ISSN 1024-8560, Atmospheric and Oceanic Optics, 2024, Vol. 37, No. 3, pp. 415–421. © Pleiades Publishing, Ltd., 2024.
Russian Text © The Author(s), 2024, published in Optika Atmosfery i Okeana.

OPTICAL MODELS AND DATABASES

Numerical Simulation of QBO and ENSO Phase Effect on the Propagation of Planetary Waves and the Evolvement of Sudden Stratospheric Warming

V. D. Lifar[a, *], K. A. Didenko[a, b], A. V. Koval[a, c], and T. S. Ermakova[a, c]

[a] *St. Petersburg State University, St. Petersburg, 199034 Russia*

[b] *Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, Moscow, 108840 Russia*

[c] *Russian State Hydrometeorological University, St. Petersburg, 192007 Russia*

**e-mail: vitaliyalif@gmail.com*

Received August 9, 2023; revised September 25, 2023; accepted September 26, 2023

Abstract—The effects of the quasi-biennial oscillation (QBO) of the zonal wind in the equatorial stratosphere and the El Niño Southern Oscillation (ENSO) on the dynamic state of the stratosphere in winter and the evolvement of sudden stratospheric warming (SSW) are studied in numerical experiments with the nonlinear general circulation model of the middle and upper atmosphere (MUAM) for winter conditions of the Northern Hemisphere (January–February). The sensitivity of the model fields of zonal wind, temperature, and geopotential to ENSO and QBO phases is estimated. The statistics of observed SSWs and their evolution differ depending on the combination of phases, e.g., the largest number of SSWs is observed under the combination of El Niño and an easterly phase of QBO; major SSWs are not reproduced by the model under the combination of La Niña and a westerly phase of QBO. The fields of hydrodynamic parameters have been averaged for combinations of El Niño/easterly phase of QBO, El Niño/westerly phase of QBO, and La Niña/easterly phase of QBO to analyze the characteristic features of the model "climatic" SSWs. The analysis shows the maximal temperature rise in the stratosphere and cooling in the mesosphere in the model under El Niño and the eastern phase of QBO; wind weakening is maximal under El Niño and the western phase of QBO. The highest planetary wave amplitudes are modeled under easterly QBO phases regardless of the ENSO phase. The results can be used in climate forecasting on time scales from one month to decades.

Keywords: numerical simulation, El Niño – Southern Oscillation, quasi-biennial oscillation, planetary wave, sudden stratospheric warming

DOI: 10.1134/S1024856024700489

INTRODUCTION

Recent studied in atmospheric dynamics have shown a significant impact of certain phenomena on the winter stratosphere. These phenomena are the El Niño–Southern Oscillation (ENSO), the quasi-biennial oscillation (QBO) of zonal wind in the equatorial stratosphere, and sudden stratospheric warmings (SSW). ENSO is known to strongly affect the winter stratosphere through wave interaction with the troposphere. It is caused by changes in the heat and mass distributions in the troposphere and affects the generation and propagation of waves through the stratosphere [1]. These atmospheric waves are generated at the equator and upward and poleward propagate [2]. This significantly changes the circulation of the winter stratosphere and decreases the overall temperature.

However, studies have also shown that the ENSO effect on the stratosphere is unstable and can depend on the season, the phase of QBO, and other factors [3]. In addition, the probability of SSW is higher during periods of strong La Niña and easterly phase of QBO than during periods of other combinations of tropical oscillations under study. Vice versa, the probability of SSW is lower during westerly phases QBO [4, 5].

The interaction between QBO and ENSO can significantly change the circulation of the winter stratosphere and affect climate conditions in the troposphere of the Northern Hemisphere [6]. For example, if an easterly phase of QBO occurs during a strong El Niño, this can increase the impact of ENSO on the stratosphere. Sudden stratospheric warmings, in turn, affect the thermodynamics of the middle atmosphere, occurrence of weather anomalies, and climate changes in the troposphere [7].

The main aim of the work is to study the effect of different phases of ENSO and QBO on wave processes in the winter stratosphere and occurrence of SSW using the general circulation model of the middle and upper atmosphere (MUAM), which enables taking into account various boundary and background conditions and sources of planetary waves.

