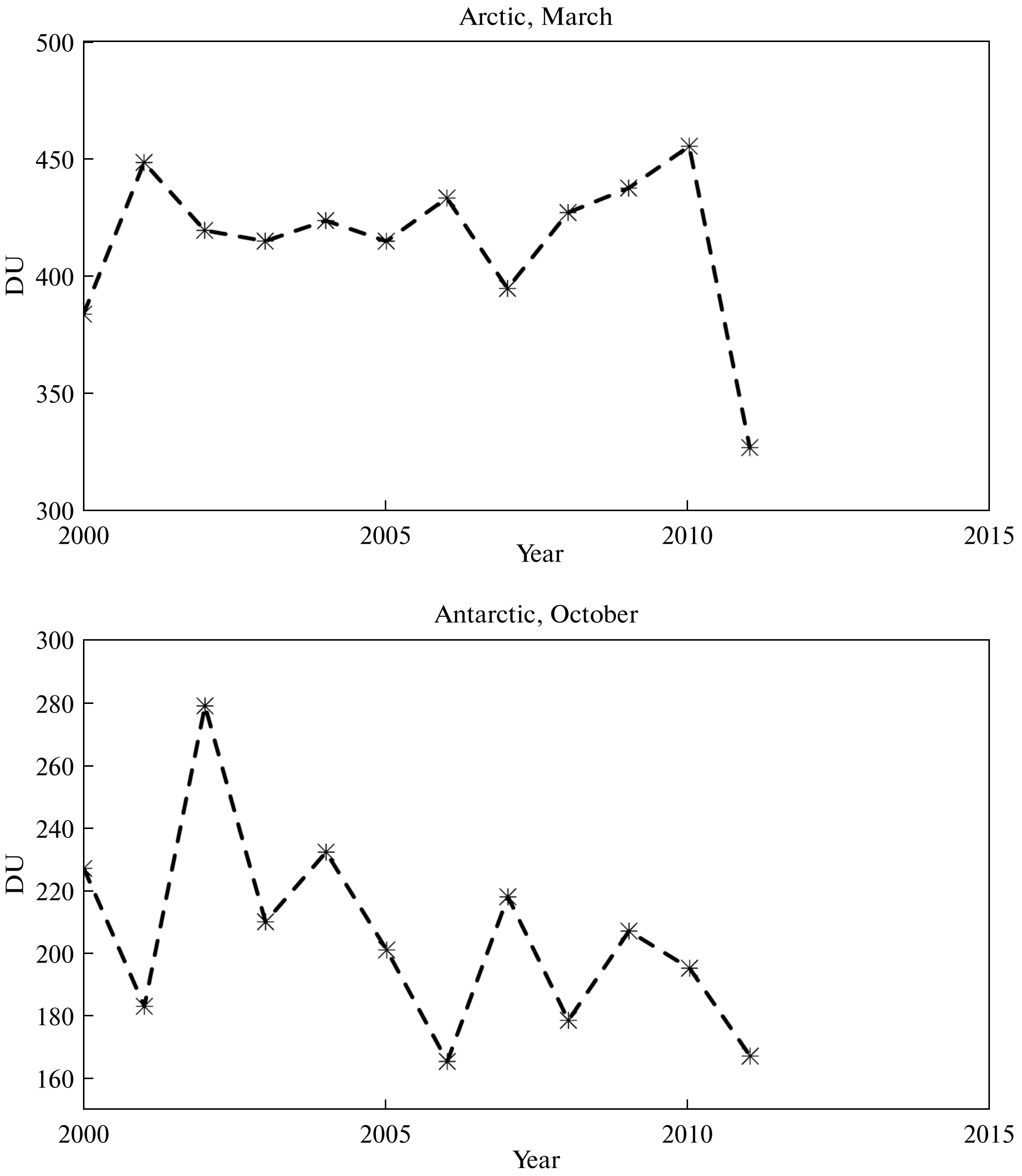

Fig. 1. Interannual variations in total ozone in polar spring in the Northern (top) and Southern (bottom) Hemispheres according to TOMS and SBUV observations.

destroy ozone during the formation of ozone holes according to the common concepts (Solomon, 1999)) in the lower troposphere has remained stable in recent years and has changed insignificantly in different years (Newman et al., 2007). In this situation the interannual variability of the polar ozone anomaly formation may be caused by wave activity variations registered in both hemispheres and independent of orographic forcings (Huck et al.,, 2005; Strahan et al., 2013). Interannual differences in the wave activity in the extratropical stratosphere can in turn be caused by variations in the sea surface temperature, resulting in changes in the wave activity vertical flux from the troposphere into the stratosphere (Hu et al., 2014).

Climate changes can result in considerable variations, not only in the sea surface temperature but also the sea ice (*IPCC*, 2013). The influence of climate changes on the properties of the underlying surface can change tropospheric wave activity, affecting the polar vortex stability and, consequently, the ozone anomaly frequency and depth in the polar stratosphere (Rex et al., 2004). Arctic ozone miniholes, which have been encountered more often recently, possibly result from the influence of climate changes on the wave activity, polar vortex, and processes proceeding within this vortex (Pogoreltsev et al., 2009; Strahan et al., 2013).

The impact of wave activity on the general atmospheric circulation, polar vortex formation, and physical and chemical processes within this vortex is well known; nevertheless, many details of the interrelation between climate change, Earth surface properties, wave activity, polar vortex stability, and ozone anomaly formation are to be discussed. The goal of this paper is to study theoretically the model of the interaction between the physical and chemical processes in the Arctic and Antarctic Regions, to elucidate the significance of global wave processes for ozone polar anomalies and the climate influence on these processes.

2. METHOD OF STUDY

The influence of planetary waves on the polar vortex stability, polar stratosphere temperature, and ozone and related gases in the Northern and Southern Hemispheres was simulated with the use of the global chemistry climate model of the lower and middle atmosphere (CCM) (Galin et al., 2007). CCM is a combination of models of the general atmospheric circulation and composition. The middle atmospheric version of the general atmospheric circulation model (GACM) of ICM RAS (Alekseev et al., 1998) is used to reproduce the spatial distribution and time variations in the atmospheric dynamic parameters: temperature, wind velocities, pressure, humidity, and certain other characteristics in the troposphere, stratosphere, and mesosphere. The model is based on the finite difference solution of hydrothermodynamic equations, which are based on an approximation of the momentum and thermodynamical equations that mathematically describe the fundamental laws of physics (Dymnikov et al., 2005).

Planetary and internal gravity waves are taken into consideration in the model. The gravity–wave drag parametrization, which considers the momentum and energy transfer by gravity waves that are generated in the troposphere and are broken in the stratosphere and mesosphere, is used to take into account the influence of atmospheric waves on the processes in the polar stratosphere (Peters et al., 2004). Two types of gravity waves are parametrically taken into consideration in the model. Waves originating due to the orographic forcing, i.e., those generated from the interaction between an incident flow and the Earth's surface inhomogeneities, belong to the first type (Palmer et al., 2004; Gavrilov et al., 2013, 2014). Precisely such waves are mainly responsible for the difference between the dynamic conditions in the polar regions of the Northern and Southern Hemispheres. Gravity waves of the second type are generated by nonorographic sources, such as the vertical wind velocity shift and convection (Hines, 1997a).

