ISSN 0016-7932, Geomagnetism and Aeronomy, 2014, Vol. 54, No. 3, pp. 357–372. © Pleiades Publishing, Ltd., 2014.
Original Russian Text © A.I. Pogoreltsev, E.N. Savenkova, N.N. Pertsev, 2014, published in Geomagnetizm i Aeronomiya, 2014, Vol. 54, No. 3, pp. 387–403.

Sudden Stratospheric Warmings: the Role of Normal Atmospheric Modes

A. I. Pogoreltsev[a], E. N. Savenkova[a], and N. N. Pertsev[b]

[a] *Russian State Hydrometeorological University, St. Petersburg, Russia*
[b] *Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Moscow, Russia*
e-mail: apogor@rshu.ru

Received December 5, 1012; in final form April 10, 2013

Abstract—The role of normal atmospheric modes in the beginning and development of sudden stratospheric warming (SSW) events is studied on the basis of calculations with the use of the general circulation model of the middle and upper atmosphere. The analysis of the effect of a phase of quasi-biennial oscillations on the dynamics of the extratropical stratosphere has shown that the conditions for SSW commencement are more favorable and the SSW events are more intense during the easterly phase of these oscillations as compared to the westerly phase. The conclusion has been drawn that fundamental normal atmospheric modes can be recorded in the temperature field at mesopause altitudes during ground-based optical measurements.

DOI: 10.1134/S0016793214020169

1. INTRODUCTION

Sudden stratospheric warming (SSW) events are among the brightest processes during which the dynamic interaction between the troposphere, stratosphere, and upper atmosphere manifests (Holton, 1980; McIntyre, 1982). According to existing concepts (Stan and Straus, 2009), SSW events can develop due to two causes: intensification of wave activity in the lower atmosphere, which is accompanied by growth of wave flow from the troposphere to the stratosphere (the so-called classical scenario suggested in (Matsuno, 1971)) and/or internal dynamic processes, i.e., nonlinear interaction of planetary waves with the average flow at stratospheric altitudes (Scott and Polvani, 2006; Pogoreltsev, 2007). SSW events have been of significantly increasing interest in the last few years. This is connected, first, with the fact that recent study results show a significant effect of stratospheric events on formation of weather anomalies and climate in the troposphere (Baldwin and Dunkerton, 2001; Baldwin et al., 2007; Sun and Robinson, 2009; Woollings et al., 2010). In addition, the influence of SSW events on the dynamics and energetics of the upper atmosphere (the mesosphere and even the thermosphere), i.e., on the formation of space weather, was discovered (Siskind et al., 2010; Kurihara et al., 2010; Fuller-Rowell et al., 2010; Funke et al., 2010; Liu et al., 2011; Yuan et al., 2012). They can also manifest in disturbances of ionospheric parameters (Pedatella and Forbes, 2010; Pancheva and Mukhtarov, 2011), which should be taken into account when solving radio communication, radiolocation, and navigation problems. Past decades, an increase in the activity of stationary planetary waves (SPW) is noted in the stratosphere (Pogoreltsev et al., 2009a) and, as a consequence, intensification of their nonlinear interaction with the average flow, which results in an increase in the intensity of irregular oscillations, the so-called stratospheric vacillations (Holton and Mass, 1976; Pogoreltsev, 2007).

Despite the increased interest in the study of SSW and their effect on the weather, climate, and upper atmosphere, including ionosphere, writers of articles usually limit themselves to the analysis of features of events observed during past years (see, e.g., (Labitzke and Kunze, 2009; Ayarzaguena et al., 2011; Kuttippurath and Nikulin, 2012)). The question of the source and/or cause of SSW beginning is still open (Sun et al., 2011). The analysis of dynamic processes in the stratosphere that we carried out on the basis of UK Meteorological Office data (Swinbank and O'Neill, 1994) shows that the relative role of different mechanisms of SSW event beginning has been reevaluated in view of the climatic changes in recent decades (1992–2012) and internal processes connected with nonlinear SPW–average flow interaction are beginning to predominate (Pogoreltsev et al., 2009a). That insufficient attention is paid to internal dynamic processes during analysis of SSW events was also pointed out in a recent work devoted to the analysis of the SSW event of January 2009 (Labitzke and Kunze, 2009).

The Earth's atmosphere is an oscillating system where global natural (resonance) oscillations can be excited, the so-called normal atmospheric modes (NAMs) (Longuet-Higgins, 1968; Dikii, 1969; Salby, 1984; Volland, 1988; Madden, 2007). There are many works at present devoted to the study of NAM parameters in the troposphere and lower stratosphere on the basis of global distribution of meteorological fields (Delan, 1964; Eliasen and Machenhauer, 1965; Dikii and Golitsyn, 1968; Madden, 1978; Ahlquist, 1982; Lindzen et al., 1984). The experimental results obtained in these works have been summarized in reviews (Madden, 1979; Salby, 1984). The global distribution of meteorological fields in the troposphere for 10 years incorporated in the ECMWF (European Center for Medium-Range Weather Forecasts) model was analyzed in (Weber and Madden, 1993) with the purpose of studying the SPW and NAM climatology in the lower atmosphere. A similar analysis for the stratosphere was carried out in (Fedulina et al., 2004). Studies of the global structure of travelling planetary waves in the upper stratosphere, mesosphere, and lower thermosphere are mainly based on time-limited observation series received from satellite measurements (Rodgers, 1976; Hirota and Hirooka, 1984; Hirooka and Hirota, 1985, 1989; Wu et al., 1994; Talaat et al., 2001), and our knowledge of the global properties of planetary waves in these regions is yet fragmentary. There are long time series of ground-based radar measurements of horizontal components of the wind speed in the mesosphere and lower thermosphere (Vincent, 1984), and comparative analysis of planetary wave parameters from different observation sites allows estimation of the zonal wave number and determination of the latitudinal structure of wave fields (Clark et al., 2001; Pogoreltsev et al., 2002a, 2002b). Further progress in the understanding of global dynamic processes in the middle atmosphere can be achieved only if the results of analysis of satellite and ground-based spectrophotometric and radar measurements in the mesosphere and lower troposphere are supplemented by the detail analysis of the dynamic conditions in the stratosphere with the use of global distributions of meteorological fields incorporated in the general atmospheric circulation model (Pogoreltsev et al., 2002b; Talaat et al., 2002; Fedulina et al., 2004). Data incorporated in the UK Met Office model (Swinbank and O'Neill, 1994) are the most promising in this context, because the upper boundary of this model was lifted recently up to the 0.01-gPa level, which allows the analysis of planetary waves at different altitudes, including the mesosphere. Data used in the NOGAPS-ALPHA (Navy Operational Global Atmospheric Prediction System—Advanced Level Physics High-Altitude) system are an alternative; they cover an even larger altitude range (0–92 km) and have been successfully used for the study of NAM parameters during past winters (Sassi et al., 2012). Alongside planetary waves, tide and gravity waves participate in the formation of a response of the mesosphere–lower thermosphere region to stratospheric warming events. Thus, it has been shown that an increase in the mesopause temperature after stratospheric warming events is accompanied by a noticeable increase in the diurnal gravity-wave dispersion of the temperature (Perminov and Pertsev, 2013). Thus, only a combination of empirical and assimilated data with different time resolutions can provide a more or less genuine pattern of a response of the mesosphere and thermosphere to stratospheric warming events.

Though NAM are an essential part of the large-scale atmospheric dynamics, they are paid insufficient attention during simulation of general atmospheric circulation. In particular, models are not analyzed for possibilities of reproducing global resonance atmospheric properties, reproducibility of intraseasonal variability, which strongly depends on correct reproduction of natural atmospheric oscillations, is not tested (Pogoreltsev, 2007). In addition, as was mentioned in (Madden, 2007), NAM generation can be caused by active weather formations, heavy precipitation, and other local processes in the troposphere, which are not reproduced in mechanistic models of atmospheric circulation. Thus, for an adequate description of natural oscillations when modeling the atmospheric circulation with the use of mechanistic models, an effective scheme of their parameterization is required (similar to parameterization of effects of internal gravity waves, reproduction of which is impossible under the current model resolution).

In this work, we make an attempt to take into NAM effects by means of introduction of additional heating sources at tropospheric altitudes into the general circulation model. These sources have the latitude structure of NAM (of Hough functions) and periods corresponding to fundamental modes of natural atmospheric oscillations are altitude localized, while their intensity is chosen so that the NAM altitudes calculated correspond to observed ones (Pogoreltsev et al., 2002a, b, 2009a; Fedulina et al., 2004; Sassi et al., 2012).

2. DESCRIPTION OF MODEL EXPERIMENTS

To simulate the general atmospheric circulation and estimate the role of NAM in the beginning and development of SSW events, a 3D nonlinear model of the middle and upper atmosphere (MUAM) was used (Pogoreltsev, 2007; Pogoreltsev et al., 2007) developed on the basis of the COMMA-LIM (Cologne Model of the Middle Atmosphere-Leipzig Institute for Meteorology) (Fröhlich et al., 2003). MUAM is a finite-difference model with a horizontal resolution of 5° × 5.625° (latitude × longitude). Log-isobaric dimensionless coordinate $x = -\ln\left(\frac{p}{1000}\right)$ (p is the pressure in hPa) is used as a vertical coordinate. Below, the dimensional log-isobaric altitude $z = x \times 7$ km is shown in figures, which approximately corresponds to the geopotential (geometric) altitude in the middle atmosphere. The calculations were carried out with the altitude step $\Delta x = 0.406$. The model version with 48 vertical levels was used; i.e., the range of altitude integration was 0–135 km. The distributions of geopotential altitude and temperature for January obtained from data in the UK

Met Office model and averaged over 1992–2011 were used as the bottom boundary conditions at a level of 1000 hPa (Swinbank and O'Neill, 1994). In contrast to earlier MUAM models (Pogoreltsev, 2007; Pogoreltsev et al., 2007), a 3D climatic (1996–2005 averaged) ozone distribution taking into account longitudinal ozone inhomogeneities was used in the simulation (Pogoreltsev et al., 2009b; Suvorova and Pogoreltsev, 2010).