MATERIALS AND METHODS

We study large-scale dynamic phenomena in numerical simulation. It has a number of significant advantages: unlike modern data of reanalysis/meteorological information assimilation, which are typically available up to altitudes of 50–70 km, model data cover the altitude range from the surface to 300–400 km with a regular grid. In addition, the simulation provides idealized experiments, with fixing all external conditions and changing only the parameters of the processes under study (QBO and ENSO). This analysis is impossible with observation data, since other atmospheric processes and phases of natural long-term oscillations are inevitably superimposed on the processes under study and introduce additional randomness.

The study uses a nonlinear mechanistic model of the middle and upper atmosphere [8], which is actively developed by a team of specialists from St. Petersburg State University and the Russian State Hydrometeorological University [9, 10]. The model reproduces the general atmospheric circulation from the Earth's surface to altitudes of 300–400 km. It is based on a standard system of primitive equations adapted to spherical coordinates [11]. MUAM uses the Marchuk–Strang splitting procedure [12, 13] to solve predictive equations and the Matsuno scheme [14] for time integration. The model horizontal grid has steps of 5.625° in longitude and 5° in latitude. The vertical grid uses the log-isobaric coordinate $z = -H\ln(p/p_0)$, where p_0 is the surface pressure and $H = 7$ km is the height of the homogeneous atmosphere. In our study, we use a model version with 56 vertical levels. The time integration step is 225 s. The main parameters calculated by the model are the zonal, meridional, and vertical velocity components, geopotential, and temperature. A more detailed description of the processes taken into account in the current version of the model and the numerical experiment can be found in [15].

Stratospheric QBO is considered in MUAM through nudging, i.e., the method for relaxing modeled zonal average fields of zonal wind to observations. Since MUAM is not capable of self-consistently reproducing QBO in the stratosphere, the simulation requires specifying the background and initial hydrodynamic fields corresponding to years with different phases of QBO [16]. Years with easterly and westerly phases of QBO were selected based on decomposing meteorological fields into empirical orthogonal functions. In the decomposition method [17], QBO divides into eight phases based on the Japanese 55-year reanalysis JRA-55; then, to increase the statistical significance when choosing years as the main (westerly and easterly) phases of QBO, the 2nd and 3rd phases are combined into the westerly phase and the 6th and 7th phases are combined into the easterly phase [18]. This procedure provided for two sets of 10 years with typical westerly (1983, 1985, 1993, 1995, 1997, 1999, 2002, 2004, 2008, and 2013) and easterly phases of QBO (1987, 1989, 1996, 1998, 2000), 2003, 2005, 2007, 2010, and 2012). Background zonal average distributions of zonal wind and temperature were calculated from these two sets for the two QBO phases and then used in MUAM.

To account the ENSO phase, we use latent heat release values averaged over years corresponding to the warm (referred to as El Niño) and the cold phases (La Niña). Years with one or another ENSO phase were selected from multidimensional MEI index. It is based on a set of six main parameters measured in the tropical Pacific: sea level pressure, zonal and meridional components of surface wind, sea surface temperature, surface air temperature, and total cloud amount. Using the table of available MEI values we have selected 1983, 1992, 1998, 2003, and 2010 for El Niño conditions and 1989, 1999, 2000, 2008, and 2011 for La Niña conditions [10].

When the model is initialized accounting different phases of ENSO and QBO, even minor changes in initial conditions can strongly affect the evolution of the simulated stratosphere. The slightest deviations in the structure and amplitude of planetary waves in the nonlinear model change the average flow, thus changing the propagation conditions for these waves. As a result, the stratospheric dynamics become extremely unstable and changeable with time. Therefore, for model calculation results to be statistically significant, ensemble calculations of the general atmospheric circulation are required. Within MUAM, ensembles are formed during many iterations—model calculations ("runs"), which show different phases of oscillation of the average wind and planetary waves in the middle atmosphere. These phases in MUAM are controlled through changing the date of switching on diurnal variations in solar heating and generation of normal atmospheric modes. The initial and background conditions are taken the same in all model calculations. Note that the monthly average amplitudes of planetary waves, the average flux intensity, and the temperature of the winter stratosphere can significantly vary from one iteration to another. This variability is treated as internal variation in model calculations.