The parametrization of the gravity–wave drag based on (Palmer et al., 2004) is used in the model to calculate the wind velocity and temperature tendencies related to the orographic drag. The data on orography and the orography subgrid dispersion, which are used to calculate the friction stress on the surface caused by gravity waves as well as the stress vertical variation, are specified empirically in this case (Alekseev et al., 1998). The friction stress vertical variation is used to calculate the wind velocity and temperature tendencies.

It is especially important to take into account the nonorographic wave drag in order to reproduce the interannual variability of the stratospheric processes, when the internal gravity wave (IGW) breaking decisively affects the mean flow and, correspondingly, the polar vortex stability (Haynes et al., 2001). The parametrization from (Hines, 1997b), which considers the spectrum of waves with different vertical wave numbers propagating from the troposphere, is used in the present work in order to take into account the IGW effects. It is assumed that IGWs are generated at a specified level in the troposphere and propagate upward, transferring the momentum and energy. The momentum and energy flux convergence due to wave breaking results in a change in the horizontal momentum and temperature.

Considering the influence of the nonorographic drag, we took into account 12 azimuthal directions of the wave propagation in the model. We estimated the Doppler broadening of the spectrum of waves propagating in specified azimuthal directions. In this case we considered the nonlinear interaction between waves over the spectrum and waves with a background wind. Based on these calculations, we estimate the tendency of the temperature and wind velocity variability and the vertical eddy coefficient. We took into account the influence of the underlying surface on the wave energy by estimating the surface temperature, which was calculated for land and was specified for the sea surface responsible for the wind shear and convective instability.

The atmospheric composition model (ACM) considers the variations in the concentrations of 74 main gas components of the atmosphere, which directly or indirectly affect the photochemical ozone variation rate (Smyshlyaev et al., 1998). The model takes into account 174 chemical reactions and 51 photolysis processes with the participation of oxygen, hydrogen, nitrogen, chlorine, bromine, and sulfuric gases, which makes it possible to consider the influence of chemical processes on the trace gas and sulfate aerosol production and evolution. The number and type of the photochemical reactions taken into account allow to study the variations in the concentration of the basic gases affecting ozone in the stratosphere and troposphere (Smyshlyaev et al., 2002). To calculate the photolysis coefficients, we take into account the spectral variations in the incoming solar radiation with regard to the influence of solar activity, absorption, and radiation scattering in the atmosphere on this radiation (Dvortsov et al., 1992).

The model of the formation and evolution of PSCs, which play a key role in the ozone hole formation in late winter—early spring in the Antarctic and Arctic Regions, is used to study influence of wave processes on the changes in the polar stratospheric composition (Smyshlyaev et al., 2010). The model allows to calculate the PSC appearance in polar winter in the lower stratosphere (15—25 km) based on the sulfate aerosol particles that exist at these altitudes when the air temperature decreases below 200 K. The PSC formation leads to an increase in the aerosol particle surface area, where heterogeneous reactions proceed and result in the redistribution of chlorine and bromine gas constituents of the atmosphere with subsequent ozone depletion in the chlorine and bromine catalytic cycles. On the other hand, PSCs absorb nitric acid and water vapor, which results in the denitrification and dehydration of the polar atmosphere.

The influence of the decrease in nitrogen and hydrogen gases on the increase in the relative role of chlorine and bromine gases in the ozone catalytic depletion is taken into account in ACM, which leads to an increase in the ozone depletion effect if the heterogeneous activation on the PSC surface is taken into account (Sovde et al., 2008). Photodissociation of heterogeneous reaction gas-phase products on the PSC surface leads to a release of halogenous radicals (Cl and Br), which destroy ozone in catalytic cycles. The role of wave processes during PSC formation is taken into account as a result of the interaction between ACM and GACM when the polar vortex formation is simulated. This vortex prevents the polar stratosphere from the air and heat exchange with midlatitudes, as a result of which the region of low temperatures is formed during the polar night. The latter promotes the formation and prolonged existence of PSCs and the accumulation of optically active reservoir gases (Cl_2, HOCl, BrCl, and HOBr). When the Sun returns, accumulated halogenous radicals are released, which is followed by rapid ozone depletion.

However, if nitrogen gases are present in the atmosphere, chlorine and bromine radicals can rapidly return in the reservoir state. In the bound state, the halogenous components in the form of $ClONO_2$ and $BrONO_2$ are safe for ozone, and the heterogeneous reactions do not proceed when the Sun returns and temperature rises since PSCs evaporate. In this situation the denitrification of the polar atmosphere plays a defining role, since the above heterogeneous reactions cause the produced nitric acid to remain among PSC particles, the precipitation of which leads to the removal of nitric acid from the stratosphere (de Zafra and Smyshlyaev, 2001). As a result, the amount of HNO_3 in PSCs, which is a predominant nitrogen-containing gas in the lower stratosphere, becomes insignificant by the instant of PSC evaporation when the Sun returns.

Since the nitric acid content decreases, the nitrogen dioxide (NO_2) concentration, as well as the total amount of nitrogen-containing gases, considerably decreases in comparison with the level at the polar night onset, when the PSCs were not yet formed. As a result of the polar stratosphere denitrification, chlorine and bromine radicals still remain active for a long time and continue to destroy ozone in catalytic cycles.

Thus, in modeling of the polar region gas composition, it is important to correctly describe the polar vortex formation by the mean flow, the influence of wave processes on the vortex stability the variation in the polar stratosphere temperature, the formation and variation in the PSC surface area and heterogeneous process rates on PSCs, and the denitrification of the polar stratosphere. In the CCM used in the present work, all of these processes are taken into account in the scope of the interaction between GACM and ACM. Two PSC types are considered in the model. When the temperature decreases below 200 K during polar night, clouds composed of liquid particles containing sulfuric and nitric acids and water appear in the stratosphere. Similar clouds are called polar stratospheric clouds of the first type (PSC-1). These clouds are composed of nitric acid trihydrate (NAT) and ternary solution $H_2SO_4/HNO_3/H_2O$. At temperatures lower than 190 K, PSCs of the second type (PSC-2) composed of ice particles are registered in the polar stratosphere.

CCM, which interactively combines GACM with ACM, includes the lower atmosphere (i.e., the troposphere) from the surface to the tropopause (10—16 km), as well as the middle atmosphere (i.e., the stratosphere and mesosphere) at altitudes from the tropopause to the mesopause (of about 90 km). We selected this altitude region because it is necessary to describe the physical processes responsible for the spatial—time distribution of the tropospheric and stratospheric dynamic and chemical parameters, and the mesosphere is considered a buffer zone, which allows to remove the upper boundary and decrease the error in modeling the processes in the stratosphere due to the effect of the upper boundary conditions.

