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Trends of the Vertical Component of the Wave Activity Flux in the Northern Hemisphere

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Abstract—Long-term trends of the three-dimensional Plumb wave activity flux are studied using data from the JRA-55 global atmospheric reanalysis. The vertical component of the Plumb flux characterizes the propagation of atmospheric planetary waves generated in the troposphere to the upper atmosphere and is used for the analysis of the stratosphere–troposphere dynamic interaction. The study of the wave activity flux covers three latitudinal sectors of the Northern Hemisphere from December to March for a 64-year period since 1958. It is shown that in January and March over the Russian Far East there is a statistically significant trend for an increase in the wave activity flux from the troposphere to the stratosphere, which can contribute to an increase in the frequency of cold wave formation in the mid-latitude troposphere. The study of the stratosphere–troposphere dynamic interaction in general and wave activity fluxes in particular is necessary for solving problems related to both global and regional climatic changes and mixing of long-lived atmospheric components.

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1. INTRODUCTION

The dynamics of the troposphere and stratosphere are fundamentally inseparable, and their dynamic interaction is observed during the winter season. However, the mechanisms generating and sustaining circulation differ between these atmospheric layers, as do the extent and strength of the influence of one atmospheric layer on the other (Baldwin and Dunkerton, 2001; Chan and Plumb, 2009; Baldwin et al., 2019). In contrast to tropospheric circulation, the complexity of which is due to a large number of processes of different scales related to interaction of the atmosphere with Earth's surface, the stratosphere is geostrophic to some extent and its dynamics is determined mainly by interaction of the mean flow with wave and vortex structures (Haigh and Blackburn, 2006; Haynes et al., 1991; Haigh et al., 2005). Generated by orography and heating differences between oceans and continents, planetary waves propagate from their sources in the troposphere, transfer energy and momentum, and cause variations in the stratospheric circulation. These variations, especially variations in the intensity of the stratospheric polar vortex, elicit a response in the troposphere and involve a feedback mechanism by which the stratosphere influences the troposphere (Charney and Drazin, 1961; Chen and Robinson, 1992; Reichler et al., 2005).

Studies of troposphere–stratosphere coupling have long been central to atmospheric dynamics research and have focused on analyzing both dynamic and radiative interactions (Baldwin et al., 2019; Solomon et al., 2010). This is because interannual changes in these relationships are not only indicators of ozone-layer and climate changes but can also be used as predictors of extreme winter weather events (Robock, 2001; Jadin et al., 2010; Smyshlyaev et al., 2016). For example, the enhanced vertical wave activity flux leading to a blocking mode of the stratosphere–troposphere interaction is favorable for the occurrence of sudden stratospheric warming (SSW). Their development determines variations in the temperature regime of the usually weakly variable stratosphere, and they also affect the tropospheric temperature regime and cyclogenesis (Scott and Polvani, 2006; Polvani and Waugh, 2004; Pogorel'tsev et al., 2014; Vargin et al., 2015; Gechaite et al., 2016). At present, the prediction of SSW, as the phenomenon most strongly affecting the stratospheric dynamics, by the best predictive numerical models is limited to ~10 days on average (Karpechko et al., 2018). Therefore, studies of stratospheric dynamics in general and the influence of tropospheric dynamics on it in particular have remained relevant in recent years and are related to the possibility of improving seasonal forecasts by improving the simulation of stratospheric dynamics in models.

Using reanalysis data, Rakushina et al. (2018) analyzed the climatic variability of stationary planetary wave amplitudes with different zonal wave numbers from the troposphere to the lower mesosphere. Different datasets showed a statistically significant intraseasonal variability of the amplitudes of stationary planetary waves with zonal wave number $m = 2$ (SPW2), which has been increasing in recent decades in the midlatitude stratosphere. The analysis of changes of stationary planetary waves with the zonal wave number $m = 1$ (SPW1) showed a significant increase of amplitudes in December and their weakening in January–February in the stratosphere of high and middle latitudes. Wei et al. (2021) investigated the role of the interaction of atmospheric waves with zonal wave numbers 1 and 2 in the dynamic coupling between the stratosphere and troposphere, as well as its intraseasonal features. In particular, it was shown that there are differences in wave activity propagation and inter-wave interaction in the first and second halves of the winter season.

The variability of planetary wave amplitudes and their influence on the dynamic and temperature regimes were also analyzed using the results of numerical simulations of the global atmospheric circulation (Liu et al., 2004; Koval et al., 2022a; 2023). The results showed that the consideration of planetary waves with different periods in the numerical experiments leads to significant changes in the mean zonal wind speed, meridional circulation components, and, as a consequence, the background temperature. Variations in the stratosphere–troposphere interaction are a consequence of observed and modeled variations in planetary wave amplitudes (Thompson et al., 2006; Pogoreltsev et al., 2009; Koval et al., 2022b).