RESULTS AND DISCUSSION

To study the effect of combinations of QBO and ENSO phases on the dynamics of the winter stratosphere, a series of model experiments were carried out for January–February. Four ensembles of solutions each of 10 realizations have been compiled, i.e., four scenarios have been implemented: El Niño/easterly phase of QBO, El Niño/westerly phase of QBO, La Niña/easterly phase of QBO, and La Niña/westerly phase of QBO.

Table 1. Time intervals before, during, and after SSW used for averaging fields of hydrometeorological parameters (the number of realization is given in parentheses)

Period	El Niño/easterly phase of QBO	El Niño/westerly phase of QBO	La Niña/easterly phase of QBO
Before SSW	Dec. 25–Jan. 3 (1)	Jan. 20–29 (2)	Jan. 17–26 (1)
	Jan. 3–12 (3)	Jan. 10–19 (5)	Dec. 25–Jan. 3 (4)
	Jan. 1–10 (6)	Feb. 5–14 (6)	Jan. 12–21 (5)
	Jan. 1–10 (7)	Feb. 5–14 (7)	Jan. 27–Feb. 5 (5)
	Jan. 18–27 (8)	Jan. 22–31 (8)	Jan. 26–Feb. 4 (6)
	Dec. 16–25 (9)	Jan. 28–Feb. 6 (9)	Jan. 31–Feb. 9 (9)
During SSW	Jan. 5–14 (1)	Jan. 31–Feb. 9 (2)	Jan. 28–Feb. 6 (1)
	Jan. 14–23 (3)	Jan. 21–30 (5)	Jan. 5–14 (4)
	Jan. 12–21 (6)	Feb. 16–25 (6)	Jan. 23–Feb. 1 (5)
	Jan. 12–21 (7)	Feb. 16–25 (7)	Feb. 7–16 (5)
	Jan. 29–Feb. 7 (8)	Feb. 2–11 (8)	Feb. 6–15 (6)
	Dec. 27–Jan. 5 (9)	Feb. 8–17 (9)	Feb. 11–20 (9)
After SSW	Jan. 16–25 (1)	Feb. 11–20 (2)	Feb. 8–17 (1)
	Jan. 25–Feb. 3 (3)	Feb. 1–10 (5)	Jan. 16–25 (4)
	Jan. 23–Feb. 1. (6)	Feb. 27–March 8 (6)	Feb. 3–12 (5)
	Jan. 23–Feb. 1 (7)	Feb. 27–March 8 (7)	Feb. 18–27 (5)
	Feb. 9–18 (8)	Feb. 13–22 (8)	Feb. 17–26 (6)
	Jan. 7–16 (9)	Feb. 19–28 (9)	Feb. 22–March 3 (9)

Distributions of Model Hydrodynamic Fields

For each model implementation ("run"), the fields of zonal wind, temperature, and amplitude of planetary waves with zonal wave numbers $m = 1–3$ in the geopotential height field were derived and analyzed to detect model SSWs. Under the combination El Niño/easterly phase of QBO, SSWs were observed in nine of ten realizations. Major SSWs, accompanied not only by an increase in the stratospheric temperature, but also by a change in the zonal wind direction, were simulated in four realizations. Under the combination El Niño/westerly phase of QBO, SSWs were simulated in eight of ten realizations, with two major SSWs. For cold ENSO phase and the easterly phase of QBO, SSWs were simulated in half of the implementations, with one major SSW. No SSW occurred in the model under the combination La Niña/westerly phase of QBO.

Model Composite SSW

To study the characteristics of SSW and planetary wave amplitudes simulated under three combinations of QBO and ENSO (except La Niña/westerly phase of QBO), the fields of wind, temperature, and geopotential were averaged over six realizations relative to the day of beginning of temperature rise for three 10-day intervals: before, during, and after an SSW. Table 1 shows the selected realizations in each of the three ensembles and the time intervals corresponding to the days before, during, and after an SSW. In addition, fields of hydrodynamic parameters averaged over two-month intervals (a month before and a month after the day of start of temperature rise) were calculated. After the averaging, distributions of the fields for the model composite SSW were derived for three combinations of ENSO and QBO.