We run the CCM for the period from 2000 to 2015 in order to study the influence of wave processes on the polar vortex stability, stratospheric temperature variation, PSC formation, polar stratosphere denitrification, and ozone hole formation. We analyzed the calculations of variations in the dynamic and chemical parameters in the Northern and Southern Hemispheres in 2010 and 2011, when substantial interannual differences were observed in the Antarctic and Arctic Regions (Fig. 1). The specification of the variations in the sea surface temperature and sea ice (Rayner et al., 2003), which influence the wind shear in the boundary layer and the upward propagating gravity wave spectrum, was the main factor effecting a change in the nonorographic drag in 2010 and 2011. The main goal of the analysis was to compare the influence of wave activity on the interannual differ-

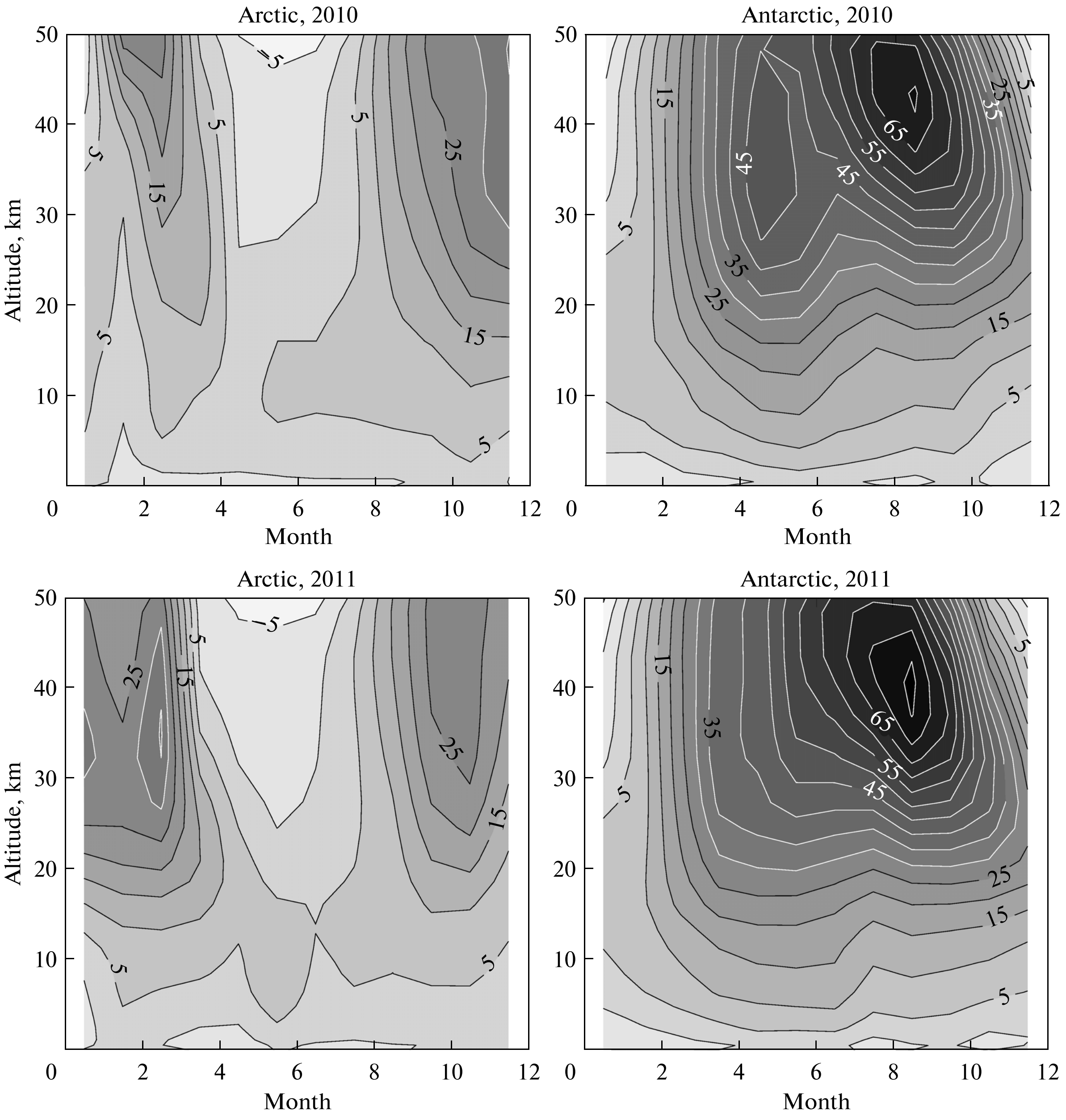

Fig. 2. Altitude–time variations in the zonal wind at the boundary between polar and middle latitudes in the Arctic (64° N) and Antarctic (64° S) Regions in 2010 (top panel) and 2011 (bottom panel).

ences in the processes affecting the gas composition of the lower polar stratosphere in the Northern and Southern hemispheres. We should note that this work was not aimed at a comparison of the calculations with the observations performed in 2010 and 2011. We were mainly interested in analyzing qualitative differences in the dynamic conditions registered at that time, i.e., how these conditions affect the physical and chemical variations in the gas composition of the polar stratosphere.

3. RESULTS OF MODEL EXPERIMENTS

Figure 2 presents the altitude–time variations in the mean zonal wind at the boundary between polar and middle latitudes (64°) in the Northern and Southern Hemispheres in 2010 and 2011 calculated with CCM. According to the concepts of the dynamics of the interaction between the troposphere and stratosphere (Haynes et al., 1991), the heat and mass vertical transport is controlled by the Eliassen–Palm flux divergence at a slightly varying zonal wind ($\partial \overline{u} / \partial t \approx 0$).