The aim of this work is to investigate the interannual variability of the stratosphere–troposphere dynamic interaction. For this purpose, the propagation of planetary waves in the atmosphere was analyzed using three-dimensional wave activity fluxes calculated using the Plumb approach, which are an indicator and an important factor of the aforementioned interaction, based on JRA-55 reanalysis data (Kobayashi et al., 2015). The vertical component of the wave activity flux was averaged over three latitude–longitude sectors of the Northern Hemisphere for December through March, time series were constructed, and the significance of the detected trends was evaluated.

2. METHODOLOGY

Wave activity fluxes using the approach proposed by R.A. Plumb are usually considered in analyzing the flux divergence in the horizontal plane of planetary wave propagation in the atmosphere and its effect on the zonal circulation (Plumb, 1985; Andrews and McIntyre, 1976). This approach involves calculating the propagation direction of the wave packet in a 3D coordinate system, which has been successfully applied in the study of the vertical propagation of waves from the stratosphere and troposphere (Zyulyaeva and Zhadin, 2009; Gechaite et al., 2016) and their reflection in the opposite direction (see, e.g., (Vargin et al., 2022)). The three-dimensional Plumb wave activity flux, compared with the two-dimensional Eliassen–Palm flux, makes it possible to analyze the regional dynamic interaction between the stratosphere and troposphere, as well as regional features of wave activity propagation (Gečaitė, 2021; Wei et al., 2021). The three-dimensional wave activity flux vector describes the propagation of planetary waves along longitude (F_x), latitude (F_y), and height (F_z):

$$\mathbf{F}_\mathrm{s} = \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = \frac{P}{P_0}\cos\varphi \begin{pmatrix} v'^2 - \dfrac{1}{2\Omega a \sin 2\varphi}\dfrac{\partial(v'\phi')}{\partial\lambda} \\ -u'v' + \dfrac{1}{2\Omega a \sin 2\varphi}\dfrac{\partial(u'\phi')}{\partial\lambda} \\ \dfrac{2\Omega\sin\varphi}{S}\left[v'T' - \dfrac{1}{2\Omega a \sin 2\varphi}\dfrac{\partial(T'\phi')}{\partial\lambda}\right] \end{pmatrix}, \tag{1}$$

where P is pressure; P_0 is a pressure of 1000 hPa; Ω is the angular velocity of Earth's rotation; λ is longitude; φ is latitude; a is Earth's radius; S is the static stability parameter; u' is the zonal velocity perturbation (deviation from the longitude-averaged value); v' is meridional velocity perturbation; T' is temperature perturbation; and ϕ' is geopotential perturbation. The static stability parameter is defined as follows:

$$S = \frac{\partial\hat{T}}{\partial z} + \frac{k\hat{T}}{H}, \tag{2}$$

where $\hat{T}$ is the temperature averaged over the area north of 20° N; k is the thermal conductivity coefficient; and H is the height scale.

3. NORTHERN HEMISPHERE WAVE ACTIVITY DATA AND FLUXES

Air temperature, zonal and meridional wind speed, pressure, and geopotential height data were taken from the JRA-55 database and averaged for each month from 1958 to 2021. These data were used to calculate Plumb wave activity fluxes, which characterize planetary wave propagation and stratosphere–troposphere dynamic interaction. The averaged values of the verti-