Quasi-biennial oscillations (QBOs) of a zonal flow, which are observable at low latitudes, are a feature of the dynamics of the middle atmosphere (Baldwin et al., 2001; Devyatova and Mordvinov, 2011). To take into account the effect of the QBO phase on the dynamics of extratropical stratosphere, an additional term was introduced into the prognostic equation for the zonal flow, which is proportional to the difference in the calculated and observed values of zonally averaged wind speed and was taken into account at the 17.5° S–17.5° N latitudes at altitudes of 0–50 km. Figures 1a and 1b show the distributions of the zonally averaged flow and rms deviations obtained from averaging the UK Met Office data for January for 20 years (1992–2011). Figure 1b shows that the maximum variability of the zonal flow is observed over the equator at an altitude of 30 km; therefore, to select years with a westerly (the zonal flow is eastward directed) and easterly (the zonal flow is westward directed) QBO phase, the sign of the deviation of the zonal flow averaged over January for each year from the climatic flow shown in Fig. 1a at this altitude was analyzed. Finally, we chose years with the westerly (1993, 1995, 1997, 1999, 2002, 2004, 2006, 2008, 2011) and easterly (1994, 1998, 2000, 2001, 2003, 2005, 2007, 2010, 2012) QBO phases and averaged the zonal flow and temperature data over these years. We should note that only zonally averaged values of wind and temperature were considered.

Figures 2a and 2b show deviations of the average wind from climatic one for 2008 (westerly QBO) and 2007 (easterly QBO). In addition to the above incorporation procedure for zonally averaged wind, a term proportional to the difference between the calculated and observed zonally averaged temperature in the troposphere and lower stratosphere was introduced into the prognostic equation for temperature at low latitudes characteristic for different QBO phases, as was suggested in (Pogoreltsev et al., 2007). This was done to reproduce correctly the tropospheric jets and their connection with circulating cells in the stratosphere. The proportionality constant in prognostic equations for the zonal component of wind and temperature is a parameter inversely proportional to the characteristic relaxation time of zonal flow and temperature calculated to the observed ones. The relaxation time was set equal to 5 days.

To consider NAM effects during the simulation, an additional heating source localized at tropospheric altitudes was introduced in the prognostic equation for

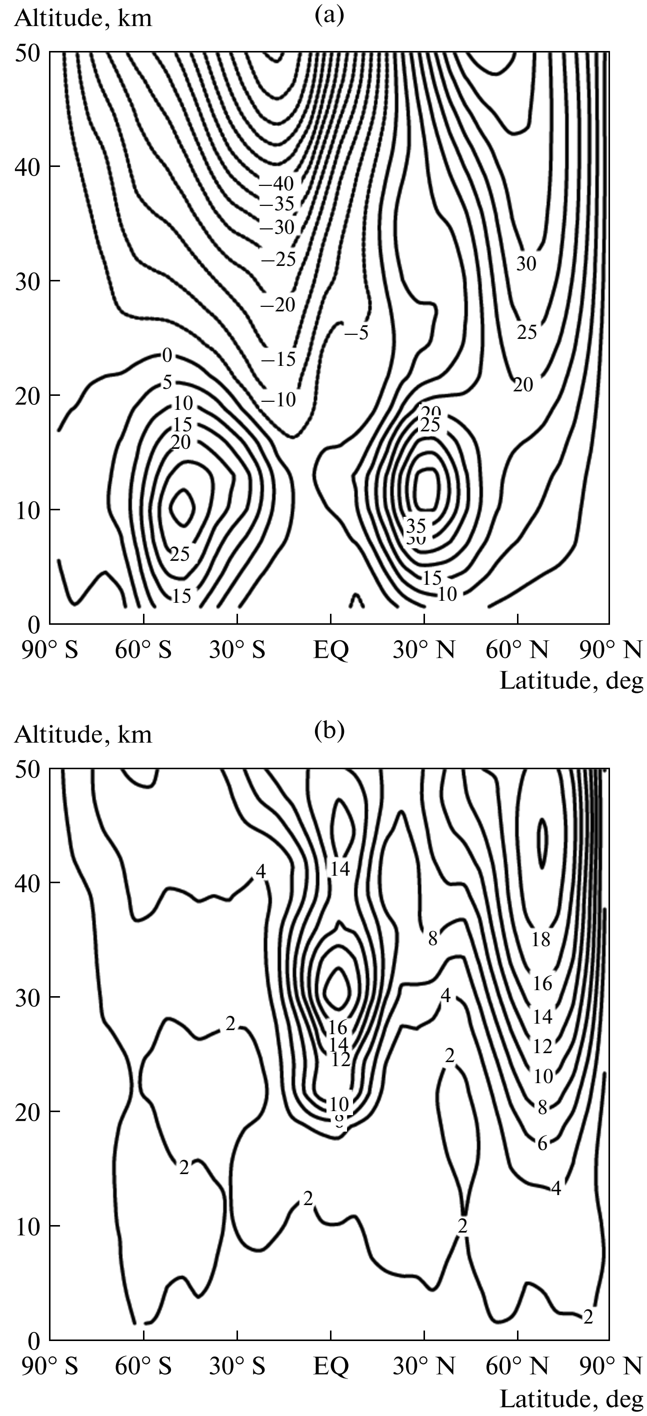

Fig. 1. (a) Latitude-altitude structure of the (a) zonally averaged flow and (b) its rms deviations from climatic values obtained from averaging of 20-year (1992–2011) UK Met Office data for January.

the temperature; it included a set of temporal harmonics with periods corresponding to fundamental modes of natural oscillations with zonal wave numbers $m = 1$ and 2. Each harmonic had the latitude structure of a corresponding Hough function, which was calculated using the algorithm suggested in (Swartztrauber and

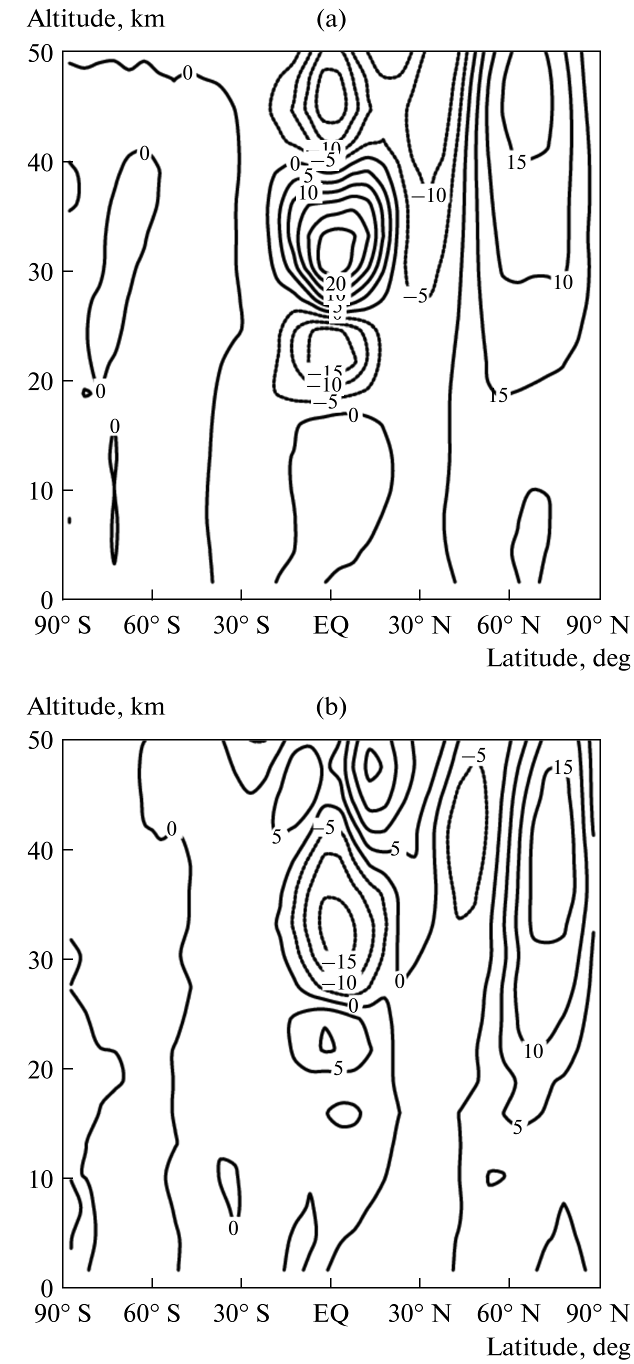

Fig. 2. Deviations of the zonally averaged flow from climatic one (Fig. 1a) for (a) 2008 during westerly QBO and (b) 2007 during easterly QBO.

