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PLANETARY SCALE ROSSBY WAVES IN THE TOTAL OZONE OVER THE SOUTH POLAR REGION

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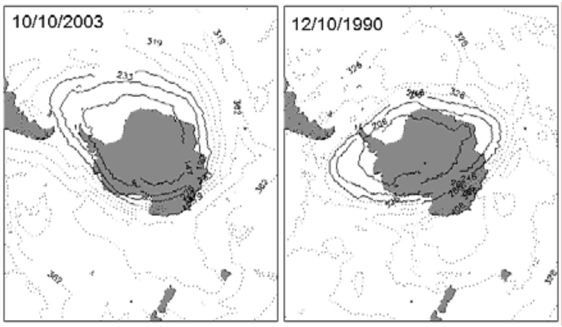
Abstract. The total ozone column (TOC) variations in the latitude interval 60°S-75°S is analyzed based on the measurements of the Total Ozone Mapping Spectrometer (TOMS) during Antarctic ozone hole existence. The TOC large-scale disturbances were considered in terms of barotropic Rossby waves. They propagate in zonal direction at the lower stratosphere heights. It is shown that wave velocity depends directly on the atmospheric pressure change with latitude and meridional profile of the zonal wind.

Introduction. Normal-mode Rossby waves are westward propagating planetary waves which are the free or resonant oscillations of the atmosphere. Planetary scale Rossby waves have an influence on the TOC spatial distribution. Disturbances of the Antarctic ozone hole shape under planetary waves influence are shown in Fig.1. The lowest zonal wave numbers determine the main features of ozone hole edge distortion. In this article, measurements from the TOMS are analyzed with a simple model based on the linearized stationary ozone continuity equation. The connection of TOC with atmosphere dynamical processes was discussed earlier in many papers (for example, [1-4]). The westward phase speeds are well described by linearized, quasigeostrophic theory that takes into account the modification of disturbances by stratification and by mean geostrophic motion. The planetary scale wave disturbances depend on the global atmosphere circulation and nonlinear effects [5, 6]. The theory of planetary scale waves is discussed in [7, 8].



a b

Fig. 1. The Antarctic ozone hole disturbances with dominance of a) zonal wave 1 (10 October 2003) and b) zonal wave 2 (12 October 1990) from the TOMS data.

Rossby waves in planetary atmospheres. Dynamics of the waves in the atmosphere of the rotating planet can be described with the equation system

$$\begin{cases} \dfrac{d\vec{V}}{dt} = -\vec{\nabla}(gH) + \Omega\left[\vec{V}, \vec{\zeta}\right] \\ \dfrac{\partial H}{\partial t} + \mathrm{div}\left(\vec{V}H\right) = 0 \end{cases}, \qquad (1)$$

where $\vec{V}$ is the horizontal component of the flow velocity in the atmosphere, $\vec{\zeta}$ is the vector normal to surface, φ is the latitude, Ω is the planet rotating frequency, g is the acceleration of gravity near the planetary surface, H is the effective atmosphere depth, which has a direct connection to see level pressure (for the atmosphere with molecules of effective masses M and temperatures T, undisturbed effective atmosphere depth is $H_0 = k_B T / Mg$, where k_B is the Boltzmann constant; for Earth H_0 is about 8 km, for Jupiter H_0 is about 25 km) [7, 8]. So, using this approximation the atmosphere is presented as incompressible layer of liquid with depth equal to H. We have dispersion equation for oscillations with small amplitudes

$$\omega\left(1 + k^2 r_R^2 - \frac{\omega^2}{\Omega^2}\right) = -k_\varphi v_*, kR >> 1, \qquad (2)$$

where $r_R = \frac{(gH_0)^{\frac{1}{2}}}{\Omega}$ is the barotropic Rossby radius (it is about 2000 km for Earth and 6000 km for Jupiter), $v_* = gH_0 / 2\omega_0 R \sin^2\alpha$ is Rossby velocity, k_φ is longitudinal projection of the wave vector. From equation (1) two dispersion equations can be obtained. For frequencies less than Ω the dispersion equation for Rossby waves can be found

$$\omega = -\frac{k_\varphi v_*}{1 + k^2 r_R^2},$$

where k is the wave vector.