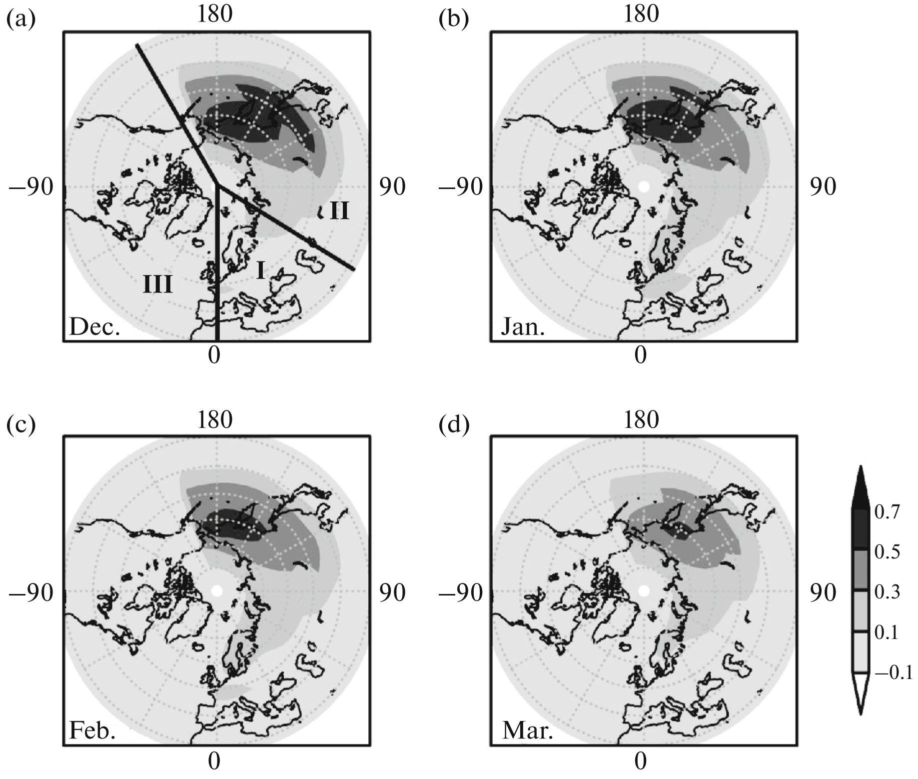

Fig. 1. Vertical component of three-dimensional wave activity flux (m^2/s^2) averaged over 64 years (1958–2021): (a) Dec., (b) Jan., (c) Feb., and (d) Mar., 20 km height. JRA-55 data.

cal component of the flux for all years of observations for December, January, February, and March in the Northern Hemisphere at 20 km are presented in Fig. 1.

The results show the zone of upward propagation of the wave activity flux over the Russian Far East and the absence of a noticeable zone of downward propagation. In the first winter months, the highest values of the vertical component of the Plumb wave activity fluxes from the troposphere to the stratosphere are observed (Figs. 1a and 1b).

As an example, Fig. 2 shows the 10-year (2008–2017) averaged values of the vertical component of the wave activity flux from December through March. Downward fluxes of wave activity from the stratosphere to the troposphere are observed over Greenland and northern Canada, but the values are almost an order of magnitude smaller compared with the values of upward fluxes.

The obtained averaging made it possible to determine the areas of division of the territory of the Northern Hemisphere into latitude–longitude sectors for further study of the interannual variability of the vertical component of the flux and construction and estimation of the linear trend. The selected sectors are presented in Fig. 1a. The first sector (I) includes most of Europe, northern Africa, European Russia, and the Middle East, the second sector (II) includes Asian Russia and Asian countries (where the maximum upward wave activity flux is observed), and the third sector (III) includes Canada, Greenland, the United States, and the North Atlantic (where the maximum downward wave activity flux is observed).

4. RESULTS

In order to investigate the interannual variability of the stratosphere–troposphere interaction, the monthly averages of the vertical component of the wave activity flux were averaged in each sector in the regions of its observed variations, i.e., in the band 37.5°–77.5° N. The averaging was performed for a 20 km (50 hPa) level, and the results were obtained separately for each month from December through March for the period 1958 through 2021. Calculations were also performed for higher levels, and the trends obtained were retained. Linear trends were constructed for the time dependences, and their statistical significance was determined. The values of significance levels for all sectors and months for the period from 1958 to 2021 are presented in Table 1.

Figure 3 shows the temporal variability of the vertical component of the wave activity flux in each sector for December. It was expected that the most interesting results would be in sector II, where maximum values of the upward wave activity flux are observed, and