Figure 1 shows the altitude-time distributions of the amplitudes of a planetary wave with wavenumber 1 (PW1), zonal wind, and temperature deviations from its two-month average values during SSW under El Niño/easterly phase of QBO. Altitude-time distributions of the amplitudes of planetary waves with wavenumbers 2 and 3 (PW2 and PW3) were also constructed (not shown here). The composite SSW simulation results for this combination of ENSO and QBO show a 27 K increase in the simulated stratospheric temperature at 40 km, which is accompanied by mesospheric cooling by 30 K at 70 km and corresponds to maximal temperature changes over all combinations under study (Fig. 1a). For the presented composite SSW (consisting of major and minor individual SSWs), a change in the direction of the zonal-average jet stream is not simulated (Fig. 1b). The zonal average wind speed at an altitude of 40 km weakens from 50 to 20 m/s and is returned to values close to original ones after the SSW. The zonal wind speed changes the most under the combination El Niño/westerly phase of QBO (Fig. 2b). Amplitudes of PW1 are the highest in the first days of SSW in the upper stratosphere (~2200 m)

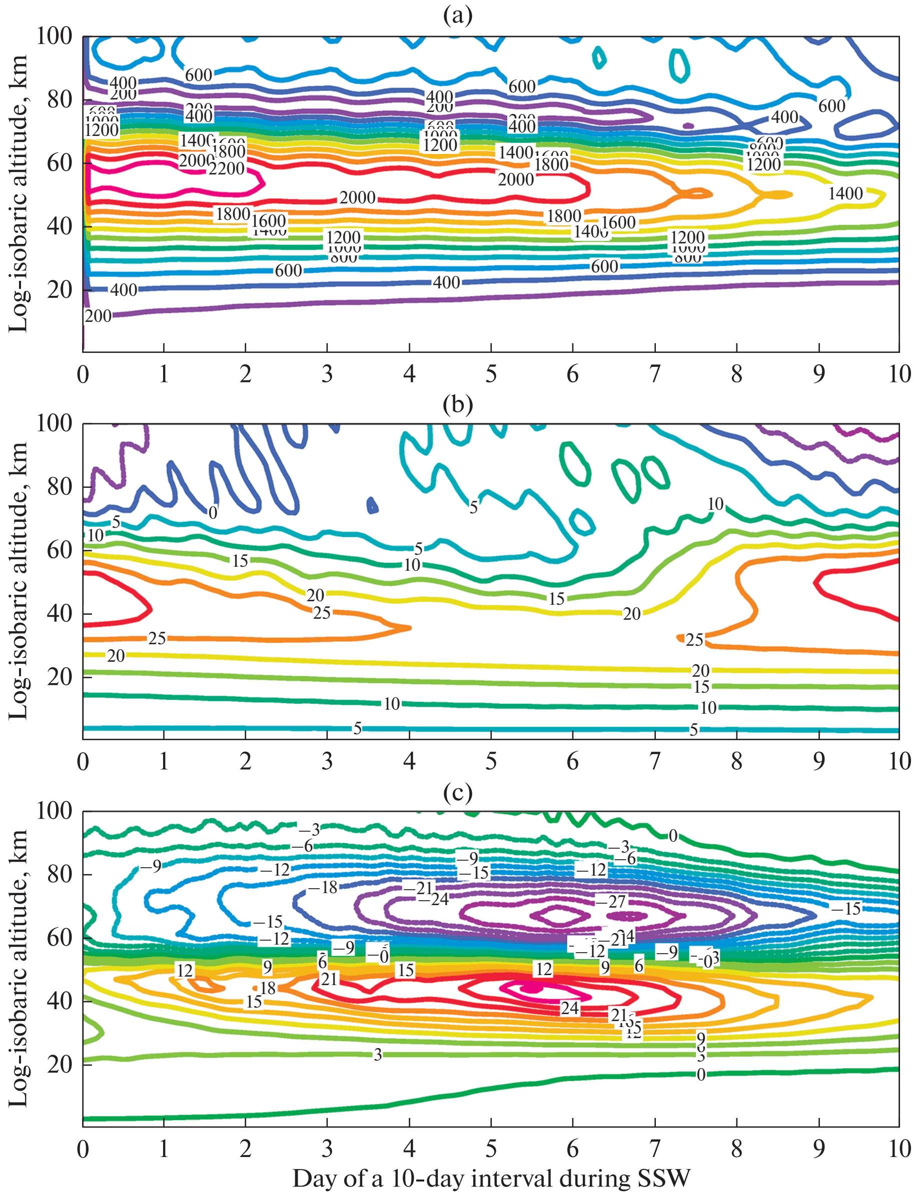

Fig. 1. Altitude-time distributions of (a) amplitudes of zonal harmonics in geopotential height, m, with $m = 1$ and (b) zonal average wind, m/s, at 62.5° N; (c) deviation of the zonal average temperature from the two-month average, K, at 87.5° N during SSW under the combination El Niño/easterly phase of QBO.

(Fig. 1a); amplitudes of PW3 do not significantly change with this combination; The amplitudes of PW2 before warming and in the first days of SSW are ~ 350 m at an altitude of 60 km for the three combination. Maximal amplitudes of PW2 are ~ 400 m after SSW at an altitude of 40 km; a similar amplitude distribution is reproduced by numerical simulation under La Niña/easterly phase of QBO conditions.

Figure 2 shows the altitude-time distributions for the combination El Niño/westerly phase of QBO. The composite model SSW for this combination is characterized by the minimal increase in the stratospheric temperature compared to other combinations (Fig. 2c), by only 15 K, which is accompanied by mesospheric cooling by 24 K. These temperature changes are the longest among the three combinations. The small changes in the temperature are accompanied by the strongest weakening of the zonal average wind (Fig. 2b): the speed decreases from 50 to 10 m/s and does not return to its original values after the SSW. In addition, PW1 amplitudes are the smallest, of ~2000 m, during the SSW (Fig. 2a). The maximal amplitudes of PW2 are ≈350 m and, unlike other combinations, have maxima not only in the upper, but also in the middle stratosphere. Significant PW3 amplitudes are simulated at 50-km level during the SSW.