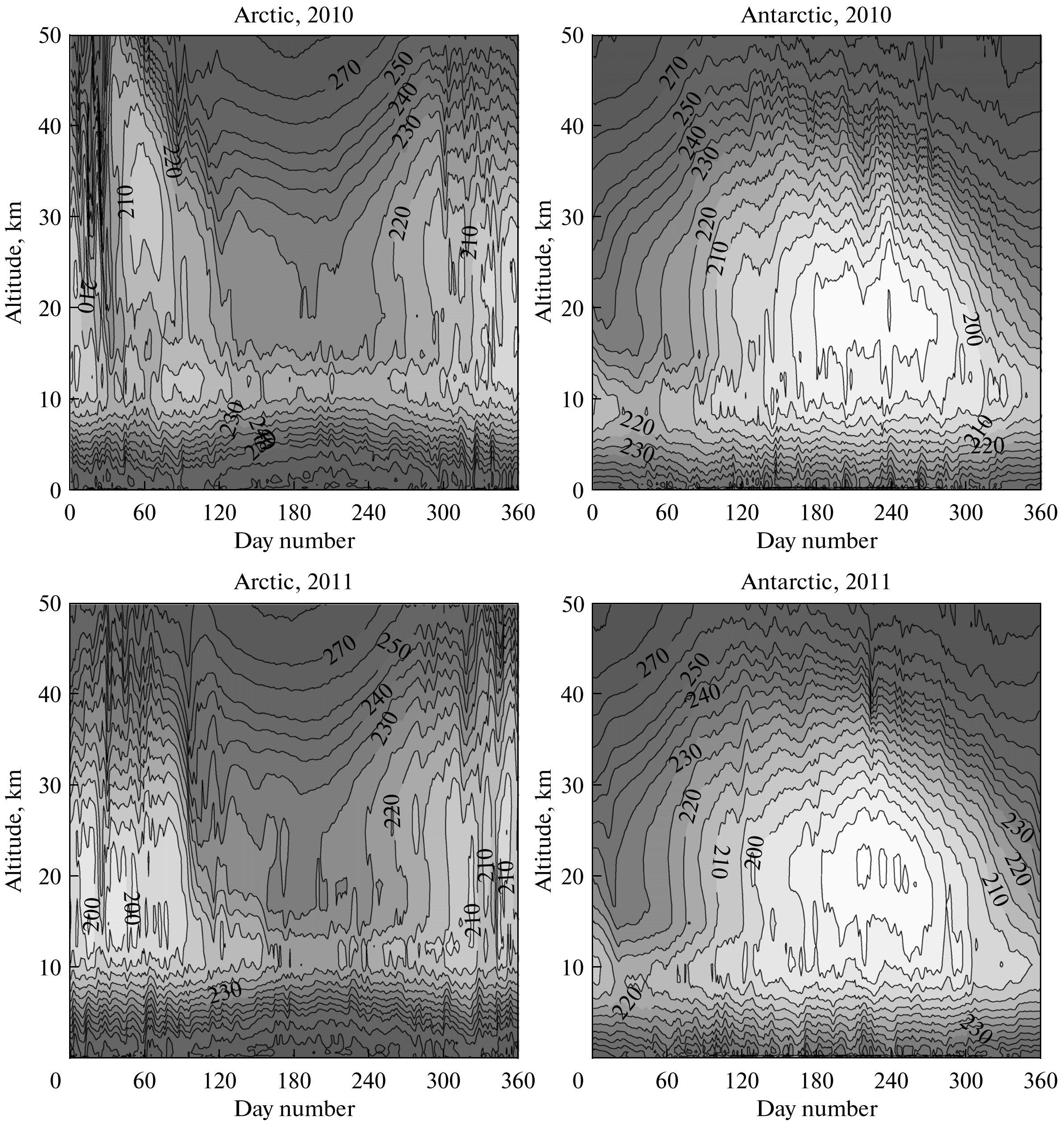

Fig. 3. Altitude–time variations in the atmospheric temperature (K) near the pole: the Arctic (88° N) and Antarctic (88° S) Regions in 2010 (top panel) and 2011 (bottom panel).

For the polar vortex stability, this means that heat and mass mainly moves in the zonal direction and the meridional transfer is weakened in the lower stratosphere if the effect of planetary waves propagating from the troposphere is insignificant. When the wave flow from the troposphere increases, the zonal flow becomes destabilized and the zonal wind velocity starts varying in time, which increases the meridional exchange between polar and middle latitudes. The zonal flow stability and value characterizes the polar vortex stability, since this vortex is stable and the meridional air circulation is weak when zonal wind is stable.

If we consider the time variations in the mean zonal wind in the lower stratosphere (15–25 km altitudes) in winter at the boundary between polar and middle latitudes in the Arctic and Antarctic Regions (Fig. 2), we can find both common features and differences typical of polar regions in the Northern and Southern Hemispheres. First, we should note that the absolute values of the mean zonal velocity at the boundary between polar and middle latitudes in the lower stratosphere during the

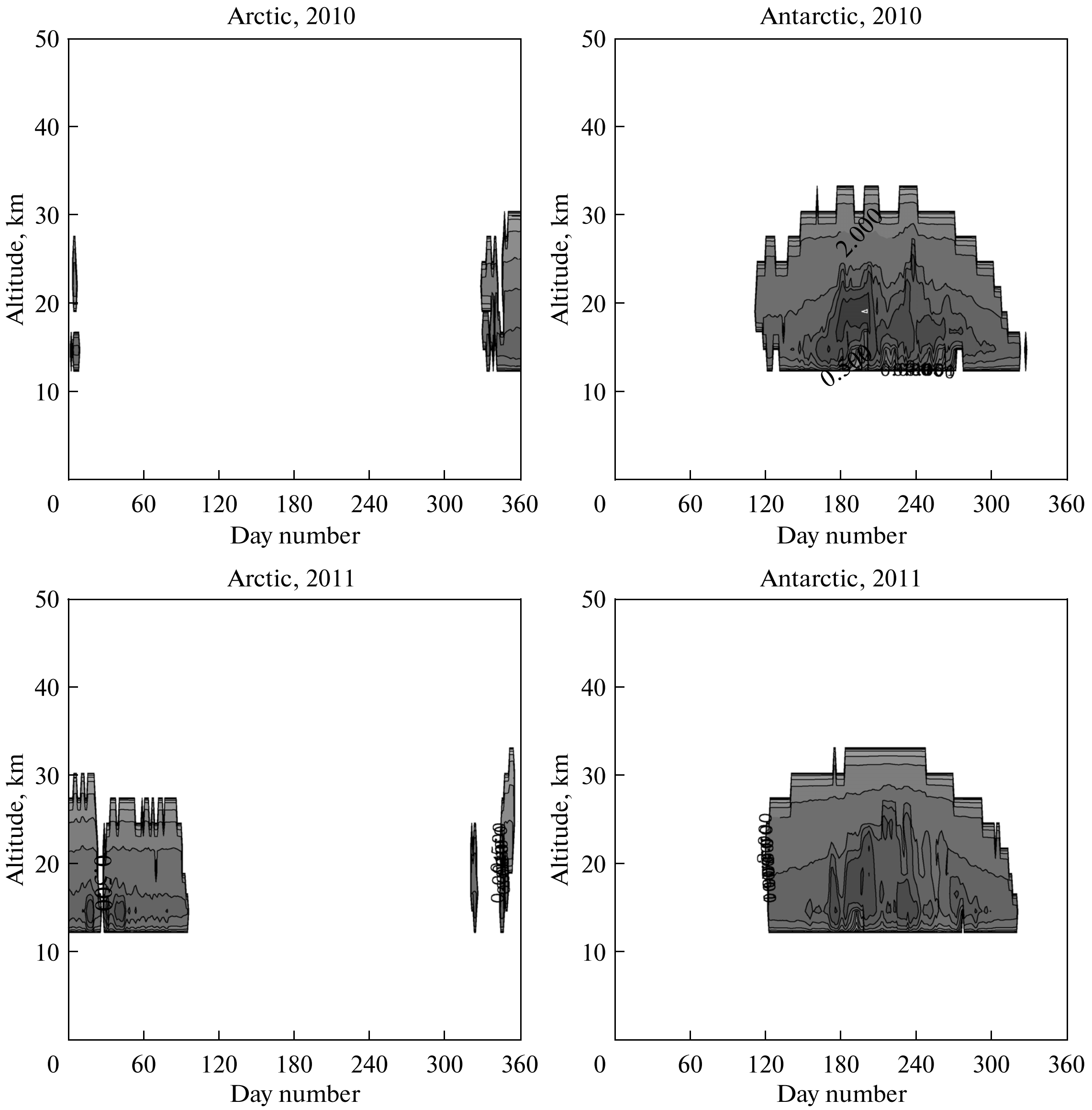

Fig. 4. Altitude–time variations in the PSC-I surface area ($\mu m^2\ cm^{-3}$) near the pole: the Arctic (88° N) and Antarctic (88° S) Regions in 2010 (top panel) and 2011 (bottom panel).

winter period in the Southern Hemisphere are twice as large as those in the Northern Hemisphere, because the orographic forcing in the Arctic Regions is larger than in the Antarctic Regions.

The interannual variations in the zonal wind in the lower stratosphere in the Arctic Region are substantially more significant than in the Antarctic Region. In the Northern Hemisphere, a change in the conditions at the lower boundary results in a fundamental difference in the time variations in the mean flow around the pole. In the early 2010, the zonal wind was weak near 20 km (5–8 m/s) and strongly varied in time. At the same time, during the same period in 2011, the flow around the pole was stable during the entire winter and at the beginning of spring with a strong zonal wind (10–20 m/s). Thus, in 2011 the Arctic dynamic conditions qualitatively corresponded to the Antarctic conditions, but the values were smaller. At the same time, the dynamic pattern in the Arctic in 2010 absolutely differs from the Antarctic pattern.