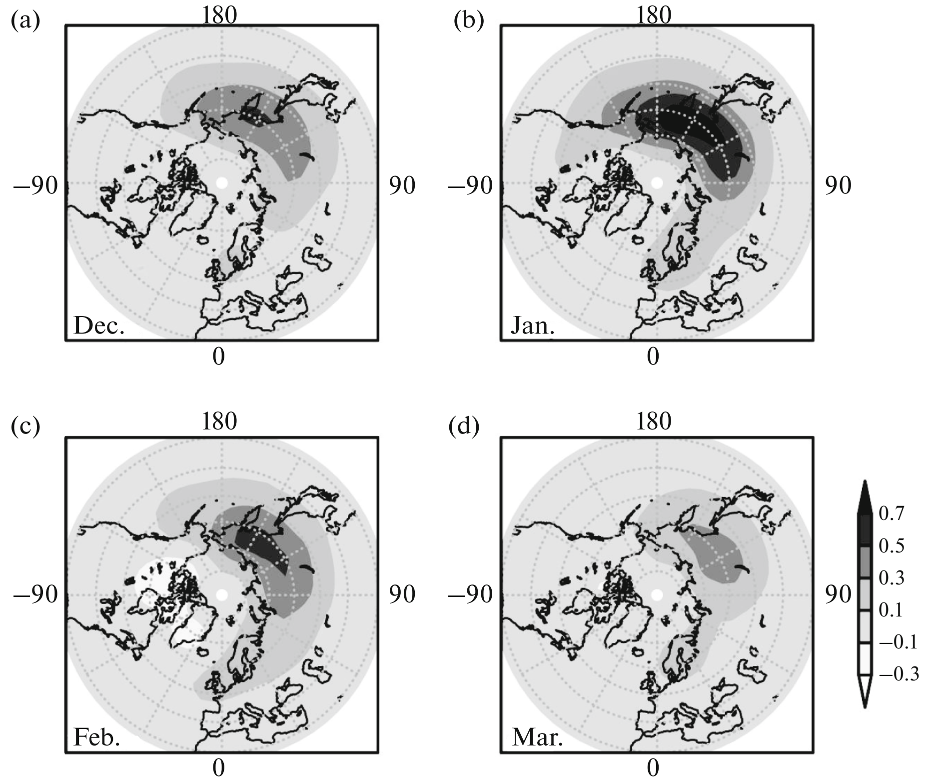

Fig. 2. Vertical component of three-dimensional wave activity flux (m^2/s^2) averaged over 10 years (2008–2017): (a) Dec., (b) Jan., (c) Feb., (d) Mar., 20 km height. JRA-55 data.

special attention should be paid to sector III, where negative values of the vertical component of the Plumb flux are observed in some years. The values of the wave activity flux in sector II are two times greater than the values in sector III and 3–4 times greater than the values in sector I, which is typical for all months under consideration.

Figure 3c shows that in sector III in December there is a slight increase in wave activity for the period from 1958 to 2021, but the statistical significance of the obtained results is low. No statistically significant trends are observed in the remaining sectors. However, it was decided to separately consider the interannual variability of the vertical component of the flux averaged over the same parameters for the period from 1980 to 2021 (Fig. 4), because since 1980 the reanalysis data, including those used in this work, have been significantly improved due to satellite data assimilation (Gelaro et al., 2017). The values of significance levels for all sectors and months for this period are presented in Table 2.

Table 1. Significance levels of trends in each sector for months under study from 1958 to 2021

Sector	Dec.	Jan.	Feb.	Mar.
I	Insignificant	5%	Insignificant	Insignificant
II	Insignificant	5%	Insignificant	10%
III	Insignificant	5%	Insignificant	Insignificant

The results of calculating and averaging by sector the vertical component of the wave activity flux since 1980 for December in Fig. 4 show that there is also no statistically significant trend in sector II, but the linear trend is not significant in sector III either. The trend in sector I becomes significant (significance level 10%), where a decrease in the wave activity flux from the tro-

Table 2. Significance levels of trends in each sector for months under study for period from 1980 to 2021

Sector	Dec.	Jan.	Feb.	Mar.
I	10%	20%	Insignificant	25%
II	Insignificant	1%	Insignificant	5%
III	Insignificant	Insignificant	Insignificant	Insignificant