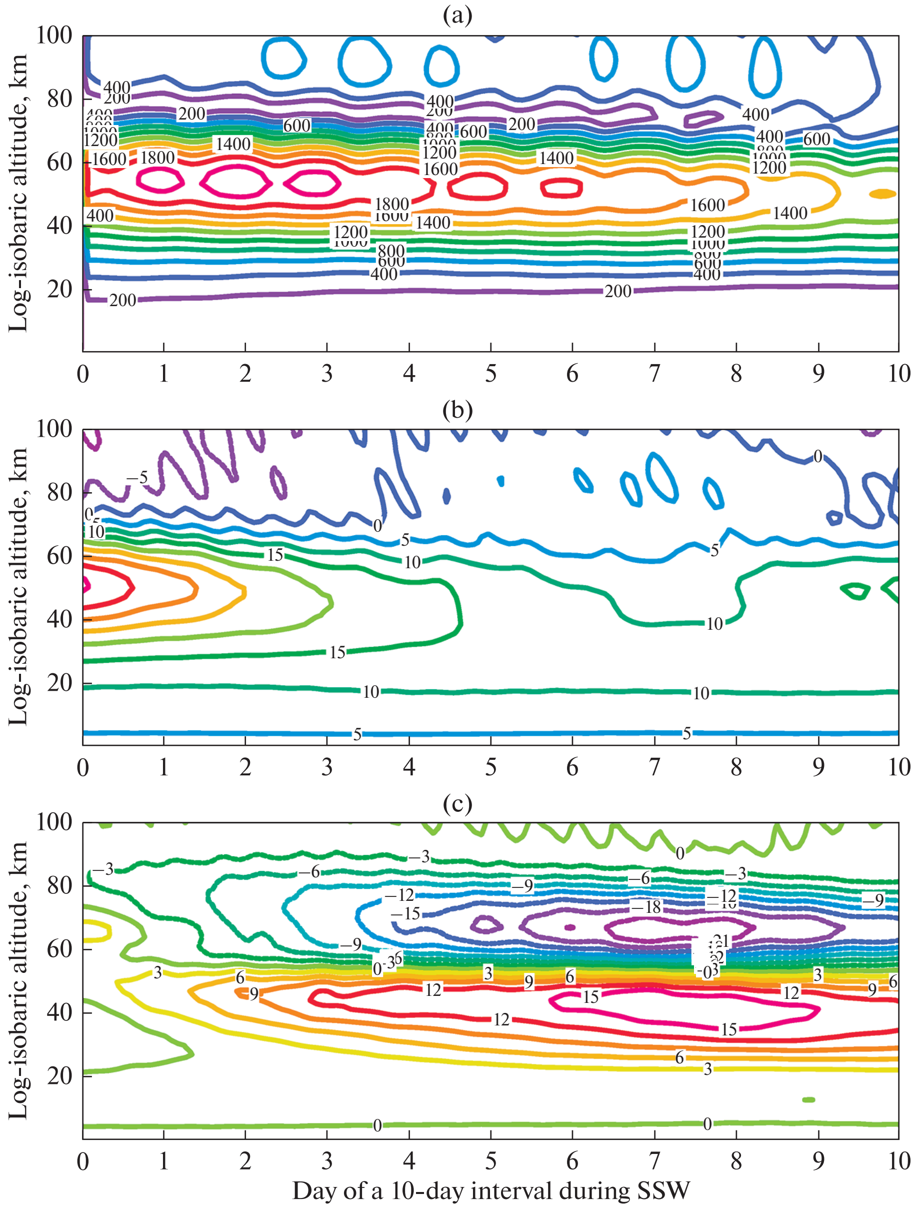

Fig. 2. Same as in Fig. 1, for the combination El Niño/westerly phase of QBO.

The altitude-time distributions of model hydrodynamic fields for La Niña/easterly phase of QBO are shown in Fig. 3. The increase in the simulated temperature for this combination is slightly larger (21 K) than for the combination El Niño/westerly phase of QBO, but lower than for the combination El Niño/easterly phase of QBO. The temperature in the mesosphere decreases by 24 K (Fig. 3c).

A change in the zonal average wind is insignificant for this combination (the wind weakens by 10–15 m/s at an altitude of 40 km), and PW1 amplitudes are large (~2200 m), like in the case of El Niño/easterly phase of QBO. The amplitude distribution for PW2 is similar, i.e., the PW2 amplitudes are ~350 m before and in the first days of SSW at a level of 60 km, and the amplitudes are maximal, of ~400 m, after the SSW at an altitude of 40 km. The amplitudes of PW3 are ~200 m at an altitude of 50 km during SSW, unlike the combination El Niño/easterly phase of QBO, where they are insignificant.

CONCLUSIONS

Using the nonlinear mechanistic general circulation model of the middle and upper atmosphere, a series of numerical experiments with different scenarios were carried out in order to study the effects of different phases of ENSO and QBO on the wave pro-