In the Antarctic region, at low interannual variability in 2010, planetary waves in July–August penetrate to higher altitudes (up to 30 km) than in 2011 (up to 20 km). In the zonal wind, it is expressed by the higher time stability in the winter lower stratosphere in 2011 as compared to 2010. Thus, the analyzed model calculations of the zonal velocity variability presented in Fig. 2 indicate that the Antarctic polar vortex exists for a long time independently of wave activity. It varies owing to the variations in the conditions at the lower

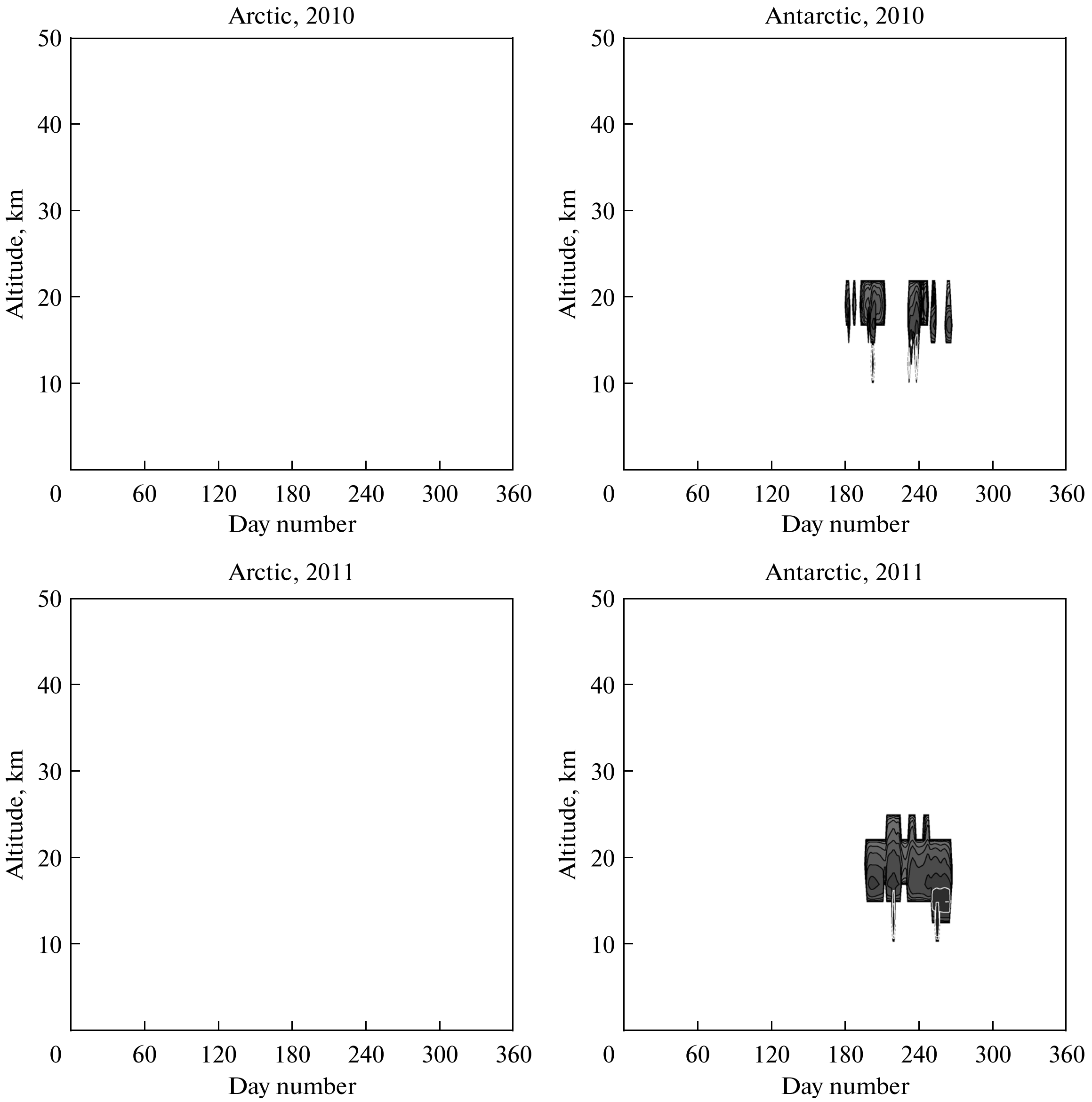

Fig. 5. The same as in Fig. 3 but for PSC-II (μm^2 cm^{-3}).

boundary, which affect only the degree of vortex stability. At the same time, wave activity in the Arctic region is responsible for the polar vortex stability. For low wave activity in 2011, the polar cyclone stably exists for a long time, whereas the polar vortex was almost imperceptible in 2010, when wave activity was high.

The influence of the polar vortex depending on wave activity, on the atmospheric temperature is shown in Fig. 3. The higher activity of the Antarctic polar vortex as compared to the Arctic vortex causes the winter temperature in the lower stratosphere in the southern polar zone to be 10–20 degrees lower than in Arctic winter. In this case the region of low temperatures in the Antarctic Region stably exists for several months, whereas the temperature time variations in the Arctic Region are more pronounced. The interannual time variations studied in 2010 and 2011 depend on variations in the polar vortex stability, which is also expressed by zonal velocity variations (Fig. 2). In the Antarctic region, the higher wave activity in 2010 results in the absence of regions with a temperature lower than 190 K observed in 2011. In this case the pattern of altitude–time temperature variations mainly coincides in these years with such a pattern in the southern polar zone. At the same time, the different wave activities in the Arctic region in the studied years means that regions with a temperature lower than 200 K almost do not appear in 2010; they do exist in 2011, although less stably than in the Antarctic region.

The formation of polar stratospheric clouds critically depends on the temperature: PSC-1 and PSC-II can be formed if the temperature falls below 200 and