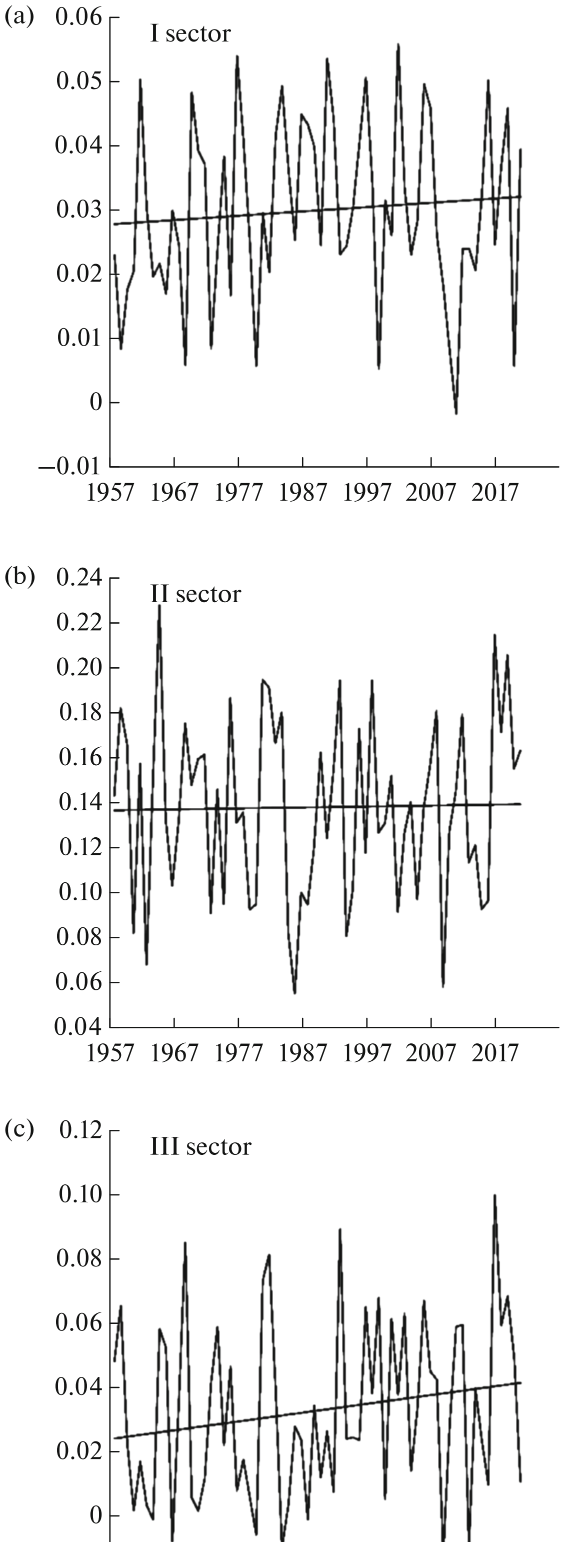

Fig. 3. Temporal variability of vertical component of wave activity flux over 64 years (1958–2021) for Dec. at 20 km level, averaged for (a) Sector I, (b) Sector II, (c) Sector III in 37.5°–77.5° N band. JRA-55 data.

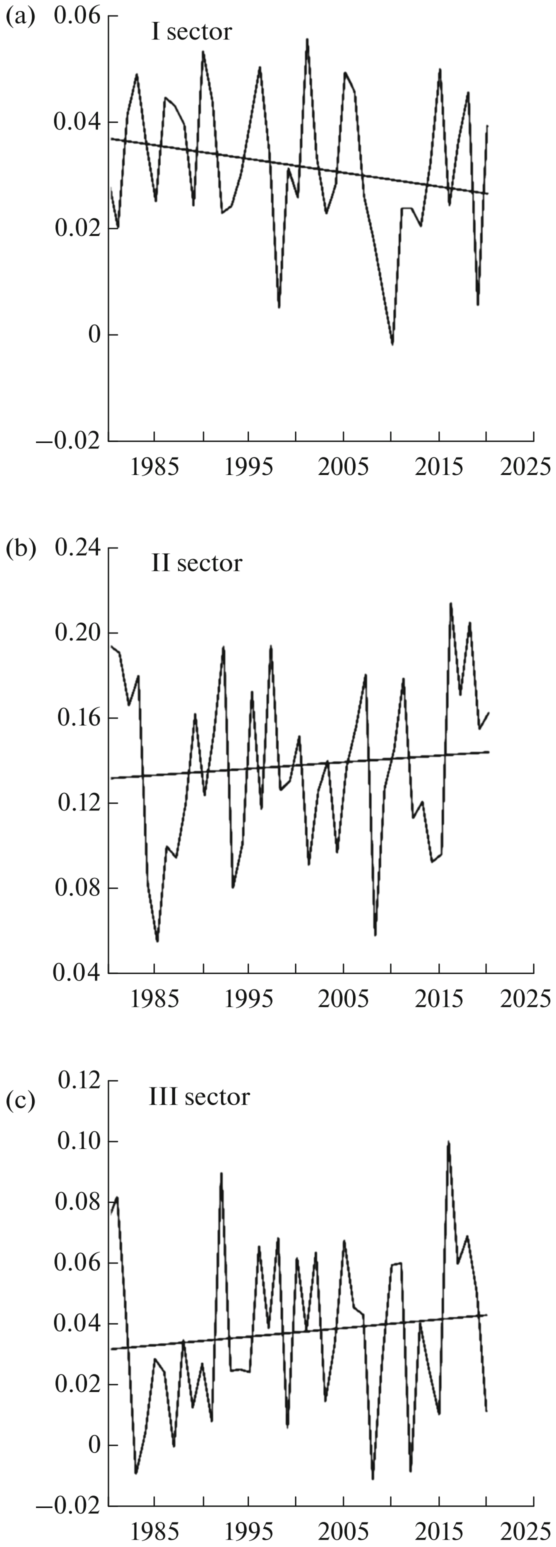

Fig. 4. Temporal variability of vertical component of wave activity flux for 1980–2021 for Dec. at 20 km level, averaged for (a) sector I, (b) sector II, and (c) sector III in 37.5°–77.5° N band. JRA-55 data.

