ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2018, Vol. 54, No. 1, pp. 32–38. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © G.M. Shved, Ya.A. Virolainen, Yu.M. Timofeyev, S.I. Ermolenko, S.P. Smyshlyaev, M.A. Motsakov, O. Kirner, 2018, published in Izvestiya Rossiiskoi Akademii Nauk, Fizika Atmosfery i Okeana, 2018, Vol. 54, No. 1, pp. 36–44.

Ozone Temporal Variability in the Subarctic Region: Comparison of Satellite Measurements with Numerical Simulations

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Received November 3, 2016; in final form, January 11, 2017

Abstract—Fourier and wavelet spectra of time series for the ozone column abundance in the atmospheric 0–25 and 25–60 km layers are analyzed from SBUV satellite observations and from numerical simulations based on the RSHU and EMAC models. The analysis uses datasets for three subarctic locations (St. Petersburg, Harestua, and Kiruna) for 2000–2014. The Fourier and wavelet spectra show periodicities in the range from ~10 days to ~10 years and from ~1 day to ~2 years, respectively. The comparison of the spectra shows overall agreement between the observational and modeled datasets. However, the analysis has revealed differences both between the measurements and the models and between the models themselves. The differences primarily concern the Rossby wave period region and the 11-year and semiannual periodicities. Possible reasons are given for the differences between the models and the measurements.

Keywords: atmospheric composition, ozone variability, satellite measurements, atmospheric composition models, the Subarctic

DOI: 10.1134/S0001433817060111

1. INTRODUCTION

The anthropogenic depletion of ozone, primarily in the form of ozone holes over Antarctica, was discovered in the 1980s [1]. Ozone depletion has also been observed at other latitudes of the globe. For example, ozone miniholes are regularly observed at high and middle latitudes of the northern hemisphere [2, 3]. The thinner the ozone layer, the larger the amount of ultraviolet (UV) solar radiation incident on the Earth's surface, and an excess of UV radiation is detrimental to ecology [4]. Ozone plays an important role in the radiation balance of the stratosphere and largely determines its thermal structure. Finally, high concentrations of ground-level ozone are harmful for human health and vegetation.

These and other traits of ozone motivate numerous experimental and model studies. Regular data both on total ozone and its vertical distribution come from ground-based and satellite ozone monitoring. Researchers use numerical 3D models of the atmosphere and its composition to describe ozone spatial and temporal variabilities in the atmosphere, including forecasts of the regeneration of the ozone layer. In this article, we investigate ozone temporal variability over 15 years from satellite measurements and numerical models for three locations in the Subarctic: St. Petersburg (59.9° N, 29.8° E), Harestua (60.2° N, 10.8° E), and Kiruna (67.8° N, 20.4° E). The measurements and simulations are compared to analyze the quality of the numerical models.

2. INPUT DATA AND THEIR PROCESSING

The satellite measurements in our study were the measurement data from the Solar Backscatter Ultraviolet Instrument (SBUV), which provides ozone data from the troposphere heights to the lower mesosphere. Instruments such as the SBUV measure scattered and reflected solar UV radiation. Descriptions of the instrument and measurement interpretation algorithms, including an analysis of their errors, are given, e.g., in [5].

Ozone abundances were simulated using the chemistry–transport model for the composition of the lower and middle atmosphere, which was developed by the Russian State Hydrometeorological University (RSHU) [6], and the EMAC (ECHAM/MESSy Atmospheric Chemistry) chemistry–climate model [7]. The main difference between the models is as follows: in the EMAC simulations, the variability of the atmospheric parameters is calculated using the assimilation of ERA-INTERIM reanalysis results [8], while