Kasahara, 1985). This approach also allows calculation of resonance frequencies; however, it does not take into account the background wind effect (the calculations were carried out for windless atmosphere). Therefore, the simulation results of the atmospheric response to disturbances near the bottom boundary, obtained with the use of the linearized model of planetary waves from (Pogoreltsev, 1999), were used for the choice of resonance frequencies (periods). Thus, the following modes were considered in the model (according to the classification suggested in (Longuet-Higgins, 1968)): a 5-day wave, a period of 120 h (1, 1); a 10-day wave, a period of 220 h (1, 2); a 16-day wave, a period of 360 h (1, 3); a 4-day wave, a period of 90 h (2, 1); and a 7-day wave, a period of 168 h (2, 2). A value of additional heating of 2×10^{-5} K/s was considered equal for all the modes. Furthermore, we suggest a finer adjustment of the parameters on the basis of preliminary calculation results and the analysis of observed NAM amplitudes. However, we have to note that the chosen heating value provides us with the NAM amplitudes in the stratosphere close to the observed ones (Pogoreltsev et al., 2000a, 2000b, 2009a; Fedulina et al., 2004; Sassi et al., 2012).

Two model experiments were carried out (resulting in two ensembles of solutions) on calculation of the atmospheric circulation for winter conditions of the Northern Hemisphere (January–February), but for different QBO phases. Each ensemble includes ten variants (Runs) calculated with different initial conditions. Variations in the atmospheric-circulation parameters from variant to variant can be interpreted as an analogue of natural interannual variability (Pogoreltsev, 2007). To estimate the QBO effect on SSW events and their frequency, statistical analysis of the resulting ensembles of solutions is required. However, this problem is beyond the scope of this investigation, and the results will be presented in a separate work. The main purpose of the paper is the estimation of the role of NAM in formation and development of SSW events. However, we chose two cases from the ensembles of solutions where an SSW event was observed in January during different QBO phases.

3. SIMULATION RESULTS

The simulation results for the cases chosen are shown in Figs. 3 and 4 for the westerly and easterly QBO phases. These figures show the altitude-time cross sections of zonal harmonics amplitudes in the field of geopotential altitude with the wave numbers $m = 1$ and 2 (a and b, respectively) and the average zonal wind at the latitude of 62.5° N (c), as well as deviations of the zonally averaged temperature from the January average values at the latitude of 87.5° N (d). It is seen that in both cases irregular oscillations of amplitudes of zonal harmonics and average flow intensity are observed. The planetary wave activity increases in the second half of January, and SSW occurs, which is more clearly seen in the case of easterly QBO phase (circumpolar vortex breaks down and reversion of circulation is observed). In addition, the second zonal harmonic in the stratosphere immediately before the SSW event is much stronger during the easterly QBO phase than during the westerly QBO phase. During the SSW event, noticeable cooling is observed at upper stratospheric and mesospheric alti-

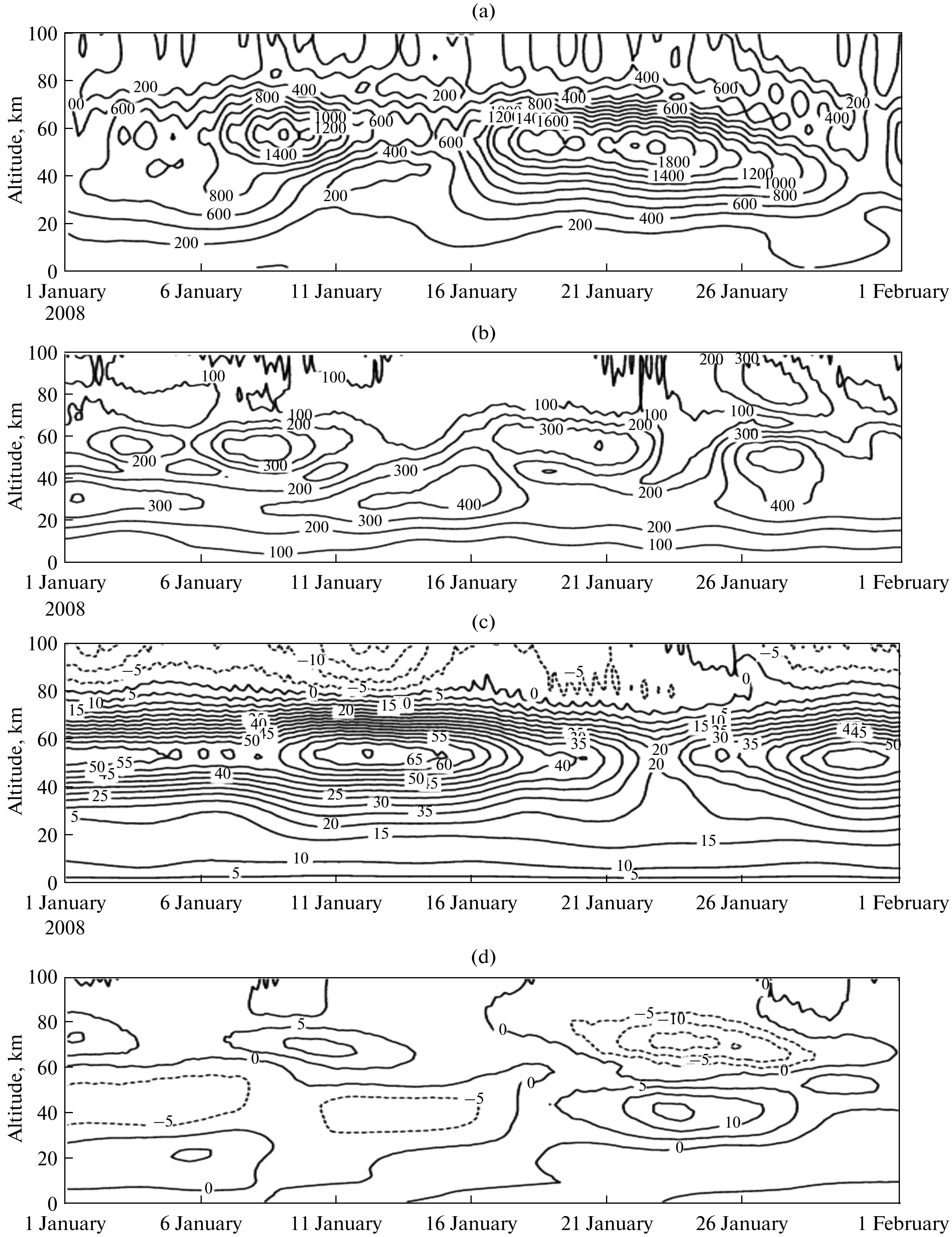

Fig. 3. Altitude-time cross sections of zonal harmonics amplitudes in the geopotential height field with wave number (a) $m = 1$ and (b) $m = 2$ and (c) mean zonal wind at the latitude of 62.5° N, as well as (d) deviations of the zonally averaged temperature from the January average values at the latitude of 87.5° N. Westerly QBO phase.

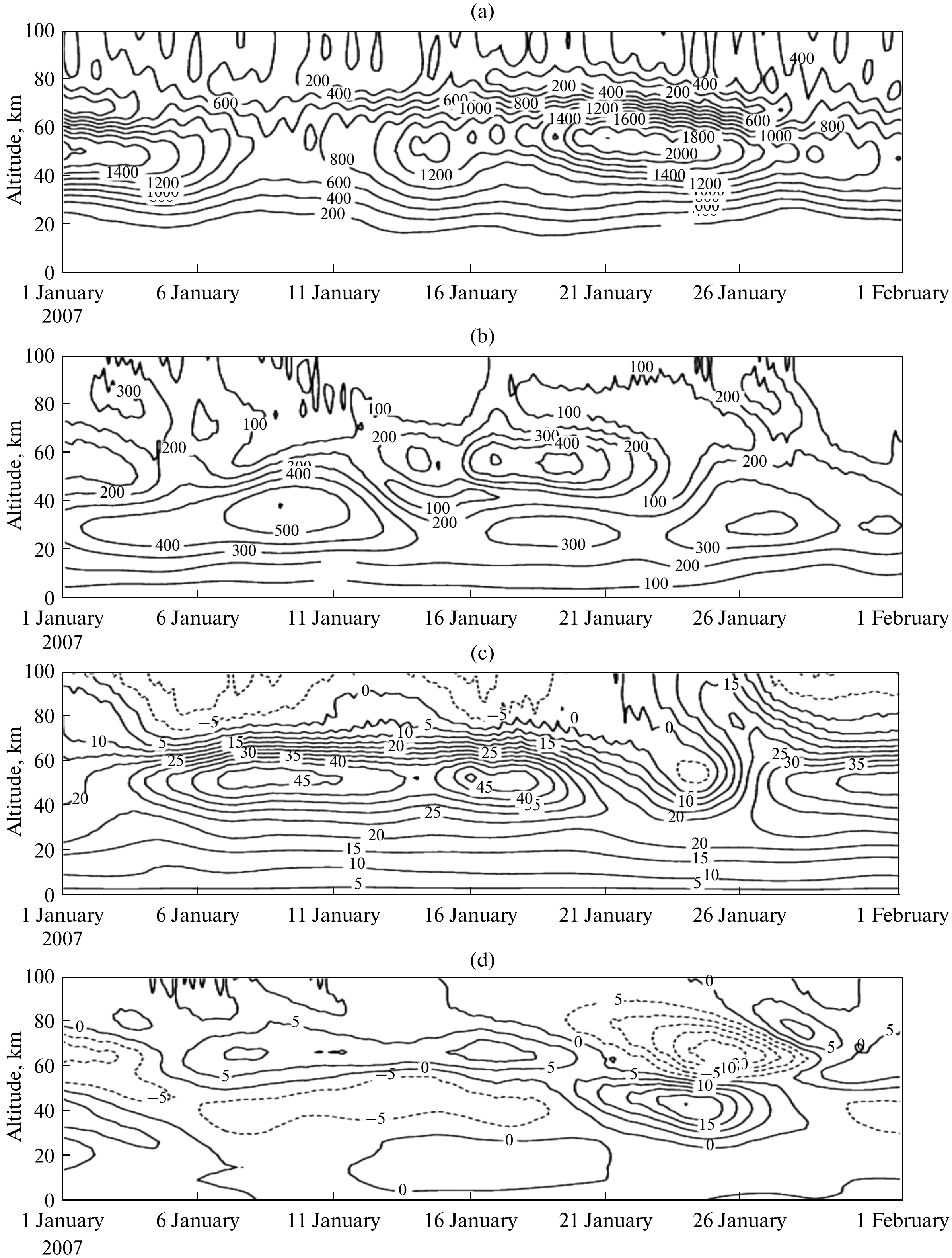

Fig. 4. Altitude-time cross sections of zonal harmonics amplitudes in the geopotential height field with wave number (a) $m = 1$ and (b) $m = 2$ and (c) mean zonal wind at the latitude of 62.5° N, as well as (d) deviations of the zonally averaged temperature from the January average values at the latitude of 87.5° N. Easterly QBO phase.