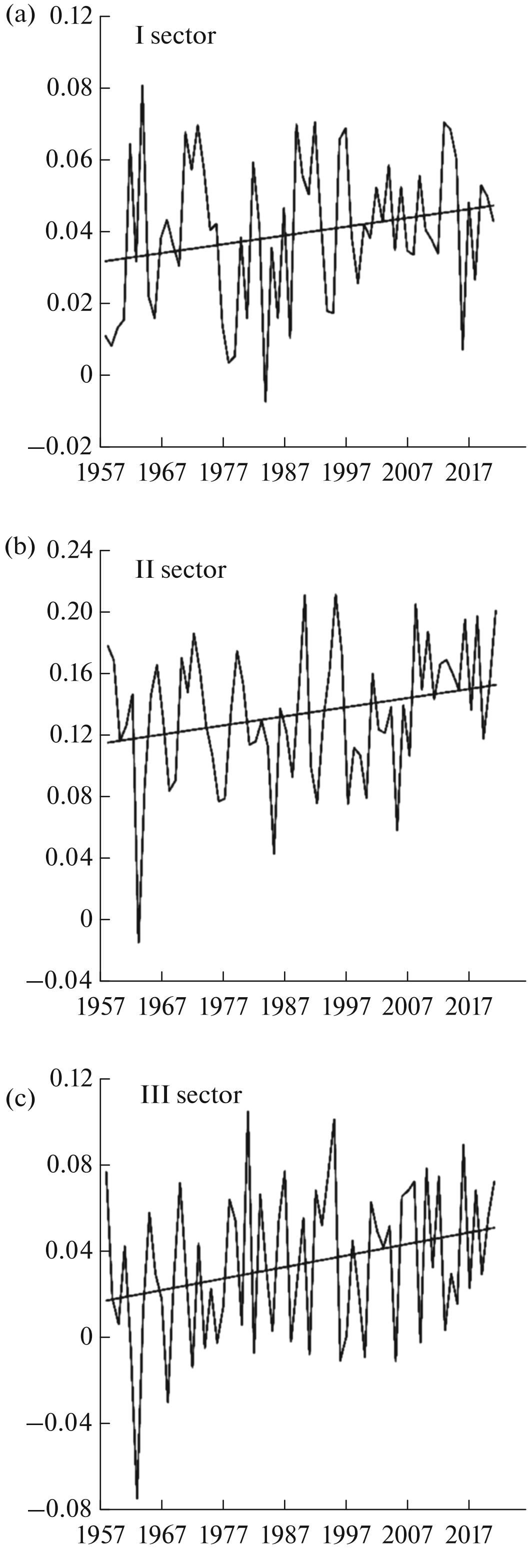

Fig. 5. Temporal variability of vertical component of wave activity flux over 64 years (1958–2021) for Jan. at 20 km level, averaged for (a) sector I, (b) sector II, and (c) sector III in 37.5°–77.5° N band. JRA-55 data.