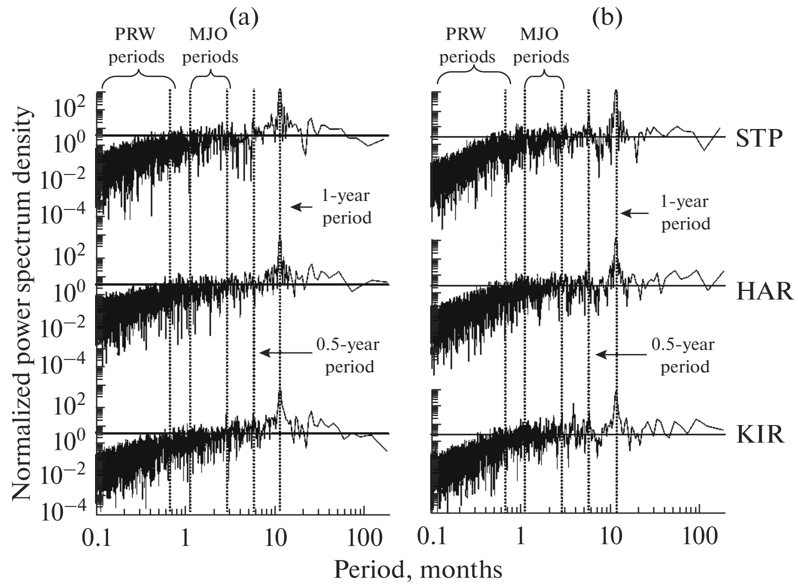

Fig. 1. Fourier spectra of ozone variations in (a) the 0–25 km and (b) 25–60 km layers from the SBUV measurements for three locations: STP (St. Petersburg), HAR (Harestua), and KIR (Kiruna). The period ranges of planetary Rossby waves (PRWs) and Madden–Julian oscillation (MJO) are marked by vertical lines. The horizontal line corresponds to the 95% confidence level.

in the RSHU model the atmospheric parameters are borrowed from MERRA reanalysis data [9]. A detailed description of the models and their applications is given in [10–12].

This study covered the period from January 2000 to June 2014. The ozone column abundance was analyzed separately for the 0–25 and 25–60 km layers. The physical explanation for this separation is that the ozone abundance in the 25–60 km layer is usually determined by photochemical processes, whereas, in the 0–25 km layer, ozone is mainly controlled by dynamic processes in the atmosphere. The SBUV ozone measurement series for the 0–25 and 25–60 km layers for St. Petersburg, Harestua, and Kiruna were subjected to Fourier spectral analysis by the Lomb–Scargle method (Fig. 1). The series for St. Petersburg were also subjected to Morlet 6 wavelet analysis (Fig. 2) [13]. As a result, the analysis of the Fourier spectra revealed periodicities in the period range from ~10 days to ~10 years. The wavelet spectra confidently demonstrate periodicities with periods from ~1 day to ~2 years. All the periodicities were previously detected in ozone variations. A classification of periodic variations in total ozone and a detailed review of the literature are given in [14].

St. Petersburg and Harestua are located at almost the same latitude, spaced from each other at a relatively small distance of about 1000 km. Since, as we show below, the main characteristics of ozone variability spectra depend on global processes in the atmosphere, these characteristics are, as expected, the same over these two locations. Although the distance from these locations to Kiruna is roughly the same, the latter lies beyond the Arctic Circle. This circumstance leads to major changes in ozone photochemistry and prevents SBUV ozone measurements in a certain time neighborhood of the winter solstice.

3. PHYSICAL NATURE OF THE OBSERVED OSCILLATIONS

The shortest period oscillations in the Fourier and wavelet spectra of ozone variations are due to inertia (rotational) normal modes of the atmosphere, or planetary Rossby waves. These waves are classified into families with characteristic periods of 2, 4, 5, 6.5, 10, 16, and 30 days [15]. All these families were previously detected in ozone variations from satellite and ground-based observations [14, 16–20], including the detection of Rossby waves with periods of ~5–10 days from the SBUV data [21, 22]. As was noted above, the Fourier spectra show statistically significant Rossby waves only for periods of ~10 days or longer. At the same time, the wavelet spectra demonstrate all their families. The latter clearly follows from the fact that Rossby waves intensify in the northern hemisphere in the winter half of the year, as noted previously in [15]. This feature of the excitation of Rossby waves manifests itself in the wavelet spectra also during the processing of series of ground-based barometric and even seismometric measurements [23].