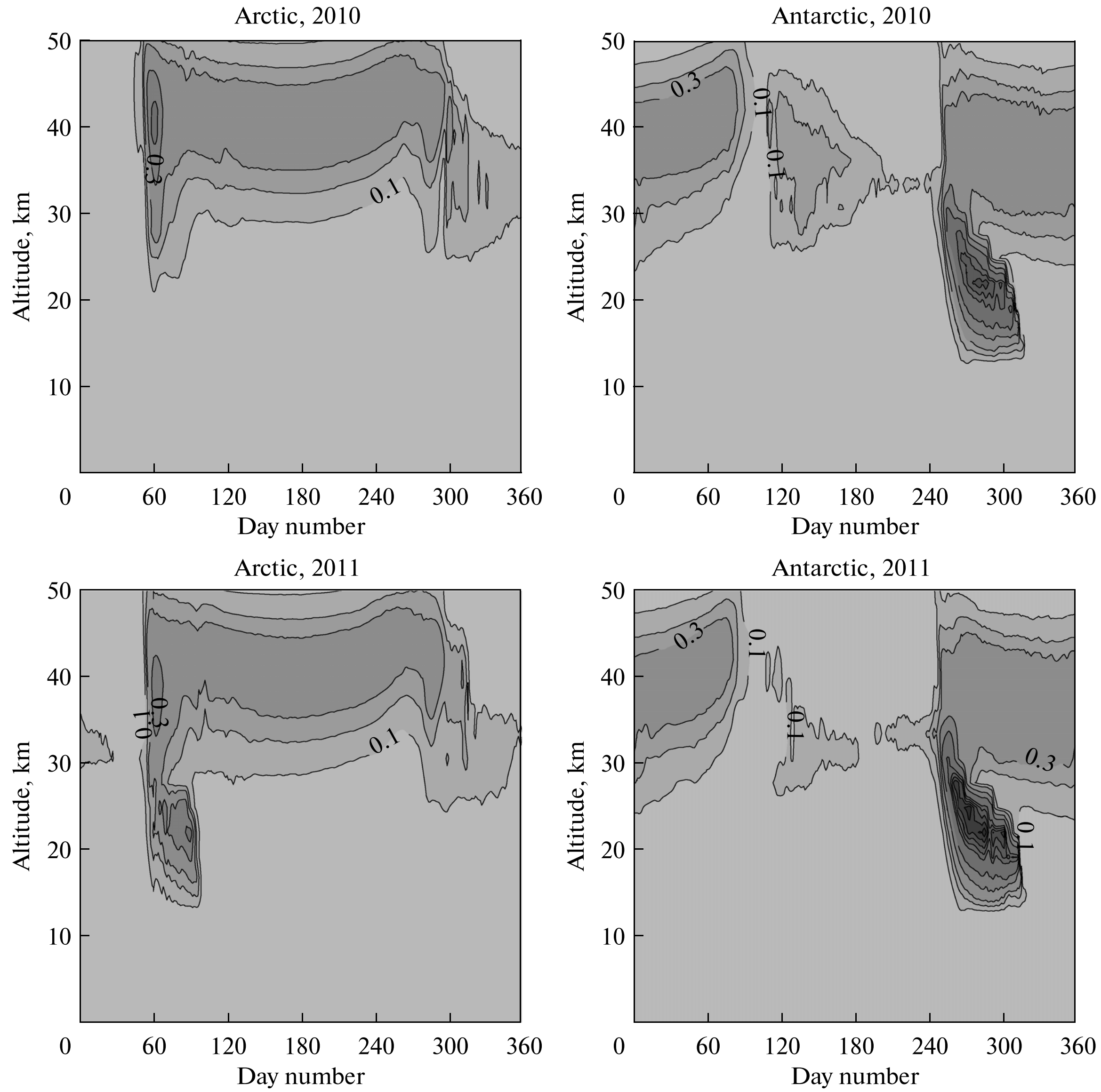

Fig. 6. Altitude–time variations in the ClO concentration (molecule cm^{-3}) near the poles: the Arctic (88° N) and Antarctic (88° S) Regions in 2010 (top) and 2011 (bottom).

190 K, respectively (Smyshlyaev et al., 2010). Therefore, the PSC-1 surface area varied in altitude and time under the Arctic and Antarctic conditions in 2010 and 2011 (see Fig. 4). In 2010 PSC-1 appear only early in the year in the northern polar zone, when the temperature of the lower stratosphere fell below 200 K for a short time (Fig. 3). Then, after sudden stratospheric warming, the polar vortex breaks (Fig. 2), the temperature rises, and PSCs evaporate and are not observed up to the end of winter (Fig. 4). Late in 2010, the conditions for polar vortex formation originate again in the Arctic region, and this vortex also stably exists early in 2011 (Fig. 2), as a result of which the temperature remains lower than 200 K during that period (Fig. 3) and PSC-1 exist within the polar zone during the entire winter of 2010–2011 (Fig. 4). At the same time, the temperature remains low for the entire winter in the Antarctic Regions in 2010 and 2011 (Fig. 3), as a result of which PSC-1 also exist during the entire winter and in early spring in the southern polar zone (Fig. 4).

PSC-II are formed as a result of the freezing of PSC-I particles at a temperature lower than 190 K (Sovde et al., 2008). In the Arctic region, wave activity remained high due to orographic effects, though the dynamic conditions were different in 2010 and 2011. As a result, the zonal velocity in the winter lower stratosphere was substantially lower than in the Antarctic region (Fig. 2), which indicates that the polar vortex was stable. This results in that the temperature does not drop below 190 K (Fig. 3) and conditions for