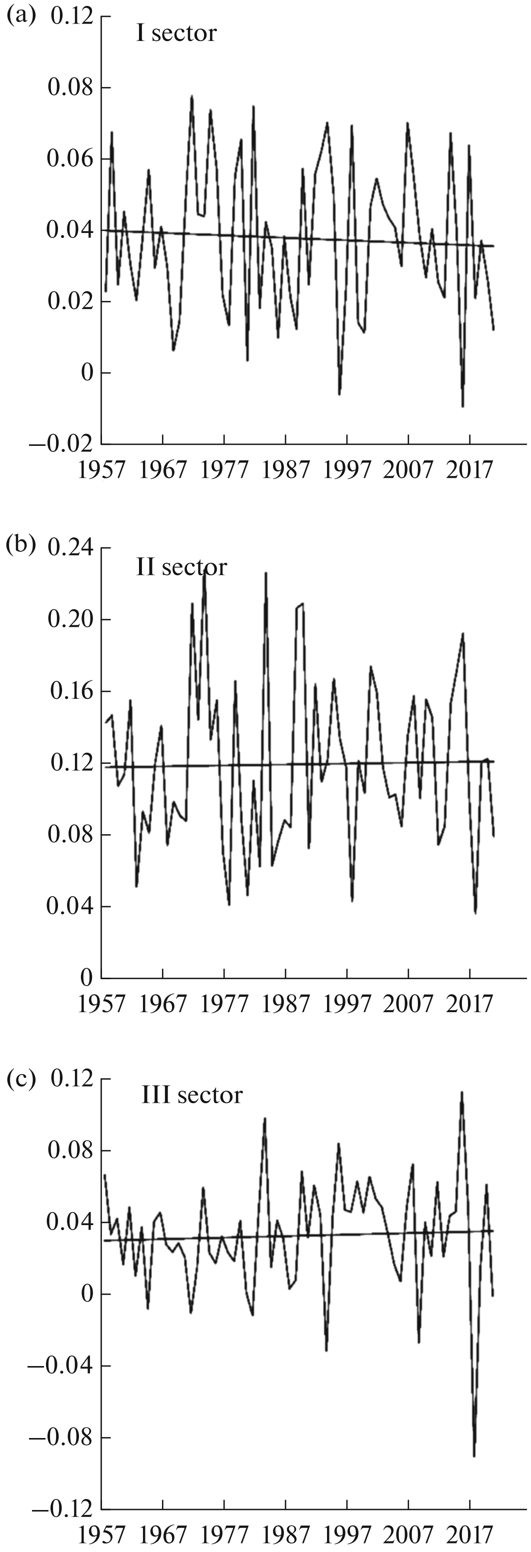

Fig. 6. Temporal variability of vertical component of wave activity flux over 64 years (1958–2021) for Feb. at 20 km level, averaged for (a) sector I, (b) sector II, and (c) sector III in 37.5°–77.5° N band. JRA-55 data.

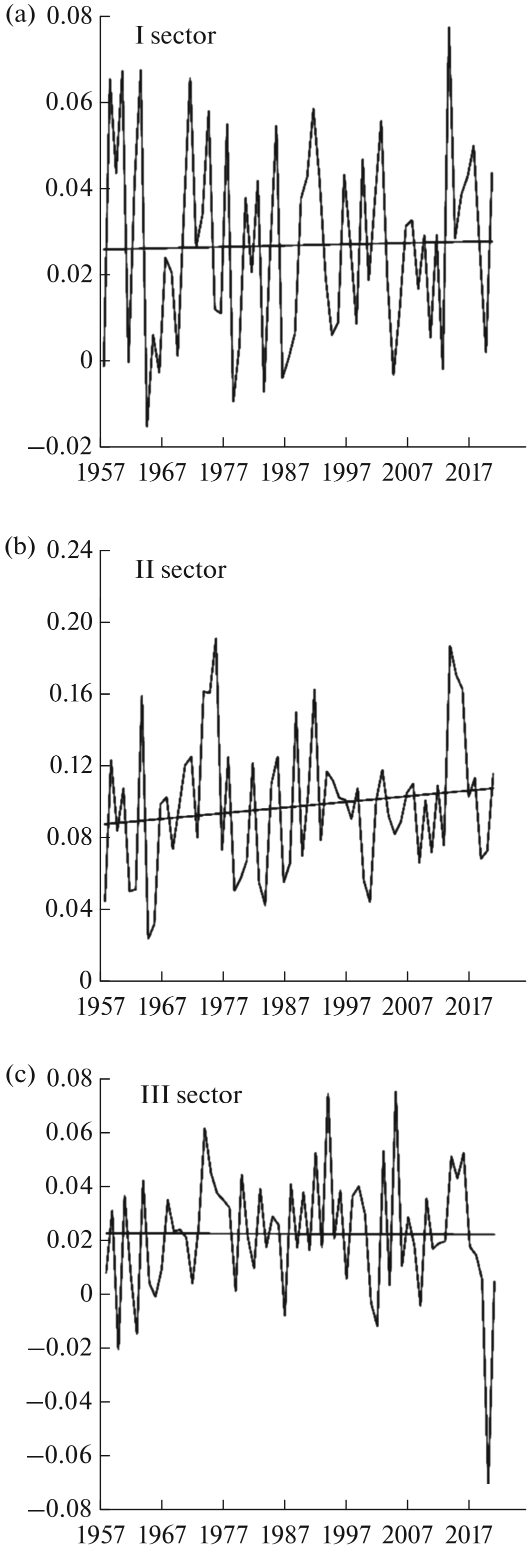

Fig. 7. Temporal variability of vertical component of wave activity flux over 64 years (1958–2021) for Mar. at 20 km level, averaged for (a) sector I, (b) sector II, and (c) sector III in 37.5°–77.5° N band. JRA-55 data.

posphere to the stratosphere is observed. It should be noted that in December, one of the maxima (for this sector) of the averaged upward wave activity flux in 2017 is observed in sector III, although downward fluxes are observed more frequently in this region.