Two more sources of periodic perturbations of the atmosphere have a period of about 1 month. Firstly, the Sun's rotation around its own axis with a period of 27 days leads to variations in solar UV irradiation [24]. Secondly, the Moon's orbiting around the Earth with a synodic period of 29.53 days, during which the

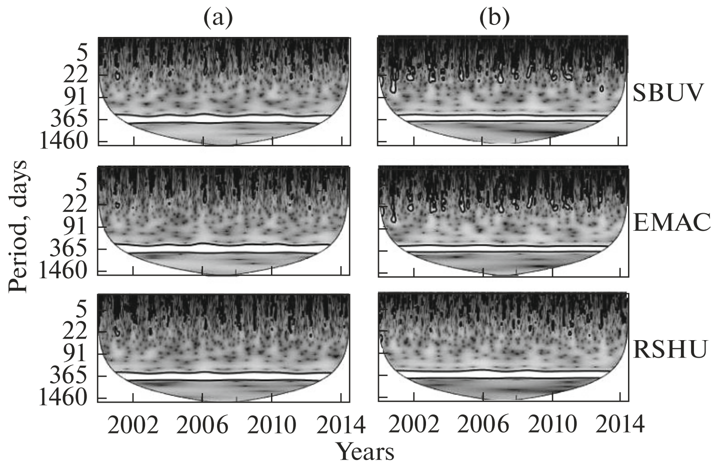

Fig. 2. Wavelet spectra of ozone variations over St. Petersburg in (a) the 0–25 km and (b) 25–60 km layers from the SBUV measurements and the EMAC and RSHU simulations. The contour lines, including the blackened areas, correspond to the 95% confidence level.

Moon's phases complete a full cycle, disturbs the Earth's gravitational field, leading to tidal motion of the atmosphere.

The amplitude of Rossby waves and tides increases with altitude [25]. Accordingly, the Rossby wave–associated atmospheric temperature and density variations affecting the rate of the photochemical processes (which determine ozone abundances) also increase with altitude. Moreover, solar UV radiation influences atmospheric processes more strongly as altitude increases. This influence can transform into changes in the rate of ozone production and loss due to variations in the rates of dissociation of molecules by solar radiation, since it leads both to variations in the concentration of photodissociation products entering chemical reactions and to a change in the atmospheric temperature, which is due to the heating of the atmosphere upon the absorption of solar radiation and affects the rate of chemical reactions. The Sun's rotation period of 27 days was found in ozone variations in the upper stratosphere from the SBUV measurements [26]. Thus, it is natural that periodicities in the period range of ~2–30 days in the Fourier and wavelet spectra of ozone variations manifest themselves more clearly in the 25–60 km layer than in the 0–25 km layer.

The cause of the observed so-called intraseasonal oscillation of all atmospheric parameters is the Madden–Julian oscillation (MJO), which forms in the tropical troposphere [27]. The time intervals between atmospheric disturbances caused by the MJO vary widely, from 1 to 3 months. The characteristic period of the MJO can be taken at 50 days. Ozone variations in this period range were observed previously [14]. The Fourier and wavelet spectra considered here show a perturbation of ozone abundance in both layers under consideration. In the period range from about 3 to 6 months, there are no tangible quasi-periodic processes in the atmosphere.