The standard theory for barotropic Rossby waves predicts westward phase speeds of [7]

$$v_{ph} = -\frac{v_*}{1 + k^2 r_R^2}.$$

When a wavelength tends to infinity, the phase velocity tends to Rossby velocity v_*. Consider $\Omega >> \omega$. Taking into account Ertel theorem and making decomposition on small parameter ω / Ω we obtain from (1) [7]

$$\frac{\partial}{\partial t}\left(h - r_R^2 \Delta h\right) - \frac{v_*}{R}\frac{\partial}{\partial \varphi}\left(h + \frac{h^2}{2}\right) = \Omega r_R^4 [\nabla h, \nabla \Delta h], \quad (3)$$

where $h = (H - H_0)/H_0$. Then, using well known β-plane approximation, we introduce a two-dimensional local Cartesian system of coordinates (x, y) with longitude $x = \phi R \cos\varphi_0$ and latitude $y = (\varphi - \varphi_0)R$. ϕ_0 and φ_0 are longitude and latitude of the β-plane in the Earth surface contact point. In this coordinate system the x-axis is directed from the west to the east and the y-axis points from the south to the north. Then with the β-plane approximation (considering Coriolis parameter $f = 2\Omega \sin\varphi$ in the form $f = f_0 + \beta y$) we get the non-dimensional Charney-Obukhov equation

$$\frac{\partial(h - \Delta_\perp h)}{\partial t} - \beta\frac{\partial h}{\partial y} = \{h, \Delta_\perp h\}, \frac{\Delta_\perp h}{h} \geq 1, \quad (4)$$

where $\Delta\perp = \partial_x^2 + \partial_y^2$ is the two-dimensional Laplacian, $\beta = g/(2\omega_0 R \sin\alpha) << 1$ is non-dimensional Rossby velocity and $\{h, \Delta h\} = \partial_x h \partial_y \Delta h - \partial_y h \partial_x \Delta h$ denotes Poisson bracket.

Strong planetary wave activity causes large total ozone zonal deviations [1, 2] and disturbances of the ozone hole shape during the Antarctic spring (Fig. 1). In the next section the total ozone column disturbances are analyzed with a simple model based on the linearized Charney-Obukhov equation (4) and linearized stationary ozone continuity equation.

Data analysis. We consider measurements of the TOMS having been operated on different platforms since 1978. TOMS samples backscattered ultraviolet radiation at six wavelengths and provides a continuous mapping of total ozone column (http://toms.gsfc.nasa.gov). It provides almost complete daily global coverage of ozone measurements outside the polar region. We use the TOMS data in the most recent version 8.0 [9]. Also sea level pressure and zonal flow velocity data from the National Centers for Environmental Prediction – National Center for Atmospheric Research (NCEP–NCAR) reanalysis project were used (http://www.cdc.noaa.gov).

Dynamics of the TOC zonal disturbances is the object of our investigation. TOMS data show that the high amplitude variations (about 100 DU, i.e. more than 40% relative to undisturbed TOC) concentrate in the latitude range from 60S to 75S. At the same time, the see level atmosphere pressure disturbances by NCER-NCAR reanalysis can be equal to a few percents relative to undisturbed level. The analysis of ozone altitude profile on 15 height levels (derived from satellite Solar Backscattered Ultraviolet (SBUV) measurements on the Nimbus-7 satellite and the SBUV/2 instruments on NOAA-11, NOAA-16 and NOAA-9 satellites; link is http://www.cpc.ncep.noaa.gov/products/stratosphere/sbuv2to/sbuv2to_v8dvd.html) shows that a large-scale zonal wave in geopotential heights has the maximal coincidence with the total ozone wave at altitudes of about 10-20 km.