Figure 5 shows the results for January. As expected, the maximum values of the upward component of the wave activity flux are observed in sector II, but the interannual increase is not characteristic of each month. In January, in turn, the increase of the wave activity flux from the troposphere to the stratosphere is characteristic of all sectors, and the trend is statistically significant at the significance level of 5%.

When analyzing the averaged values since 1980, the significance of the linear trend increases in sector II, i.e., the upward branch of the vertical component of the Plumb flux increases. In sector I, the statistical significance becomes low (significance level of 20%), and in sector III the trend is not significant. In addition, in January, along with December, the maximum (for this sector) values of the upward wave activity flux in sector III in 1980 and 1994 are observed.

The absence of statistically significant trends in February for the period 1958 through 2021 is shown in Fig. 6. The conclusions do not change when analyzing the calculation results since 1980. It should be noted here that for all the years and months under study the maximum values of the downward wave activity flux in February are observed in sectors I and III in 2015 and 2017, respectively; the maximum values of the wave activity flux from the troposphere to the stratosphere are observed in sectors II (1973 and 1989) and III (2015).

The results for March in Fig. 7 show an increase in the upward wave activity flux in sector II over the period from 1958 to 2021. In sectors I and III, the linear trend is not statistically significant. The significance in sector II increases when analyzing the results since 1980; i.e., the significance level changes from 10 to 5%. In addition, the statistical significance of the trend in sector I increases, but this is not sufficient to draw conclusions about any climatic changes. March shows the peak of the upward flux of Plumb wave activity in Sector I in 2013.

5. CONCLUSIONS

In order to investigate the interannual variability of the stratosphere–troposphere interaction, the vertical component of the three-dimensional wave activity flux calculated using the Plumb approach was analyzed using reanalysis data. This component characterizes the vertical propagation of planetary waves in the atmosphere and is an indicator of the stratosphere–troposphere energy and momentum exchange. The vertical flux component was averaged over three Northern Hemisphere regions for the months December through March and was analyzed over a 64-year period from 1958 to 2021.

Statistical estimation of the calculated trends of wave activity fluxes showed an increase in the wave activity rising from the troposphere to the stratosphere in January and March over the Russian Far East. It should be noted here that the second region (out of the three considered) is characterized by the highest values of the vertical component of the wave activity flux. In this regard, the obtained increase of this component in this region can lead to an increase in the frequency of cold wave formation in the mid-latitude troposphere in January and in February (in the case of prolonged SSWs) over the temperate latitudes of East Asia (Huang et al., 2021). The increase in wave activity in March is also supported by the development of minor and major, i.e., accompanied by a change in the zonal mean wind direction, SSWs in this month, which have become more frequently observed in this century. More often these SSWs are final, i.e., a dynamic transition of the stratosphere to the summer regime is observed. In such cases, one observes earlier destruction of the stratospheric polar vortex and, as a consequence, the ozone layer recovery above the pole. The interannual decrease of the upward component of the flux since 1980 is observed only in December over the European part of Russia, Europe, and the Middle East. This, in turn, can lead to the fact that cold waves, as a response to the weakening of the polar vortex during the SSW in December, are observed less frequently over northern Europe (Kolstad et al., 2010; Tomassini et al., 2012). Downward fluxes of wave activity are observed over northern North America, but in some years they are also detected in the first sector, over Europe, from January through March.

In order to analyze the regional influence of the wave activity flux variability on the temperature and wind regime, it is necessary to take into account different phases of natural long-period oscillations, such as the quasi-biennial oscillation (QBO) of the zonal wind in the equatorial stratosphere and/or the El Niño—Southern Oscillation (ENSO). In addition, the analysis of monthly averaged data in this article led to smoothing out possible short-term periods of abrupt changes in wave activity at different SSW stages and to excluding the influence of gravity waves. The latter, in turn, contribute to the "preparation" of the stratospheric polar vortex during the SSW formation (Cullens and Thurairajah, 2021). Therefore, in order to extend the study, it is planned to use the results of numerical modeling of the atmospheric general circulation, including taking into account various combinations of the QBO and ENSO, for a more detailed study of the wave activity trends in the future.

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CONFLICT OF INTEREST

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

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