In the tropics in the upper stratosphere and lower mesosphere, one can observe a semiannual oscillation (SAO) in zonal wind; the SAO is caused by the transfer of momentum to the atmosphere from internal gravity waves (IGWs) propagating from below [25, 28]. The tropical SAO in zonal wind leads to the perturbation of all atmospheric parameters at all latitudes. Semiannual ozone variations were observed previously [14, 29, 30]. The clear semiannual periodicity in the Fourier and wavelet spectra of ozone variations in the 25–60 km layer should be associated with the SAO. This periodicity could be taken as the second harmonic of the strong annual variations in ozone (see below). However, the weakness of the semiannual periodicity in the spectra for the 0–25 km layer in the presence of strong annual ozone variations confirms that the cause of this periodicity, at least in the 25–60 km layer, is the SAO.

The strongest periodicity in the Fourier and wavelet spectra of ozone variations is, as expected, the annual periodicity: Ozone experiences strong annual variations due to annual changes both in the rate of photochemical processes and in the system of atmospheric motions.

In the tropical lower and middle stratosphere, one observes a quasi-biennial oscillation (QBO) in zonal wind; the QBO is caused by the transfer of momentum to the atmosphere from IGWs and equatorial waves propagating from below [25, 31]. The QBO period varies from 22 to 34 months with an average of 28 months. Like the SAO, the QBO in zonal wind in the tropics leads to the perturbation of all atmospheric parameters at all latitudes. Moreover, there is a quasi-biennial mode in solar activity fluctuations [32, 33], which can affect the ozone abundance above 25 km due to variations in solar UV radiation, as discussed above regarding the effect on ozone of the Sun's rotation with a 27-day period. At middle latitudes, there are quasi-biennial temperature variations in the atmosphere from the surface to the lower thermosphere [34]. A quasi-biennial periodicity was found in the amplitude of temperature variations in planetary waves in the lower stratosphere at middle and high latitudes of the northern hemisphere [35]. Quasi-biennial variations in ozone were observed previously [14, 29, 30, 36], including with the SBUV [37]. The quasi-biennial periodicity manifests itself in the Fourier and wavelet spectra of ozone variations for both layers, but stands out most conspicuously in the 0–25 km layer.

The longest period ozone variations revealed by the Fourier spectra should be mainly associated with a quasi-periodic process in the tropical troposphere, called the El Niño Southern Oscillation (ENSO) [38], and with multiyear variations in solar activity [24, 32, 33]. The time intervals between the atmospheric disturbances caused by the ENSO vary widely, from two to seven years, and the characteristic period of the ENSO can be taken at 40 months. Like the SAO and QBO in zonal wind in the tropics, the ENSO leads to the perturbation of all atmospheric parameters at all latitudes: e.g., at middle latitudes, this oscillation manifests itself as a 3.4-year periodicity in atmospheric temperature changes from the surface to the lower thermosphere [34]. Speaking about fluctuations in solar activity, which affects ozone mainly through changes in solar UV irradiation, they include, above all, the well-known 11-year cycle, which manifests itself in variations of all atmospheric parameters and processes [39, 40]. A 7–8-year mode was also detected [33], whose effect on the atmosphere is apparently confirmed by observations of the 8-year periodicity in the amplitude of temperature variations in planetary waves in the lower stratosphere at middle and high latitudes of the Northern Hemisphere [35]. Variations in atmospheric parameters with a period of about 5 years are also observed [34, 41]. The reason for this periodicity may be, firstly, the second harmonic of the 11-year cycle of solar activity [32]. Secondly, periodic filtration of IGWs propagating from below, due to the abovementioned QBO in zonal wind, leads to the interaction of the QBO with an equatorial annual oscillation in this wind, which forms a 5-year periodicity of the wind speed in the equatorial stratosphere [41]. There are many observations of multiyear variations in ozone [14, 30, 42], including observations of its 11-year variations in the stratosphere from the SBUV data [26, 43, 44]. The Fourier spectra demonstrate, in the period range under discussion, clear signs that can be associated with the above phenomena. Expectedly, the 11-year cycle of solar activity manifests itself in ozone variations in the 25–60 km layer more clearly than in the 0–25 km layer.