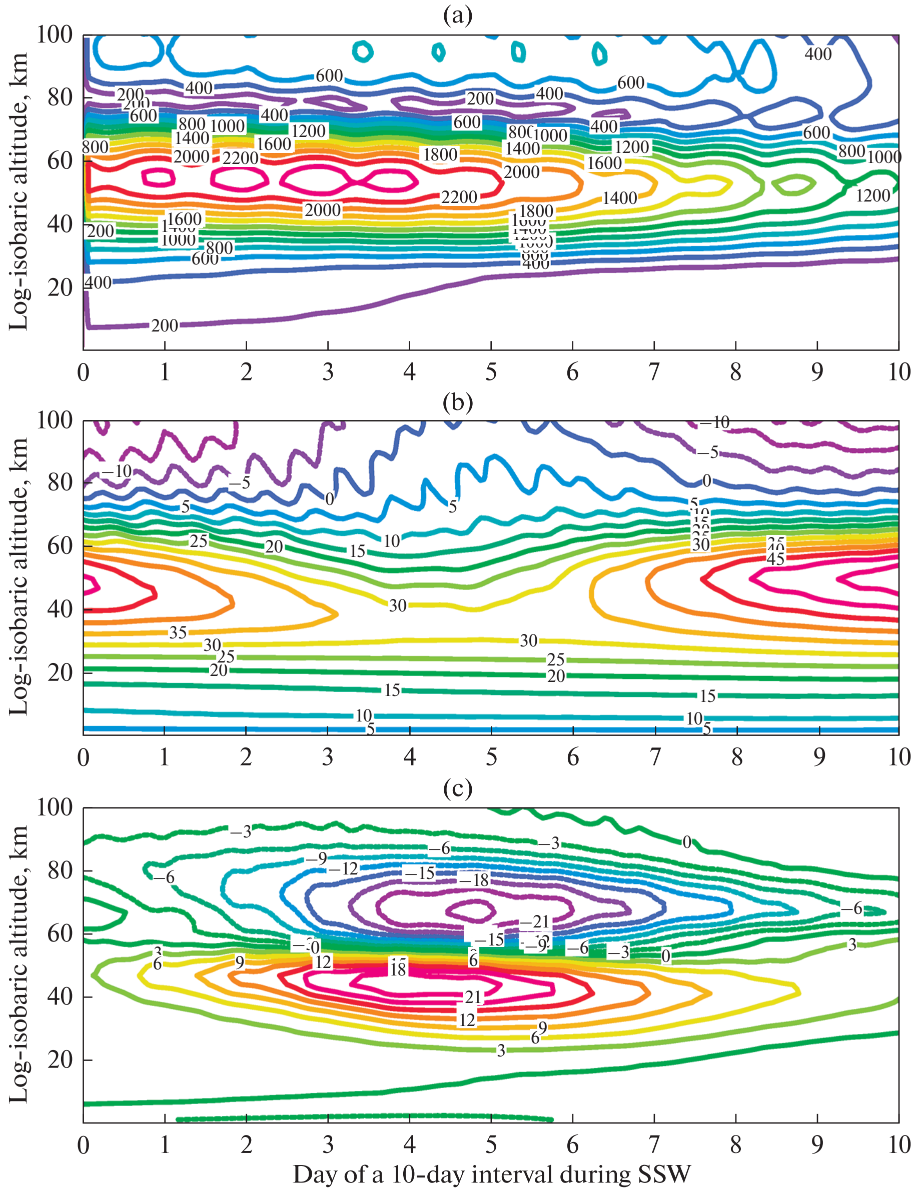

Fig. 3. Same as in Fig. 1, for the combination La Niña/easterly phase of QBO.

cesses of the winter stratosphere and occurrence of sudden stratospheric warmings. The simulation results showed the sensitivity of the dynamics of the winter stratosphere to considering the QBO and ENSO phases, which is manifested in changes in the distributions of temperature, planetary wave amplitudes, and zonal average wind and, hence, occurrence of SSW in the model.

Simulation for different combinations of ENSO and QBO phases has shown the following. The model does not reproduce SSW under the combination La Niña/westerly phase of QBO.

Results of averaging the meteorological fields over six realizations relative to the day of SSW start for ensembles considering the combinations El Niño/easterly phase of QBO, El Niño/westerly phase of QBO, and La Niña/easterly phase of QBO show the inverse relationship between QBO and ENSO with changes in the stratospheric and mesospheric temperature. The maximal increases in stratospheric temperature and cooling in the mesosphere are simulated for the combination El Niño/easterly phase of QBO. The maximal weakening of the zonal average wind speed is observed for the combination El Niño/westerly phase of QBO. The amplitudes of PW1 and PW2 are maximal during the easterly phase of QBO regardless of the ENSO phase.

Thus, out results confirm the importance of taking into account QBO and ENSO phases when analyzing the winter stratosphere. They play a significant role in the vertical and horizontal changes in the atmosphere, thus affecting the activity of planetary waves and the zonal mean wind. The database of fields of hydrodynamic parameters of the atmosphere prepared during this work for the winter months of the Northern Hemisphere based on the results of numerical simulation accounting different combinations of ENSO and QBO is to enable further studies of wave and dynamic processes in the middle atmosphere.

FUNDING

The work was supported by the Russian Science Foundation (project no. 20-77-10006-P).