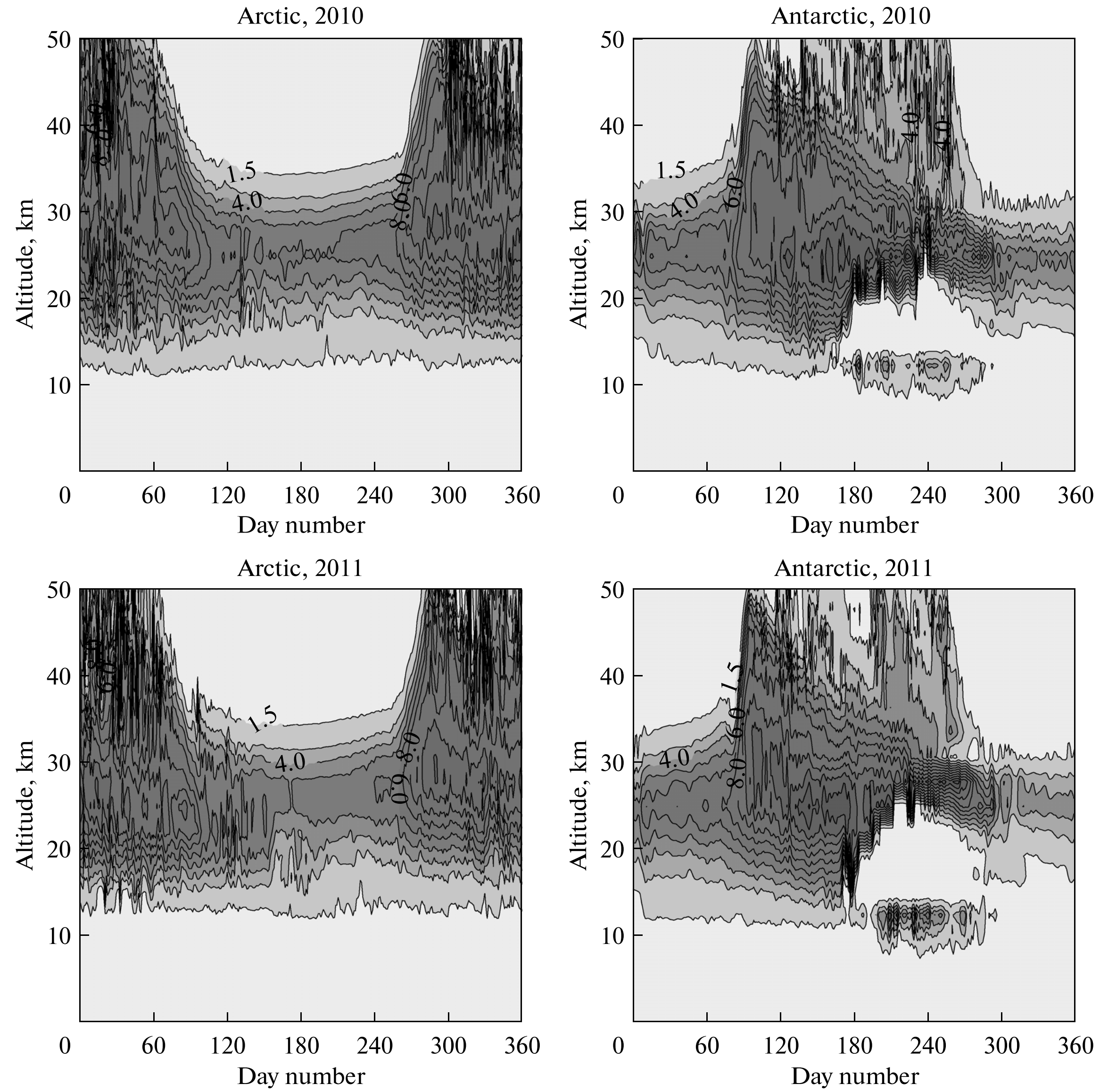

Fig. 7. Altitude–time variations in the nitric acid (HNO_3) vapor concentration (molecule cm^{-3}) near the pole: the Arctic (88° N) and Antarctic (88° S) Regions in 2010 (top panel) and 2011 (bottom panel).

the formation of PSC-II are not formed (Fig. 5). At the same time, in the Antarctic region, the variability pattern is almost the same for PSC-I in 2010 and 2011 (Fig. 4), but fundamental differences are registered for PSC-II (Fig. 5). PSC-II are periodically formed and disappear in 2010 and continuously exist during several months in 2011.

It is assumed that the heterogeneous activation of chlorine and bromine gases on the PSC surface is the main process resulting in the development of ozone anomalies (Solomon, 1999). Activation occurs during the polar night and causes the release of numerous halogenous radicals after sunrise upon completion of the polar night. Chlorine oxide (ClO) is the main halogenous radical that decisively affects ozone catalytic destruction during the formation of ozone holes (Solomon et al., 1986). Therefore, the formation of increased ClO concentrations is the necessary condition for ozone anomalies.

The calculations illustrated in Fig. 6 indicate that chlorine oxide varies in altitude and time in the polar atmosphere for the studied years. In the Arctic region, increased ClO concentrations are formed after sunrise upon completion of the polar night in the upper stratosphere either year and in the lower stratosphere only in 2011. The processes in the upper stratosphere contribute to the ozone depletion to a certain degree but are not decisive for the formation of ozone anomalies (*WMO*, 2014). At the same time, the formation of increased chlorine oxide concentrations in the lower

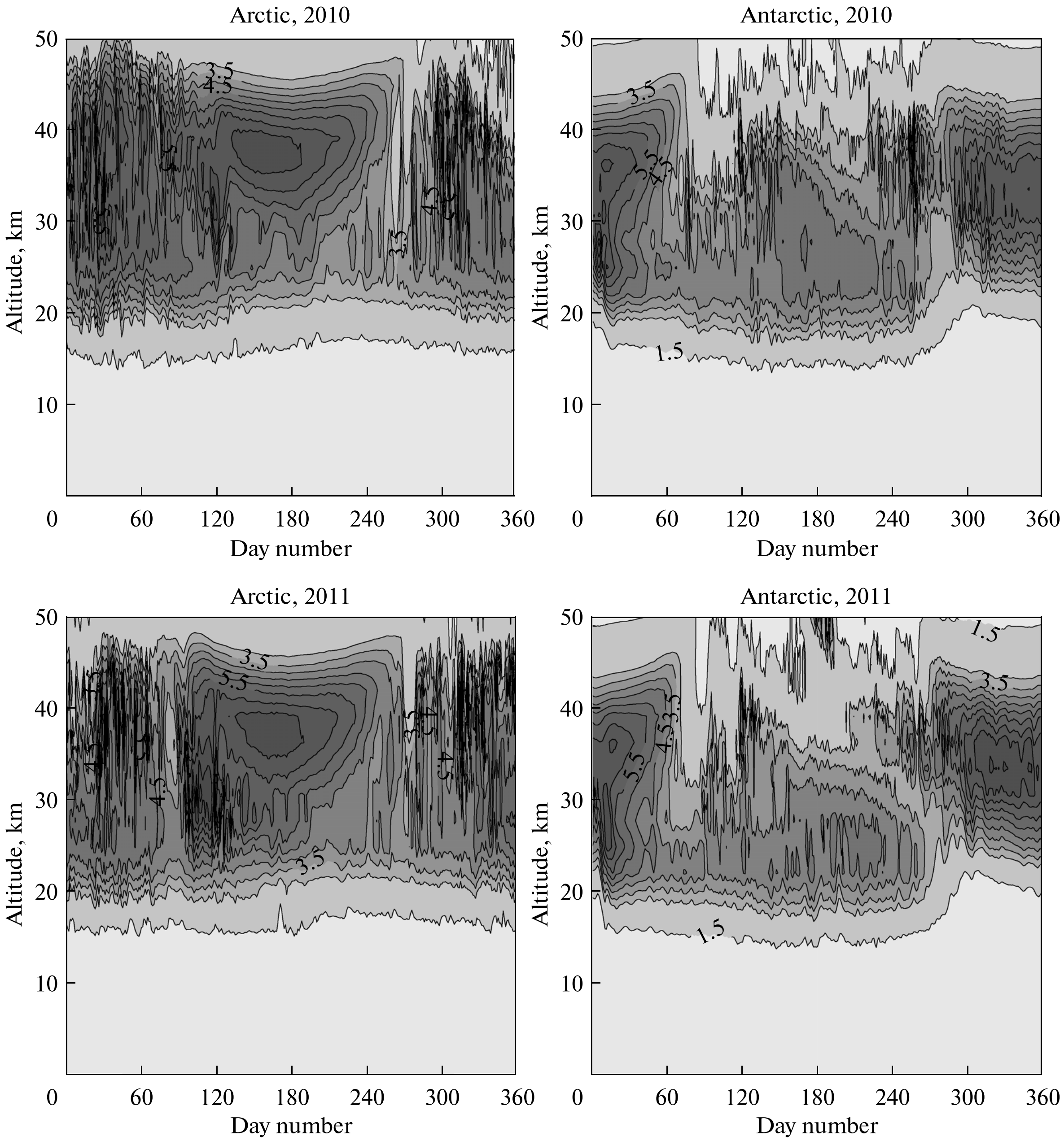

Fig. 8. Altitude–time variations in the ozone (O_3) concentration (molecule cm^{-3}) near the pole: the Arctic (88° N) and Antarctic (88° S) Regions in 2010 (top panel) and 2011 (bottom panel).

stratosphere results from heterogeneous activation on the PSC surface and, correspondingly, is directly related to the lifetime of any PSCs during polar winter. Since PSC-I are formed at higher temperatures than PSC-II, exactly that are essentially responsible for the appearance of increased ClO concentrations after sunrise.