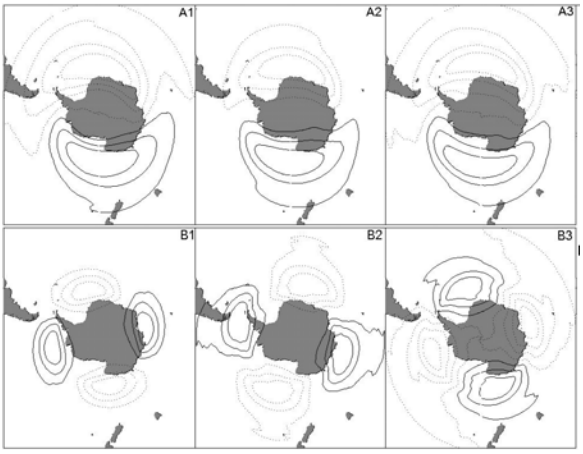


Fig. 2. Dynamics of wave motion. A1, A2 and A3 show wave 1 dynamics 10, 12 and 14 October 2003. B1, B2 and B3 show wave 2 dynamics 7, 9 and 11 October 1990.

Table 1. Zonal harmonic velocities from Rossby wave dispersion equation and from TOMS measurements for October 2003 (Fig. 2).

Zonal harmonic number	1	2	3
Wave velocity without pressure gradient and zonal wind effects, m/s	-37,63	-19,24	-10,6
Observed wave velocity, m/s	1,7	9,53	13,85

These are the altitudes of ozone maximum giving the main contribution to column ozone, therefore, TOC is the indicator of atmospheric planetary scale wave activity in the lower stratosphere of the Antarctic region. Dynamics of the wave 1 and wave 2 controls the main part of the TOC zonal disturbances, as it can be seen from Fig. 2. The average amplitudes of zonal harmonics are shown in Fig. 3A (10-20 October 2003, the first harmonic dominates) and Fig. 3B (5-15 October 1990, the second zonal harmonic has the maximal amplitude). The TOC fields for these events are shown in Fig.1 a) and b) respectively.

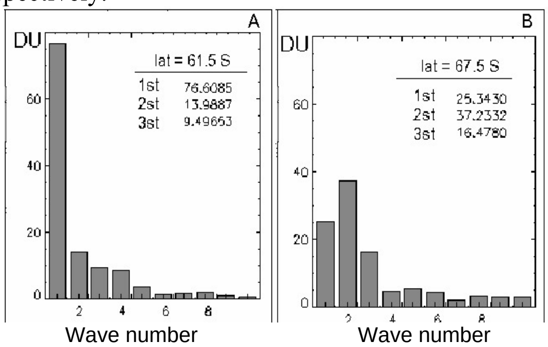


Fig. 3. Amplitudes of TOC zonal harmonics 1-10 in Dobson units for (A) 10-20 October 2003 and (B) 5-15 October 1990.

TOC zonal distribution decomposition with the first 3 harmonics is a good approximation of total wave in ozone zonal distribution. The remainder of difference between the total wave and its 3-harmonic reconstruction is normally distributed white noise. So, the regular structure of TOC zonal variations can be modeled by zonal wave dynamics represented by the first three harmonics.

Taking into account the zonal flow and sea level atmospheric pressure heterogeneity, the dispersion relation has the form [7]

$$v_{ph} = u + \frac{\omega}{k_x} = u - \frac{\beta r_R^2}{1 + k^2 r_R^2} \qquad (5),$$

where β is transformed to a form (taking into account meridional inhomogeneity of H):