4. COMPARING THE OBSERVATIONS WITH THE MODELS AND COMPARING THE MODELS BETWEEN THEMSELVES

For both layers we compared the Fourier spectra of ozone variations obtained from the SBUV observations with those obtained from the EMAC and RSHU simulations for St. Petersburg and Kiruna for the same time interval (Figs. 3, 4). We made a similar comparison for the wavelet spectra of ozone variations over St. Petersburg (Fig. 2). The spectra obtained from the observations and the models show good overall agreement. However, there are a few differences both between the measurements and the models and between the models themselves.

(1) The Fourier spectra of the observed ozone variations over Kiruna in the 25–60 km layer contain intensive harmonics of the annual variations, from the third to the seventh (Fig. 4b). The same harmonics, although much weaker, manifest themselves in the spectra for the 0–25 km layer (Fig. 3b). However, there are no such harmonics in the spectra from the simulations (Figs. 3b, 4b). Consequently, these harmonics in the spectra from the observations are an artifact due to breaks in ozone measurements near the winter solstice.

(2) The 11-year periodicity and SAO, both of which form above 25 km, manifest themselves in the Fourier spectra in the 0–25 km layer much more clearly in the models than in the observations (Fig. 3). One possible explanation for this discrepancy is that the models use an overestimated velocity of the downward transfer of ozone by motions in the stratosphere.

(3) In the 25–60 km layer, the Fourier spectra obtained from the EMAC model, like the Fourier spectra from the observations, confidently demonstrate an 11-year periodicity, but in the RSHU model this periodicity is rather weak (Fig. 4). The reason for this discrepancy may be, e.g., that the models use different frequency dependences of solar UV radiation and/or different parameters of the photochemical processes underlying ozone production and loss. The sensitivity of the model estimates for stratospheric ozone to the UV radiation models in different phases of solar activity was demonstrated in [45].

(4) In the Rossby wave period range, from ~2 to ~30 days, the wavelet spectra for the 25–60 km layer from the EMAC model show excellent agreement with those obtained from the observations. In the RSHU model, these waves have a much weaker impact on ozone variations; moreover, their impact on ozone may sometimes not coincide in time with the observations (Fig. 2b). However, for the 0–25 km layer, the RSHU model reproduces the Rossby wave effect well (Fig. 2a). Since Rossby waves form in the troposphere, a likely reason for this discrepancy is that the model inaccurately reproduces the propagation of Rossby waves in the stratosphere.

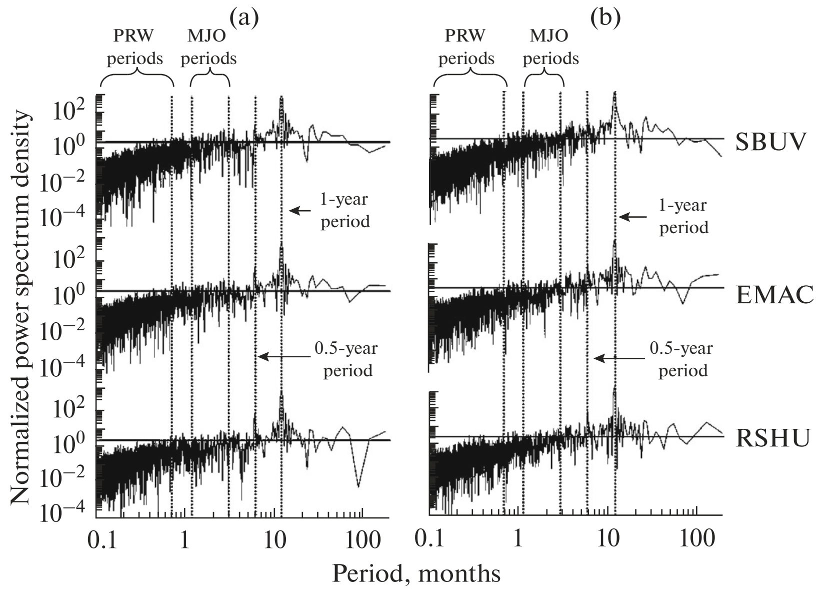

Fig. 3. Fourier spectra of ozone variations in the 0–25 km layers over (a) St. Petersburg and (b) Kiruna from the SBUV measurements and the EMAC and RSHU simulations. Further explanations are given in the captions to Figs. 1 and 2.