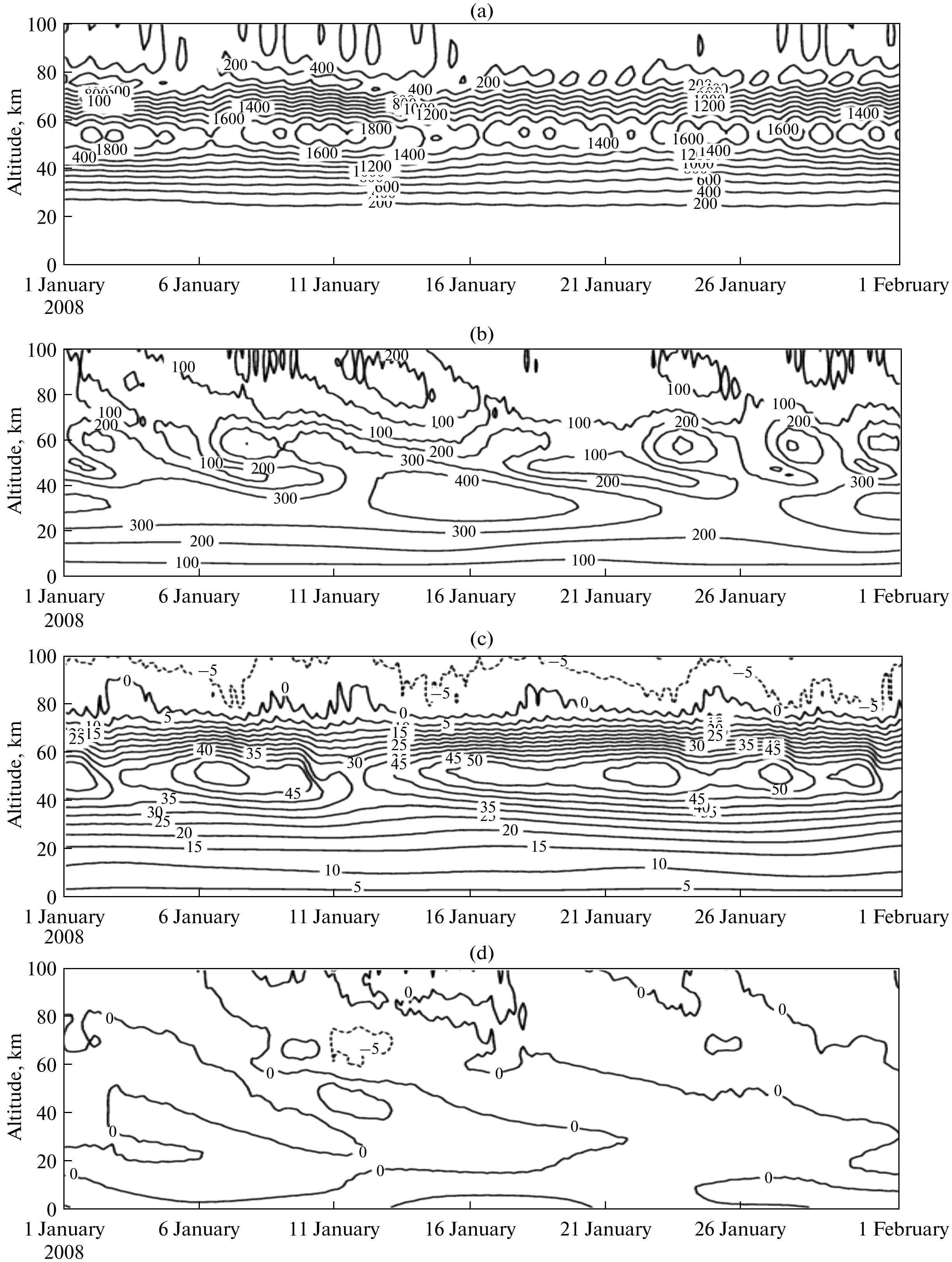

Fig. 5. The same as in Fig. 3 but without NAM parameterization.

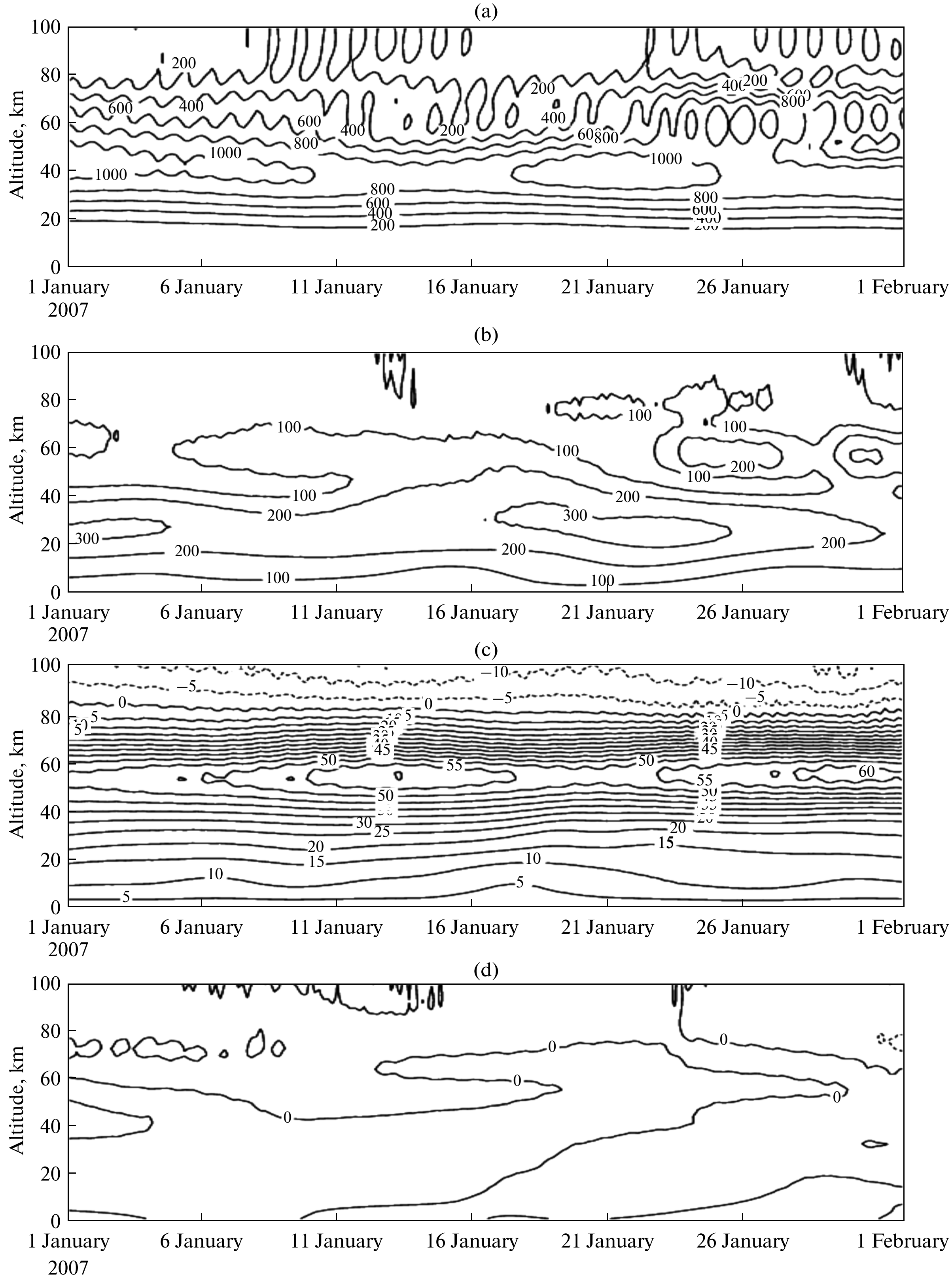

Fig. 6. The same as in Fig. 4 but without NAM parameterization.