$$\beta = \partial_y f - (f/H)\partial_y H \qquad (6).$$

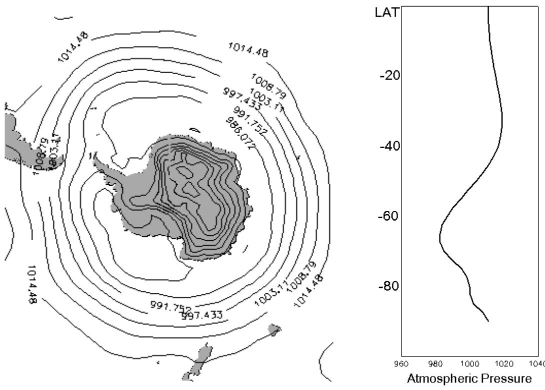


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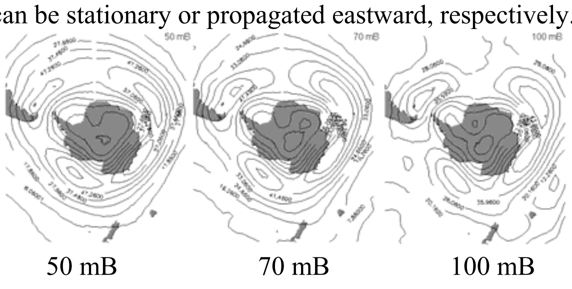
Fig. 4. a) Sea level pressure for 10.10.2003. Zonal distribution has disturbance only in the Antarctic Peninsula; b) The zonal mean sea level pressure depending on the geographic latitude for 10.10.2003. The change of gradient sign at the latitude of about 65S is seen.

Fig. 4 demonstrates that H depends on latitude and constant H is unacceptable approach (H is proportional to the sea level pressure). But mainly H-contours are concentric relative to the South Pole. So, if zonal flow velocity has the eastward direction and equals to or exceeds Rossby velocity for the given latitude (i.e., if the second item in (6) equals or exceeds the first one), Rossby wave in the zonal flow can be stationary or propagated eastward, respectively.



50 mB 70 mB 100 mB

Fig.5. Zonal flow at the levels of 50, 70, 100 mB, 10 October 2003. The maximum velocity of zonal flow is observed at the latitude 60S.

It is seen from the behavior of wave 1 (October 2003) in Fig. 2A and wave 2 (October 1990) in Fig 2B. Snapshots of zonal flow velocities at three pressure levels 100 mB, 70 mB and 50 mB are shown in Fig. 5. At these pressure levels circumpolar flow is rather zonally homogeneous. In Table 1 one can see quasi-stationary situation in the case of wave 1 (the low phase velocity of 1.7 m/s) as distinct from the steady eastward propagation of wave 2 and wave 3 (phase velocities of 9.5 and 13.8 m/s, respectively) in October 2003. Note that the theory by equation (2) gives westward propagation at velocities, which are decreasing with wave number.

Hence, from (5), latitudinal dependence of parameters β, u, r_R can be restored from linear equation system with observed Rossby wave 1, wave 2 and wave 3 velocities. Velocities of mean zonal flow in latitude interval 60S-75S and the restored ones from dispersion relation parameters are shown in Table 2. The relation of these parameters modulates the wave propagation angular velocity $v_{ph}/(R\sin\varphi)$.

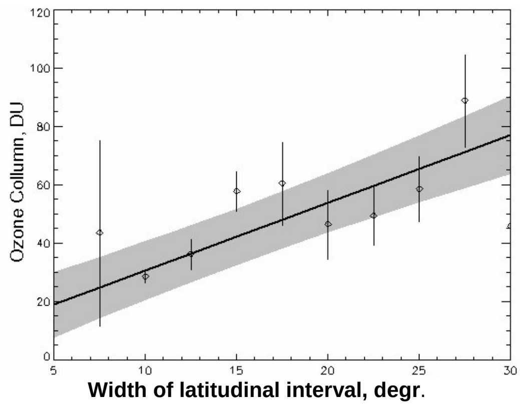


Fig. 6. Dependence of ozone wave 1 amplitude on the width of constant angular velocity latitude interval. Experimental averaged points with 95% significance are marked with ◊ symbols. The solid line is the least-squares approximation with the 95% significance interval marked gray.