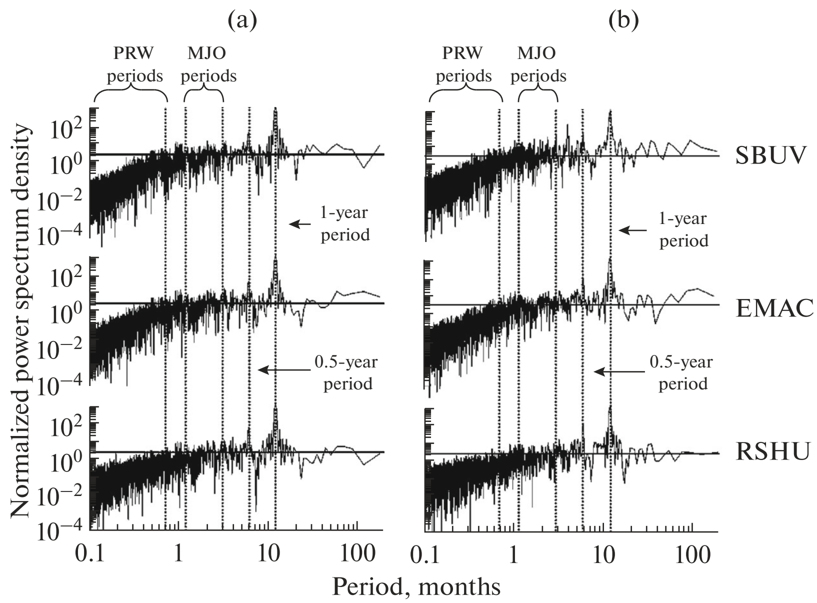

Fig. 4. The same as in Fig. 3 but for the 25–60 km layer.

5. CONCLUSIONS

For the period 2000–2014, we investigated ozone temporal variability in two layers (0–25 and 25–60 km) for three observation points in the Subarctic region (St. Petersburg, Harestua, and Kiruna) using Fourier and wavelet spectra. We analyzed both satellite measurements (SBUV) and numerical simulations (RSHU and EMAC models). The Fourier spectra revealed periodicities in a period range of ~10 days to ~10 years. The wavelet spectra confidently demonstrate periodicities with periods from ~1 day to ~2 years. The physical nature of the revealed periodicities was discussed in detail and analyzed. The Fourier and wavelet spectra obtained from ozone observations were compared with those from the simulations; a similar comparison was made between the models. The comparisons led us to the following conclusions:

(1) The 11-year periodicity and SAO in the Fourier spectra manifest themselves in the 0–25 km layer much more clearly in the models than in the observa-

tions. A likely explanation for this is that the models can overestimate the velocity of the downward transfer of ozone by motions in the stratosphere.

(2) The differences between the RSHU and EMAC model in the 25–60 km layer in the representation of the 11-year periodicity may be due to the different frequency dependences of solar UV radiation and/or a difference in the parameters of the photochemical processes underlying ozone production and loss.

(3) In the Rossby wave period range, from ~2 to ~30 days, the wavelet spectra for the 25–60 km layer from the RSHU model differ significantly from those obtained from the satellite data and from the EMAC model. A likely reason for this discrepancy is that the model inaccurately reproduces the propagation of Rossby waves in the stratosphere.

ACKNOWLEDGMENTS

The collection and analysis of the data was supported by the Russian Science Foundation, project no. 14-17-00096. The comparison with the EMAC data was supported by St. Petersburg State University, project no. 11.42.1057.2016.

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Translated by A. Kobkova