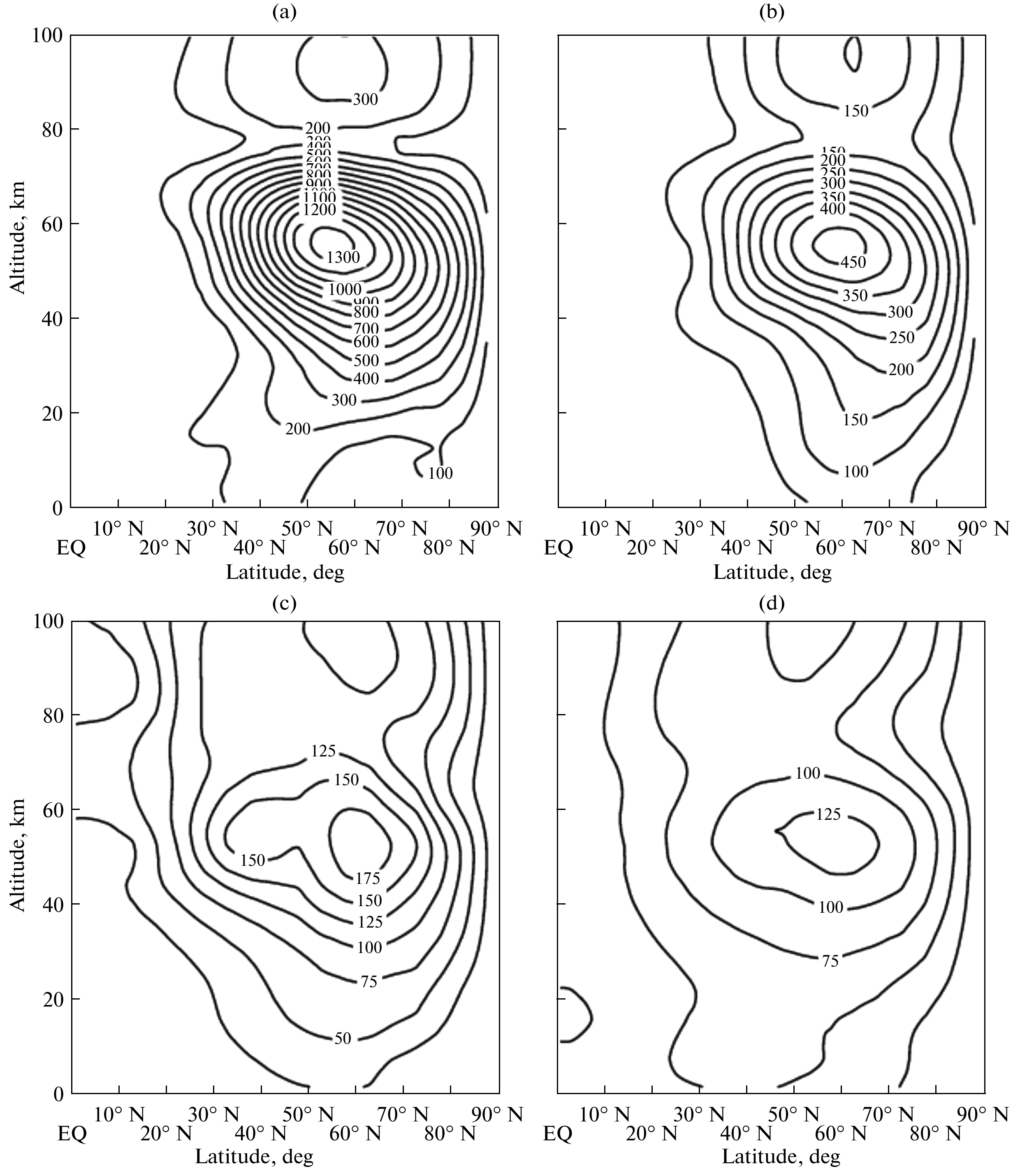

Fig. 7. Amplitudes of planetary waves with zonal wave number $m = 1$ in the geopotential height for January calculated during the westerly QBO phase: (a) SPW1, (b) 16-day wave, (c) 10-day wave, and (d) 5-day wave.

tudes at polar latitudes. To understand how significant the role of NAM is in the beginning of SSW, simulation was carried out without inserting of additional heating sources in the troposphere. The results are shown in Figs. 5 and 6 for the westerly and easterly QBO phases, respectively. These figures show that "switching on" of NAM sources in the troposphere strongly affects the dynamics of the stratosphere, i.e., irregular (vacillation) oscillations of planetary wave amplitudes and average flow intensity in the stratosphere decrease noticeably. We should note that these oscillations are irregular when considering NAM; i.e., they do not correlate with NAM periods. Analysis of the results allows the conclusion to be drawn that

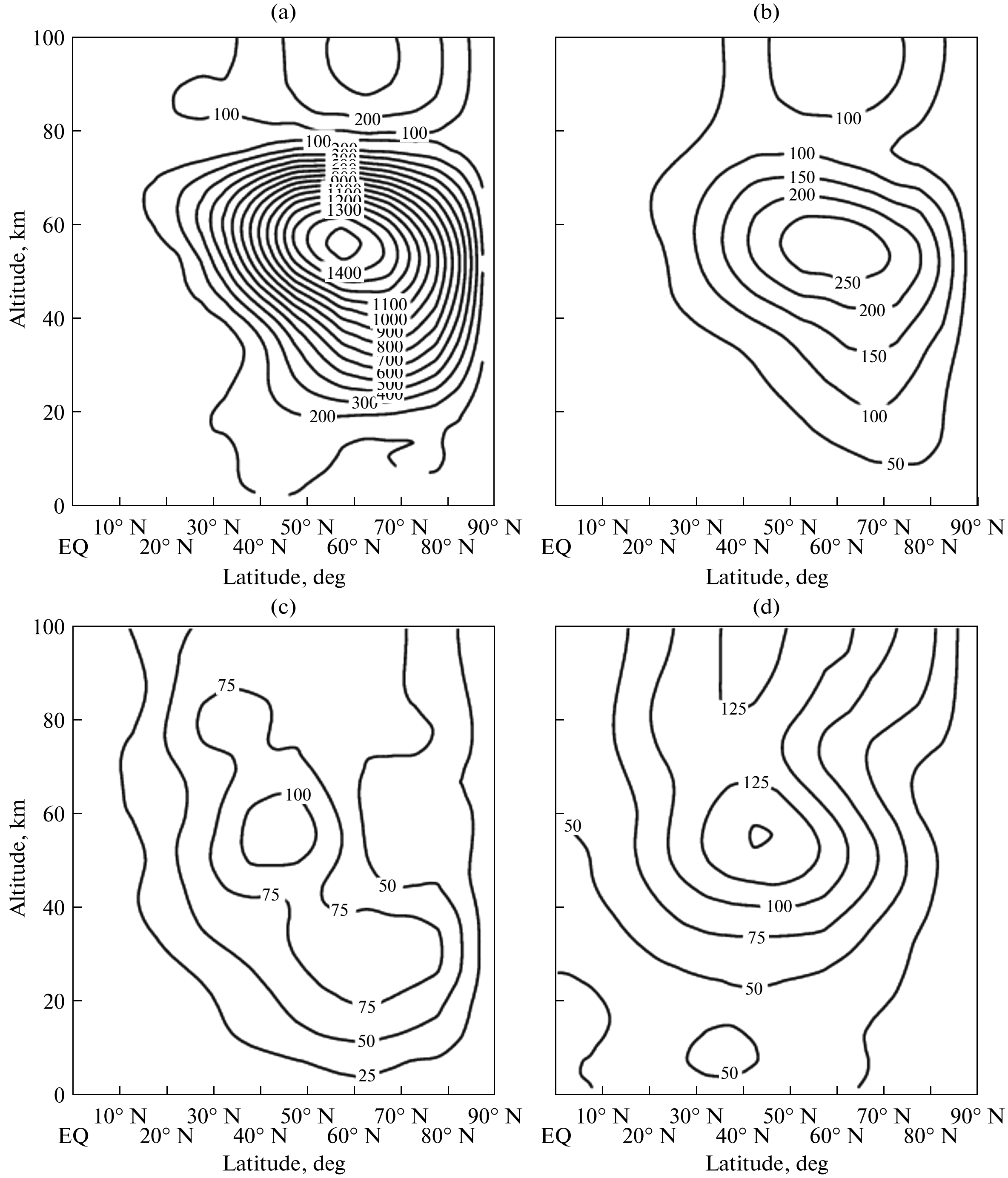

Fig. 8. The same as in Fig. 7 but for the easterly QBO phase.

NAM effects manifest in enhancement of nonlinear interaction between planetary waves and the average flow, due to which the amplitudes of stratospheric vacillations and the probability of development of SSW events increase. Although the NAM amplitude is significantly lower than the amplitude of a stationary planetary wave with wave number $m = 1$ (SPW1, see Figs. 7–10), taking NAM into account provides average flow deceleration, which results in improvement of SPW1 propagation conditions, i.e., an increase in its amplitude at stratospheric altitudes. Finally, this results in an increase in nonlinear interaction between SPW and the average flow, due to which the probability of SSW beginning and development increases. We should note that NAM amplitudes calculated with the wave number $m = 2$, i.e., (2, 1) and (2, 2) (they are not shown due to space limitations) are much lower that the amplitudes of fundamental modes shown in Figs.