The model calculations indicate that many chlorine radicals were released in 2010 and 2011 in the Antarctic region (Fig. 6), which resulted from the prolonged existence of PSC-I in the southern polar zone in these years (Fig. 4). Thus, the change in the dynamic conditions, which depend on wave activity, does not fundamentally affect the formation of the main ozone destroyers in the Antarctic region. On the contrary, the Arctic dynamic conditions are completely responsible for the appearance of halogenous radicals, which destroy stratospheric ozone in the polar spring. The total amount of chlorine gases remains approximately the same during these years, and the wave processes, temperature variations, the formation of PSCs, and heterogeneous processes on

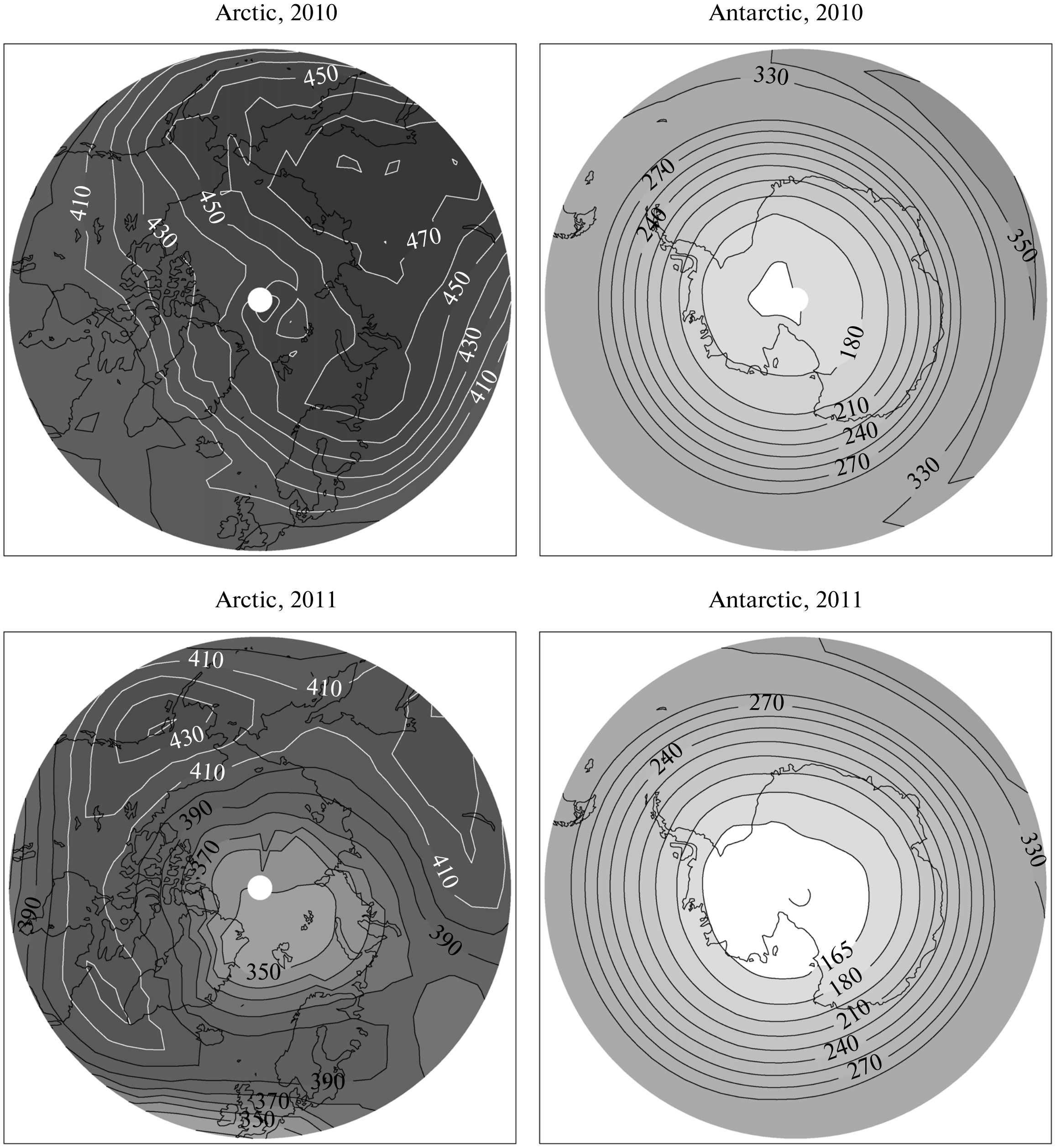

Fig. 9. Variation in total ozone (DU) at the end of March in the Arctic Regions (the left column) and in October in the Antarctic Regions (the right column) in 2010 (top panel) and 2011 (bottom panel).

their surface affect the redistribution between inert and radical chlorine and bromine gases. The chlorine components remain in the inert state at high wave activity in 2010 (Fig. 2), and many chlorine radicals are released at low wave activity in 2011, although the number of these radicals is smaller than during the comparable period in the Antarctic region (Fig. 6).

The PSC-II surface area (Fig. 5) is substantially smaller than the PSC-I particle surface area (Fig. 4); therefore, the PSC-II appearance and destruction phases slightly affect the release of chlorine and bromine radicals (Fig. 6). However, PSC-II fundamentally affect the denitrification of the polar stratosphere, since their particles are coarser than PSC-I particles and are more subjected to the gravitational fallout. As a result, the nitrogen and hydrogen gas components of PSC-II are removed from the stratosphere (de Zafra and Smyshlyaev, 2001). Modeling the nitric acid vapor variability in the Arctic and Antarctic Regions in 2010 and 2011 confirms that clouds of the second type affect the denitrification of the polar stratosphere (Fig. 7). In the Arctic region, PSC-II were not observed in the years under consideration (Fig. 4); therefore, the denitrification effect was not registered here in 2010 and 2011 despite the different dynamic conditions. On the contrary, wave activity mainly affects denitrification in the Antarctic region. In 2010 PSC-II appeared only episodically, and the denitrification was less pronounced than in 2011, when type-II clouds existed for a long time (Fig. 7).

The joint influence of increased halogen gases concentrations and denitrification on the ozone content results in deep ozone holes, like those that regularly take place in the Antarctic region. The modeling results indicate that the ozone concentration in the lower stratosphere also decreased in September–November of 2010 and 2011 (Fig. 8). In this case ozone was destroyed in a wider range of altitudes, since the denitrification took place in a wider range of altitudes in 2011 (Fig. 7). Only halogenous radicals increased in the Arctic Regions, and denitrification was altogether absent only in 2011. This meant that ozone did not decrease in 2010 and considerably decreased at the end of March in 2011, although the Antarctic anomaly values were not reached (Fig. 8).

Wave activity affects the total ozone in both hemispheres (Fig. 9). However, in the Antarctic region, this only results in a change in the ozone hole depth and in the area occupied by this hole. At the same time, in the Arctic region ozone anomalies are not registered at high wave activity, and the ozone depletion does not reach the Antarctic values at low activity (Fig. 9).

4. CONCLUSIONS

Investigation of the influence of global wave processes on the change in the polar atmospheric composition, as performed with CCM, indicated that planetary waves propagating from the troposphere into the stratosphere differently affect the stratospheric composition in the Arctic and Antarctic Regions. In the Arctic region, wave processes critically affect the polar vortex formation, the appearance of PSCs, the halogen activation on their surface, and the formation of ozone anomalies. Ozone anomalies are, as a rule, not formed at high wave activity in the Arctic region and can be observed at low activity. In the Antarctic region, wave activity influences the polar vortex formation and the subsequent processes leading to the formation of ozone holes, which appear at almost any wave activity, and the minimal ozone content values depend on the degree of wave activity.

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