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. F. Serva, C. Cagnazzo, B. Christiansen, and Sh. Yang, "The influence of ENSO events on the stratospheric QBO in a multi-model ensemble," Clim. Dyn. **54**, 2561–2575 (2020).
2. C. Garfinkel and D. Hartmann, "Different ENSO teleconnections and their effects on the stratospheric polar vortex," J. Geophys. Res. **113**, D18114 (2008).
3. R. Garcia-Herrera, N. Calvo, R. R. Garcia, and M. A. Giorgetta, "Propagation of ENSO temperature signals into the middle atmosphere: A comparison of two general circulation models and ERA-40 Reanalysis Data," J. Geophys. Res. **111**, D06101 (2006).
4. C. I. Garfinkel and D. L. Hartmann, "Effects of the El Nino—Southern Oscillation and the quasi-biennial oscillation on polar temperatures in the stratosphere," J. Geophys. Res. **112**, D19112 (2007).
5. M. P. Baldwin, L. J. Gray, T. J. Dunkerton, K. Hamilton, P. H. Haynes, W. J. Randel, J. R. Holton, M. J. Alexander, I. Hirota, T. Horinouchi, D. B. A. Jones, J. S. Kinnersley, C. Marquardt, K. Sato, and M. Takahashi, "The quasi-biennial oscillation," Rev. Geophys. **39**, 179–229 (2001).
6. J. R. Holton and H. C. Tan, "The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb," J. Atmos. Sci. **37**, 2200–2208 (1980).
7. A. Salminen, T. Asikainen, V. Maliniemi, and K. Mursula, "Dependence of sudden stratospheric warmings on internal and external drivers," Geophys. Rev. Lett. **47**, 1–9 (2020).
8. A. I. Pogorel'tsev, "Generation of normal atmospheric modes by stratospheric vacillations," Izv., Atmos. Ocean. Phys. **43** (4), 423–435 (2007).
9. A. V. Koval, "Calculation of the residual mean meridional circulation according to the middle and upper atmosphere model," Uch. Zapiski Ros. Gos. Gidrometerol. Univ., No. 55, 25–32 (2019).
10. T. S. Ermakova, O. G. Aniskina, I. A. Statnaya, M. A. Motsakov, and A. I. Pogoreltsev, "Simulation of the ENSO influence on the extra-tropical middle atmosphere," Earth, Planets Space **71** (8), 1–9 (2019).
11. N. M. Gavrilov, A. I. Pogorel'tsev, and K. Jakobi, "Numerical modeling of the effect of latitude-inhomogeneous gravity waves on the circulation of the middle atmosphere," Izv., Atmos. Ocean. Phys. **41** (1), 9–18 (2005).
12. G. I. Marchuk, *Numerical Methods in Weather Forecast* (Academic Press, New York, 1967).
13. G. Strang, "On the construction and comparison of difference schemes," SIAM. J. Numer. Anal. **5**, 516–517 (1968).
14. T. Matsuno, "Numerical integration of the primitive equations by a simulated backward difference method," J. Meteorol. Soc. Jpn. **44**, 76–84 (1966).
15. A. V. Koval, W. Chen, K. A. Didenko, T. S. Ermakova, N. M. Gavrilov, A. I. Pogoreltsev, O. N. Toptunova, K. Wei, A. N. Yarusova, and A. S. Zarubin, "Modelling the residual mean meridional circulation at different stages of sudden stratospheric warming events," Ann. Geophys. **39**, 357–368 (2021).
16. A. V. Koval, N. M. Gavrilov, K. K. Kandieva, T. S. Ermakova, and K. A. Didenko, "Numerical simulation of stratospheric QBO impact on the planetary waves up to the thermosphere," Sci. Rep. **12**, 1–12 (2022).
17. E. V. Rakushina, K. K. Kandieva, O. G. Aniskina, and A. I. Pogorel'tsev, "Use of the apparatus of natural orthogonal functions for the analysis of large-scale dynamic processes in the middle atmosphere," Trudy GGO im. A.I. Voeikova, No. 591, 105–123 (2018).
18. A. V. Koval, N. M. Gavrilov, A. I. Pogoreltsev, and K. K. Kandieva, "Dynamical impacts of stratospheric QBO on the global circulation up to the lower thermosphere," J. Geophys. Res.: Atmos. **127**, 1–14 (2022).

SPELL: OK