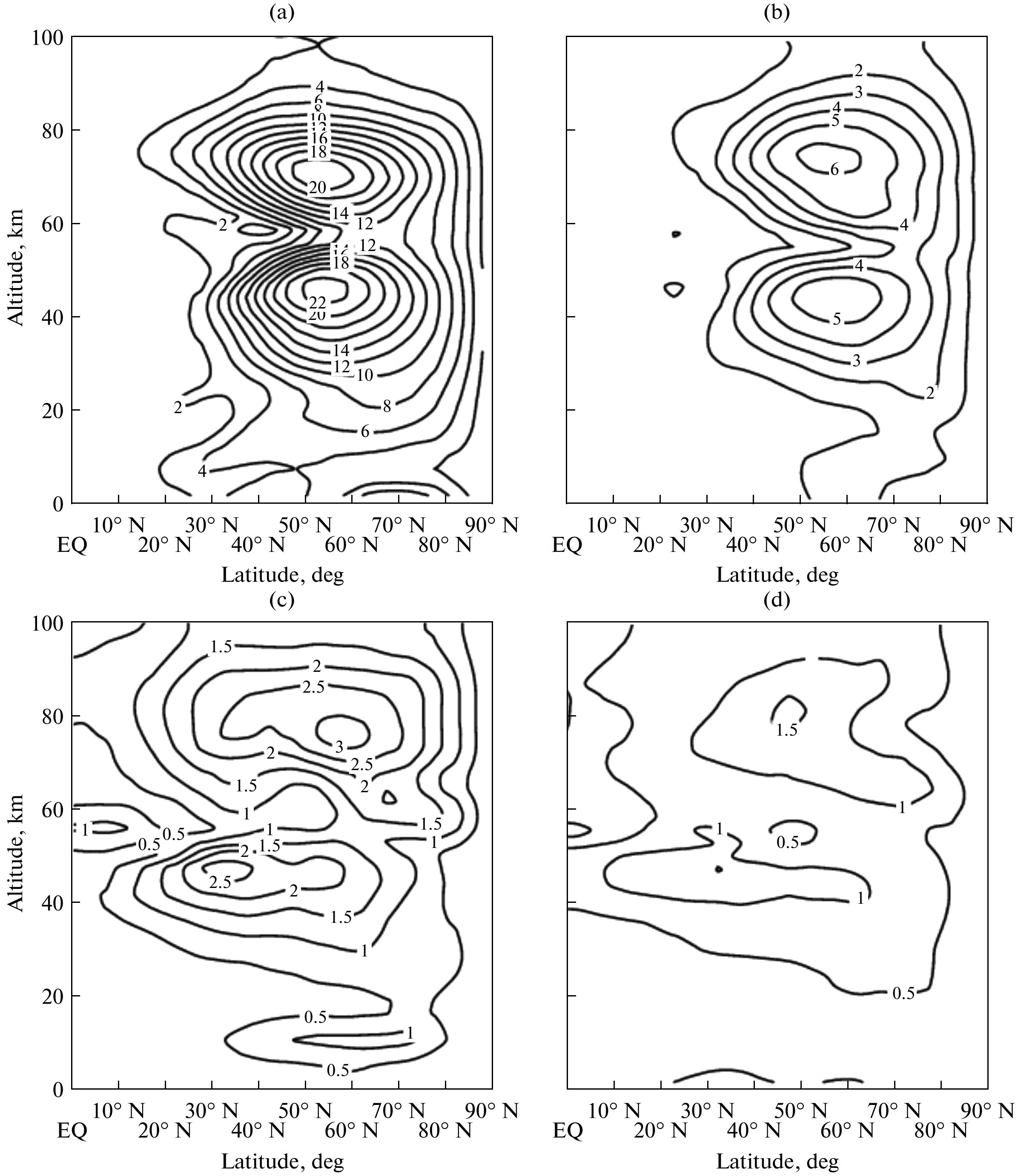

Fig. 9. Amplitudes of planetary waves with zonal wave number $m = 1$ in the temperature for January calculated during the westerly QBO phase: (a) SPW1, (b) 16-day wave, (c) 10-day wave, and (d) 5-day wave.

7–10. However, the role of these "weak" modes can also be important, since they affect the average flow at the altitudes of upper troposphere thus determining the conditions for SPW propagation from the troposphere to the stratosphere.

Analysis of the above variants of calculations allows also preliminary conclusions to be drawn regarding the dependence of the dynamics of extratropical stratosphere on the QBO phase (final conclusions can be drawn only after the analysis of statistical properties of ensembles of solutions found). The amplitudes of slow NAM (1, 2) and (1, 3), i.e., 10- and 16-day waves, are substantially smaller during the easterly QBO phase (see Figs. 7b, 7c, 8b, and 8c), which can be caused by both weakening of the resonance properties of the atmosphere (the amplitudes are lower already in

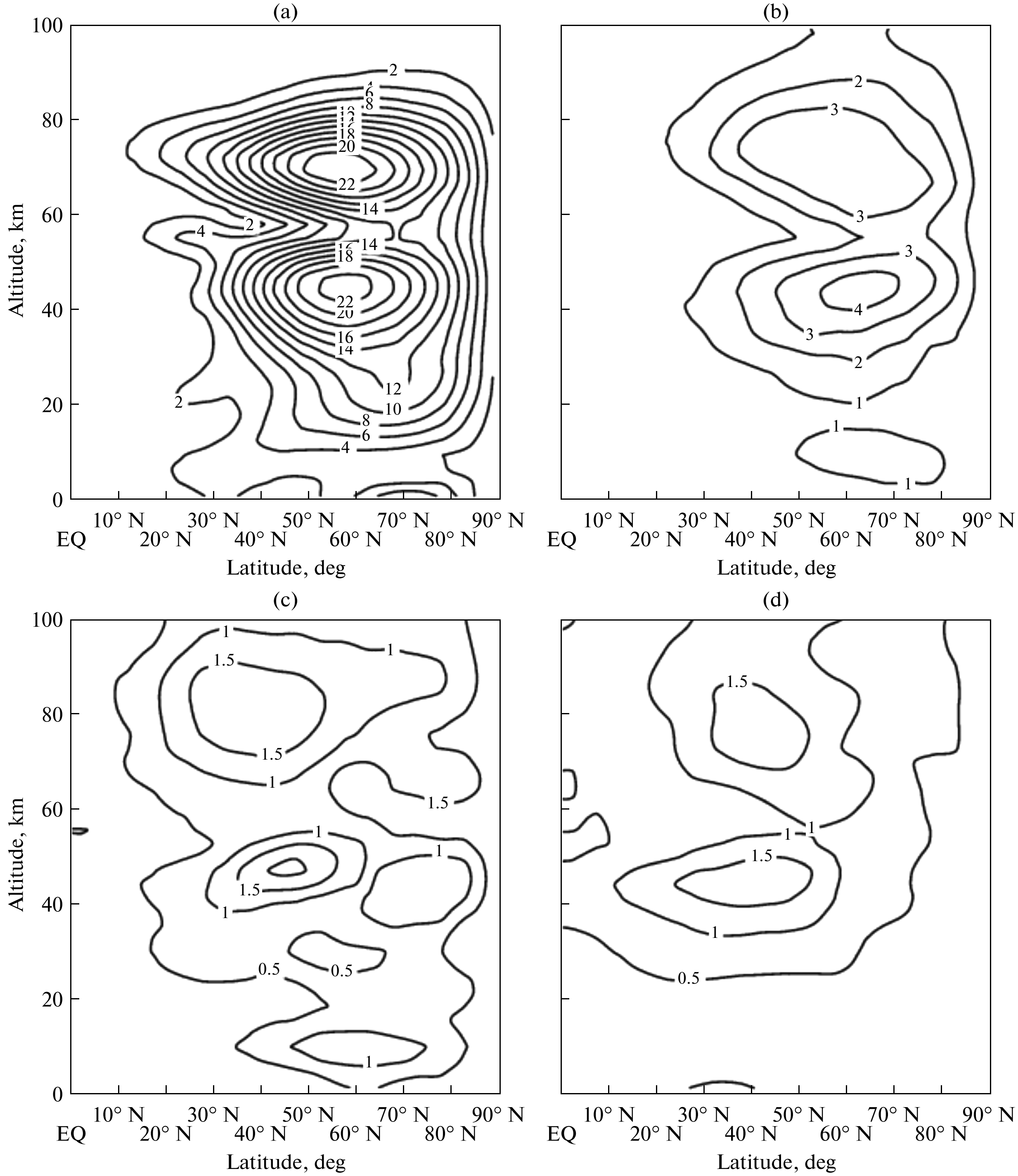

Fig. 10. The same as in Fig. 9 but for the easterly QBO phase.

the troposphere) and attenuation of troposphere–stratosphere propagation conditions. On the other hand, nonlinear interaction between planetary waves and the average flow is more effective during the easterly QBO phase (intraseasonal variability in the amplitudes of zonal harmonics is stronger and an SSW event develops more intensely). In addition, in the case of easterly QBO, the amplitude of the second zonal harmonics is much higher than in the case of westerly QBO; i.e., SSW events can commence and develop in accordance with different scenarios during different QBO phases.

To determine the possibility of recording planetary waves during ground-based measurements of temper-