If angular velocity is nearly constant in the latitude interval, then the waves move as an integral structure and tend to be stable. Thus, the large amplitude wave activity can exist only in the latitude zone where such relation is even. Also the width of the latitude interval with constant angular velocity determines wave 1 amplitude. The correlation coefficient varies from 0.3 to 0.65. The linear approximation for 1990 is shown in Fig. 6. Wave 2 amplitude can not be approximated linearly. But some anticorrelation with wave 1 amplitude is observed. As seen from Fig. 7-A1, constant angular velocity during 10-20 October 2003 is in the interval from 60S to 80S (20-degree band) for wave 1. So wave 1 is dominant in Fig. 5-B1. Such interval for October 1990 is about 10 degrees (it is roughly from 60S to 70S for wave 1). Conditions are not favorable for wave 1, but, possibly, due to anticorrelation, wave 2 has the maximal amplitude. Hence, in this region the meridional profile of zonal flow and see level atmospheric pressure determines the possibility of high-amplitude planetary wave existence.

The numerical model of polar atmosphere dynamics in geostrophic approximation is proposed. It is based on numerical solution of the Charney-Obukhov equation. The method is based on the full reduction algorithm. It is adapted to the periodic border conditions. The nonlinearity is simulated according to difference approximation proposed in [10]. It gives an opportunity to keep off numerical instability, which is typical for vector nonlinearity simulation. Charney-Obukhov equation has a form similar to the Hasegawa-Mima equation for two-dimensional motion in inhomogeneous plasmas. The results of the proposed model were compared with the results of numerical model of the Hasegawa-Mima equation [11] and a good agreement was obtained.

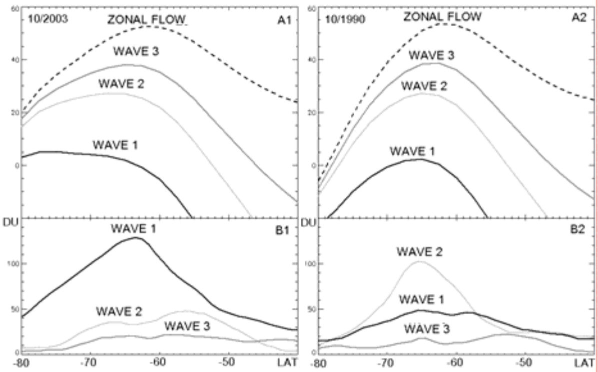


Fig. 7. A1 and A2 present the latitudinal profiles of zonal flow angular velocity at the level of 100 mB (dashed line, degrees of longitude per day for October 2003 and 1990, respectively. NCEP-NCAR reanalysis data. Latitudinal profiles of wave 1, wave 2 and wave 3 angular velocities are shown by solid lines. On plots B1 and B2 the corresponding latitudinal profiles of amplitude of zonal waves 1-3 in total ozone are shown (in Dobson Units).

The numerical simulation of atmosphere dynamic was carried out based on the real latitude profile of sea level atmospheric pressure and zonal flow velocity in the altitude range from 100 mB to 50 mB. This range of altitude includes the ozone maximum. Results of numerical modeling confirm the features of regular wave structure by TOMS observations and stable existence of wave 1 in TOC with low stability of waves 2 and 3. The characteristic lifetime of wave 1 is about one month. The characteristic lifetime of wave 2 and wave 3 is about 5-7 days. Also the possibility of phase stability (zonal stationarity) of wave 1 in zonal flow is confirmed.

Conclusion. In this study the global observations of the total ozone from TOMS were used to quantify the zonal and hemispheric variability of the lower stratosphere ozone. A spectral statistical harmonic analysis is applied to derive amplitudes and phases of the zonal wave number 1, 2 and 3. These results can be summarized as follows:

Zonal disturbances of TOC have harmonic zonal structure. Waves 1, 2 and 3 are usually presented on the border of ozone hole at 60S-75S. Restored modified dispersion equation enables to get zonal flow velocity from equation (5) and to compare it with the observed values.

The dependence of TOC dynamics in high southern latitudes on the parameters of sea level pressure and zonal flow in the lower stratosphere is confirmed. Latitudinal profile of zonal flow velocity determines harmonics with maximal amplitude of zonal Rossby wave.

Numerical model verification of wave dynamics of the polar stratosphere in geostrophical approximation is in a good agreement with the TOC wave dynamics from the TOMS measurements in the south polar region.

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