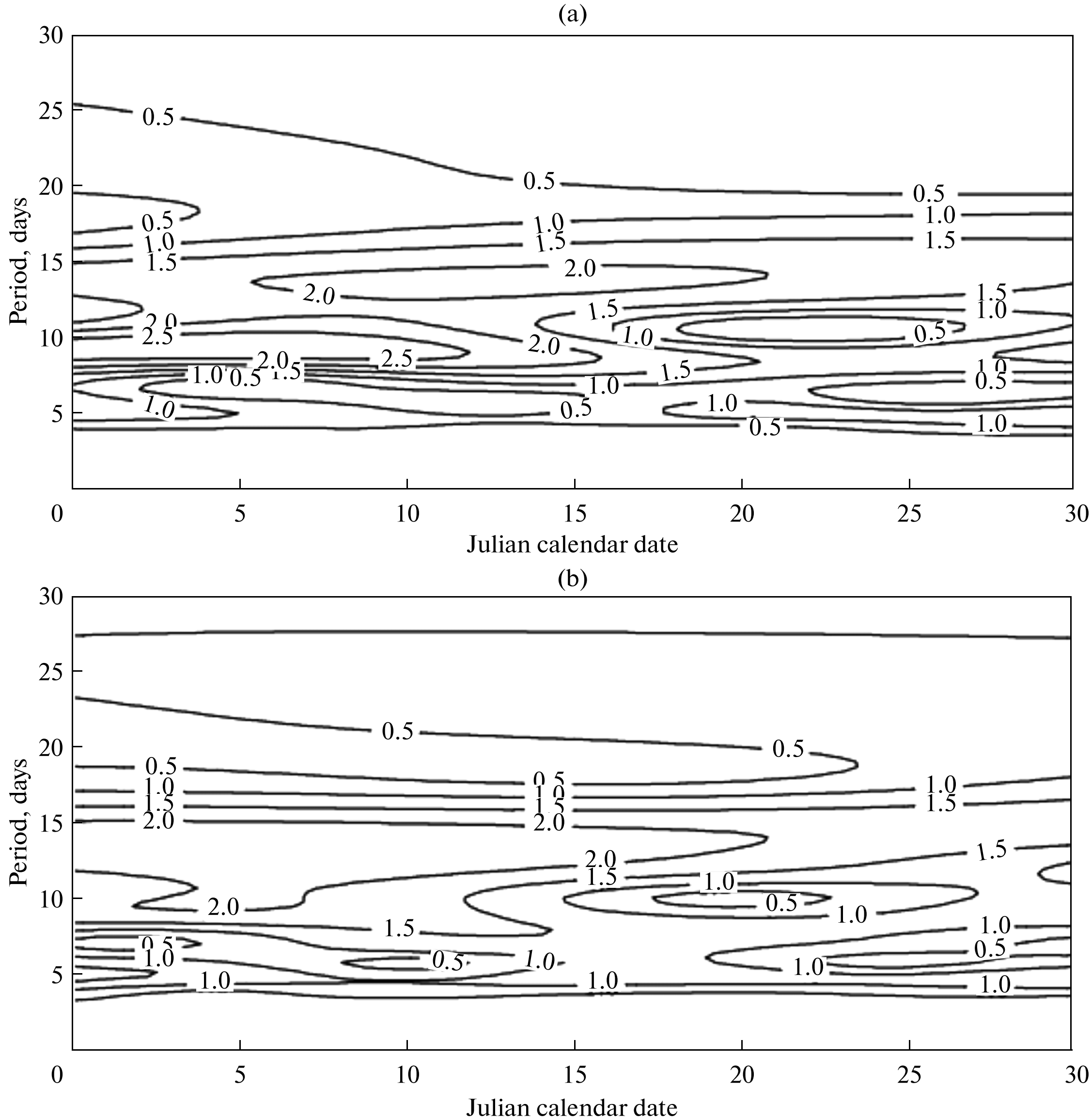

Fig. 11. Wavelet amplitudes of planetary waves in the temperature at the latitude of 57.7° N and altitude of 86 km for (a) westerly and (b) easterly QBO phases.

ature, e.g., determining the temperature from the nightglow intensity, the amplitudes of SPW1 and NAM were calculated for the westerly and easterly QBO phases (Figs. 9 and 10). Figures 9 and 10 show that planetary waves in the temperature have amplitudes of several Kelvins at middle latitudes in mesopause region, which allows their recording by optical methods. These figures show the monthly average NAM amplitudes for January. It is interesting to consider how NAM amplitudes change during SSW events. For this, we applied the Morlet wavelet transform to the time series of temperature at latitude of 57.5° N and altitude of 86 km (Torrence and Compo, 1998). The results are shown in Figs. 11a and 11 b for the westerly and easterly QBO phases, respectively. These figures show that NAM amplitudes in the temperature field at mesopause altitudes decrease significantly during SSW events, which can be explained by a change (deterioration) in conditions for their propagation at stratospheric altitudes.

4. CONCLUSIONS

The analysis of simulations results of the middle atmospheric circulation taking into account for NAM effects has shown that these waves play an important role in the process of beginning and development of SSW events. They can affect directly, through interference of traveling and stationary waves (if the phases coincide, the amplitude of the integral zonal harmonics increases and average flow deceleration becomes stronger due to the nonlinear interaction). NAM affect the probability of SSW beginning indirectly through changing SPW propagation conditions. The average flow decelerates as the wave activity of traveling waves increases. As a result, the SPW propagation conditions improve, SPW amplitude in the troposphere increases, and conditions favorable for SSW development occur. Preliminary results of analysis of the QBO phase effect on the dynamics of extratropical stratosphere allow the conclusion to be drawn that the conditions for occurrence of SSW events are more favorable and the SSW events are more intense during the easterly QBO phase. In addition, the second harmonics in the stratosphere is noticeably stronger during the easterly QBO, which might well be caused by more effective transformation of SPW1 under the presence of quadratic nonlinearity, i.e., a nonlinear self-interaction of the first harmonics (Pogoreltsev, 2001; Pogoreltsev et al., 2002a, b). This interaction results in frequency and wave-number doubling. The frequency is zero in our case (a quasi-biennial planetary wave); hence, only the wave number is doubled and SPW1 excited the second harmonics. As a result, one can expect that development of SSW events during different QBO phases will take place according to different scenarios. The simulation results also point that fundamental NAM ((1, 1), (1, 2), and (1, 3)) can be recorded in the temperature field at mesopause altitudes during ground-based optical measurements. Low-frequency planetary waves also can be recorded from satellite observation near the mesopause in winter (Day et al., 2011).

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (grants nos. 10-05-00198, 11-05-00971, and 12-05-90810-mol_rf).

REFERENCES

Ahlquist, J.E., Normal-mode global rossby waves: Theory and observations, *J. Atmos. Sci.*, 1982, vol. 39, pp. 193–202.

Ayarzaguena, B., Langematz, U., and Serrano, E., Tropospheric forcing of the stratosphere: A comparative study of the two different major stratospheric warmings in 2009 and 2010, *J. Geophys. Res.*, 2011, vol. 116, p. D18114.

Baldwin, M.P., Dameris, M., and Shepherd, T.G., How will the stratosphere affect climate change? *Science,* 2007, vol. 316, pp. 1576–1577.

Baldwin, M.P. and Dunkerton, T.J., Stratospheric harbingers of anomalous weather regimes, *Science,* 2001, vol. 294, pp. 581–584.

Baldwin, M.P., Gray, L.J., Dunkerton, T.J., Hamilton, K., Haynes, P.H., Randel, W.J., Holton, J.R., Alexander, M.J., Hirota, I., Horinouchi, T., Jones, D.B.A., Kinnersley, J.S., Marquardt, C., Sato, K., and Takahashi, M., The quasi-biennial oscillation, *Rev. Geophys.,* 2001, vol. 39, no. 2, pp. 179–229.

Clark, R.R., Burrage, M.D., Franke, S.J., Manson, A.H., Meek, C.E., Mitchell, N.J., and Muller, H.G., Observations of planetary waves with MLT radars and the UARS-HRDI instrument, *J. Atm. Sol-Ter. Phys.*, 2001, vol. 64, pp. 1217–1228.

Day, K.A., Hibbins, R.E., and Mitchell, N.J., Aura MLS observations of the westward-propagating s =1, 16-day planetary wave in the stratosphere, mesosphere and lower thermosphere, *Atmos. Chem. Phys.*, 2011, vol. 11, pp. 4149–4161.

Delan, R.J., Travelling planetary waves, *Tellus.,* 1964, vol. 16, pp. 271–273.

Devyatova, E.V. and Mordvinov, V.I., Quasi-biennial oscillation of wind in the low-latitude stratosphere and the winter wave activity of the atmosphere in the Northern Hemisphere, *Izv., Atmos. Ocean. Phys.*, 2011, vol. 47, no. 5, pp. 558–571.

Dikii, L.A. and Golitsyn, G.S., Calculation of the Rossby wave velocities in the Earth's atmosphere, *Tellus.,* 1968, vol. 20, pp. 314–317.

Dikii, L.A., *Teoriya kolebanii zemnoi atmosfery* (Theory of Earth's Atmosphere Oscillations), Leningrad: Gidrometeoizdat, 1969.

Eliasen, E. and Machenhauer, B., A study of the fluctuations of the atmospheric planetary flow patterns represented by spherical harmonics, *Tellus,* 1965, vol. 17, pp. 220–238.

Fedulina, I.N., Pogoreltsev, A.I., and Vaughan, G., Seasonal, interannual and short-term variability of planetary waves in Met Office stratospheric assimilated fields, *Quart. J. Roy. Met. Soc.*, 2004, vol. 130, no. 602, pp. 2445–2458.

Frohlich, K., Pogoreltsev, A., and Jacobi, Ch., Numerical simulation of tides, Rossby and Kelvin waves with the COMMA-LIM model, *Adv. Space Res.*, 2003, vol. 32, no. 5, pp. 863–868.

Fuller-Rowell, T., Wu, F., Akmaev R., Fang, T.-W., and Araujo-Pradere, E., A whole atmosphere model simulation of the impact of a sudden stratospheric warming on thermosphere dynamics and electrodynamics, *J. Geophys. Res.*, 2010, vol. 115, p. G08.

Funke, B., Lopez-Puertas, M., Bermejo-Pantaleon, D., Garcia-Comas, M., Stiller, G.P., von Clarmann, T., Kiefer, M., and Linden, A., Evidence for dynamical coupling from the lower atmosphere to the thermosphere during a major stratospheric warming, *Geophys. Res. Lett.*, 2010, vol. 37, p. L13803.

Hirota, I. and Hirooka, T., Normal mode Rossby waves observed in the upper stratosphere. Part I: First symmetric modes of zonal wavenumbers 1 and 2, *J. Atmos. Sci.,* 1984, vol. 41, pp. 1253–1267.

Hirooka, T. and Hirota, I., Normal mode Rossby waves observed in the upper stratosphere. Part II: Second antisymmetric and symmetric modes of zonal wavenumbers 1 and 2, *J. Atmos. Sci.,* 1985, vol. 42, pp. 536–548.

Hirooka, T. and Hirota, I., Further evidence of normal mode Rossby waves, *Pure Appl. Geophys.*, 1989, vol. 130, pp. 277–289.

Holton, J.R., The dynamics of sudden stratospheric warmings, *Annual Rev. Earth Planet. Sci.*, 1980, vol. 8, pp. 169–190.

Holton, J.R. and Mass, C., Stratospheric vacillation cycles, *J. Atmos. Sci.*, 1976, vol. 33, pp. 2218–2225.

Kurihara, J., Ogawa, Y., Oyama, S., Nozawa, S., Tsutsumi, M., Hall, C.M., Tomikawa, Y., and Fujii, R., Links between a stratospheric sudden warming and thermal structures and dynamics in the high-latitude mesosphere, lower thermosphere, and ionosphere, *Geophys. Res. Lett.,* vol. 37, p. L13806.

Kuttippurath, J. and Nikulin, G., The sudden stratospheric warming of the arctic winter 2009/2010: Comparison to other recent warm winters, *Atmos. Chem. Phys. Discuss.,* 2012, vol. 12, pp. 7243–7271.

Labitzke, K. and Kunze, M., On the remarkable Arctic winter in 2008/2009, *J. Geophys. Res.*, 2009, vol. 114, p. D00102.

Lindzen, R.S., Straus, D.M., and Katz, B., An observational study of large-scale atmospheric Rossby waves during FGGE, *J. Atmos. Sci.*, 1984, vol. 41, pp. 1320–1335.

Liu, H., Doornbos, E., Yamamoto, M., Ram, S.T., Strong thermospheric cooling during the 2009 major stratosphere warming, *Geophys. Res. Lett.*, vol. 38, p. L12102.

Longuet-Higgins, M.S., The eigenfunctions of Laplace's tidal equation over a sphere, *Philos. Trans. R. Soc. London.*, 1968, vol. 262, pp. 511-607.

Madden, R.A., Further evidence of travelling planetary waves, *J. Atmos. Sci.*, 1978, vol. 35, pp. 1605–1618.

Madden, R.A., Observations of large-scale traveling Rossby waves, *Rev. Geophys. Space Phys.*, 1979, vol. 17, pp. 1935–1949.

Madden, R.A., Large-scale, free Rossby waves in the atmosphere—an update, *Tellus,* 2007, vol. 59A, pp. 571–590.

Matsuno, T., A dynamical model of sudden stratospheric warming, *J. Atmos. Sci.*, 1971, vol. 28, pp. 871–883.

McIntyre, M.E., How well do we understand the dynamics of stratospheric warmings, *J. Meterol. Soc. Japan*, 1982, vol. 60, no. 1, pp. 37–64.

Pancheva, D., Mukhtarov, stratospheric warmings: The atmosphere–ionosphere coupling paradigm, *J. Atm. Sol.-Ter. Phys.*, 2011, vol. 73, pp. 1697–1702.

Pedatella, N.M. and Forbes, J.M., Evidence for stratosphere sudden warming—ionosphere coupling due to vertically propagating tides, *Geophys. Res. Lett.*, vol. 37, p. L11104.

Perminov, V.I. and Pertsev, N.N., The behavior of emissions and temperature of the mesopause during stratospheric warmings according to observations at midlatitudes, *Geomag. Aeron.*, vol. 53, no. 6, pp. 780–785.

Pogoreltsev, A.I., Simulation of planetary waves and their influence on the zonally averaged circulation in the middle atmosphere, *Earth, Planets and Space*, 1999, vol. 51, nos. 7–8, pp. 773–784.

Pogoreltsev, A.I., Numerical simulation of secondary planetary waves arising from the nonlinear interaction of the normal atmospheric modes, *Phys. Chem. Earth (Part C)*, 2001, vol. 26, no. 6, pp. 395–403.

Pogoreltsev, A.I., Generation of normal atmospheric modes by stratospheric vacillations, *Izv., Atmos. Ocean. Phys.*, 2007, vol. 43, no. 4, pp. 423–435.

Pogoreltsev, A.I., Pancheva, D., and Mitchel, N.J., Secondary planetary waves in the middle atmosphere: numerical simulation and analysis of the neutral wind data, *J. Atm. Sol.-Ter. Phys.*, 2002a, vol. 64, pp. 1251–1261.

Pogoreltsev, A.I., Fedulina, I.N., Mitchell, N.J., Muller, H.G., Luo, Y., Meek, C.E., and Manson, A.H., Global free oscillations of the atmosphere and secondary planetary waves in the MLT region during August/September time conditions, *J. Geophys. Res.*, 2002b, vol. 107, no. D24, pp. ACL24-1–ACL24-12.

Pogoreltsev, A., Kanukhina, A., Suvorova, E., and Savenkova, E., Variability of planetary waves as a signature of possible long-term trends, *J. Atm. Sol.-Ter. Phys.*, 2009a, vol. 71.

Pogoreltsev, A.I., Suvorova, E.V., Fedulina, I.N., and Khanna, E., 3D climate model of ozone distribution in the middle atmosphere, *Uchenye zapiski Rossiiskogo gosudarstvennogo gidrometeorologicheskogo universiteta* (Memories of Russian State Hydrometeorological University), St. Petersburg: RGGMU, 2009b, is. 10, pp. 43–52.

Pogoreltsev, A.I., Vlasov, A.A., Frohlich, K., and Jacobi, Ch., Planetary waves in coupling the lower and upper atmosphere, *J. Atmos. Sol.-Terr. Phys.*, 2007, vol. 69, nos. 17–18, pp. 2083–2101.

Rodgers, C.D., Evidence for the five-day wave in the upper stratosphere, *J. Atmos. Sci.* 1976, vol. 33, pp. 710–711.

Salby, M.L., Survey of planetary-scale traveling waves: The state of theory and observations, *Rev. Geophys.,* 1984, vol. 22, pp. 209–236.

Sassi, F., Garcia, R.R., and Hoppel, K.W., Large-scale Rossby normal modes during some recent Northern Hemisphere winters, *J. Atmos. Sci.*, 2012, vol. 69, pp. 820–839.

Scott, R.K., Polvani, L.M., Internal variability of the winter stratosphere. Part I: Time independent forcing, *J. Atmos. Sci.*, 2006, vol. 63, pp. 2758–2776.

Siskind, D.E., Eckermann, S.D., McCormack, J.P., Coy, L., Hoppel, K.W., and Baker, N.L., Case studies of the mesospheric response to recent minor, major and extended stratospheric warmings, *J. Geophys. Res.*, 2010, vol. 115, no. 03, p. D00.

Stan, C. and Straus, D.M., Stratospheric predictability and sudden stratospheric warming events, *J. Geophys. Res.,* 2009, vol. 114, pp. D12103.

Sun, L., Robinson, W.A., and Chen. G., The predictability of stratospheric warming events: more from the troposphere or the stratosphere?, *J. Atmos. Sci.*, 2011, vol. 69, no. 2, pp.768–783.

Sun, L. and Robinson, W.A., Downward influence of stratospheric final warming events in an idealized model, *Geophys. Res. Lett.*, 2009, vol. 36, p. L03819.

Suvorova, E.V. and Pogorel'tsev, A.I., Modeling of nonmigrating tides in the middle atmosphere, *Geomagn. Aeron.,* 2011, vol. 51, no. 1, pp. 105–1115.

Swarztrauber, P.N. and Kasahara, A., The vector harmonic analysis of Laplace's tidal equations, *SIAM J. Sci. Stat. Comput.*, 1985, vol. 6, pp. 464–491.

Swinbank, R. and O'Neill, A., A stratosphere-troposphere assimilation system, *Mon. Weather Rev.*, 1994, vol. 122, pp. 686–702.

Talaat, E.R., Yee, J.-H., and Zhu, Xun, Observations of the 6.5-day wave in the mesosphere and lower thermosphere, *J. Geophys. Res.*, 2001, vol. 106, pp. 20715–20724.

Talaat, E.R. and Yee, J.-H., Zhu Xun, The 6.5-day wave in the tropical stratosphere and mesosphere, *J. Geophys. Res.*, 2002, vol. 107, no. D12, pp. ACL 1-1–ACL 1-5.

Torrence, Ch. and Compo, G.P., A practical guide to wavelet analysis, *Bull. Amer. Meteorol. Soc.*, 1998, vol. 79, pp. 61–78.

Vincent, R.A., MF/HF radar measurements of the dynamics of the mesosphere region—A review, *J. Atmos. Terr. Phys.*, 1984, vol. 46, pp. 961–974.

Volland, H., *Atmospheric, tidal, and planetary waves*, Dordrecht: Kluwer Academic, 1988.

Weber, R.O. and Madden, R.A., Evidence of travelling external Rossby waves in the ECMWF analyses, *J. Atmos. Sci.*, 1993, vol. 50, pp. 2994–3007.

Woollings, T., Charlton-Perez, A., Ineson, S., Marshall, A.G., and Masato, G., Associations between stratospheric variability and tropospheric blocking, *J. Geophys. Res.*, 2010, vol. 115, p. D06108.

Wu, D.L., Hays, P.B., and Skinner, W.R., Observations of the 5-day in the mesosphere and lower thermosphere, *Geophys. Res. Lett.*, 1994, vol. 21, pp. 2733–2736.

Yuan, T., Thurairajah, B., She, C.-Y., Chandran, A., Collins, R.L., and Krueger, D.A., Wind and temperature response of midlatitude mesopause region to the 2009 sudden stratospheric warming, *J. Geophys. Res.*, 2012, vol. 117, p. D09114.

Translated by O. Ponomareva