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Analysis of Three-dimensional Eliassen–Palm Fluxes in the Lower Stratosphere

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Abstract—Using the monthly mean NCEP/NCAR reanalysis dataset, the three-dimensional Eliassen–Palm (EP) fluxes of quasi-stationary wave propagation in the lower stratosphere were computed for each month from November to March for the period from 1958 to 2007. It is shown that the upward planetary wave propagation from the troposphere to the stratosphere generally occurs over the northern Eurasia, while their weak downward propagation is observed in Labrador and southern Greenland regions in the lower stratosphere. Interannual variations of the vertical EP fluxes also have the dipole-like spatial pattern with the opposite anomalies in the West and East hemispheres which are most prominent in January–February. Significant differences in the interaction of the zonal circulation of the stratosphere in the beginning of winter (November–December) and mid-to-late winter (January–March) are revealed. Intensification of the planetary waves' penetration into the stratosphere in December causes changes in the stratospheric dynamics, creating the "preconditions" for the stratospheric warming appearances in January, but such a mechanism is not detected in February. In the years with the cold polar vortex, the "stratospheric bridge" is formed with the strengthening of the upward EP flux over the northern Eurasia and downward EP flux over the North Atlantic.

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INTRODUCTION

In recent years, the studies of the stratosphere-troposphere dynamic relations and their role in the ocean–atmosphere interaction acquired the large scientific and practical significance [1, 3, 19–21]. Interannual and decadal variations of stratospheric parameters are not only the indicators of changes in the ozone layer and climate, but some of them can be used as predictors of extreme weather events in the wintertime [3]. Using the stratospheric predictors, it is possible to improve significantly the traditional long-range weather forecasts, because the lifetime of dynamic disturbances in the stratosphere is much longer (~10–40 days) than that in the troposphere (3–7 days), and the downward wave propagation from the stratosphere to the troposphere is often observed [4]. This is the basis for the statistical long-range (out to month) forecasting the abnormally cold or warm winters in the particular regions using different stratospheric predictors, for example, changes in the zonal wind component at the 10 hPa surface, which is averaged over the latitudinal circle, or the Arctic Oscillation (AO) index [20, 21], or total ozone content [2], or monsoon variability in China using the wave activity indices in the stratosphere and troposphere [6]. Therefore, the analysis of the three-dimensional propagation of the upward/downward wave signal in the troposphere and stratosphere is important for future methods of the predictions of extreme weather events using stratospheric predictors.

There are many studies of the wave signal penetration from the troposphere to the stratosphere [7, 13, 16, 19], whereas their downward propagation has not been studied well. Usually, to analyze the stationary planetary wave propagation and their forcing on the zonal atmospheric circulation, two-dimensional Eliassen–Palm (EP) fluxes are considered. Use of two-dimensional EP fluxes for the atmospheric wave activity diagnostics is based on the AO zonal symmetry (so-called "annular" mode), which is especially pronounced in the stratosphere [4, 20]. However, as it will be shown below, there are significant longitudinal peculiarities in the planetary wave propagation and their forcing on the zonal flow, which have the important significance for the stratosphere-troposphere interaction. There are evidences of large intraseasonal differences in the beginning of winter (November–December) and mid-to-late winter (February–March) between the interannual variations of the stratospheric wave activity [13], interaction of the Aleutian and Icelandic lows in the troposphere [9, 10], relations of the sea surface temperature (SST) anomalies in the North Atlantic and North Atlantic Oscillation (NAO) [17]. That is why, in this work, unlike most of researches of the stratosphere-troposphere interaction, we took into account the longitudinal and intraseasonal peculiarities of the stratospheric dynamics.

DATA AND METHOD OF ANALYSIS

Three-dimensional Eliassen–Palm vector describes the quasi-stationary planetary wave propagation along the latitude (F_x), longitude (F_y) and height (F_z) [18]:

$$\vec{F}_s = \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = \frac{p}{p_0}\cos\varphi \begin{pmatrix} v'^2 - \dfrac{1}{2\Omega a \sin 2\varphi}\dfrac{\partial(v'\phi')}{\partial\lambda} \\ -u'v' + \dfrac{1}{2\Omega a \sin 2\varphi}\dfrac{\partial(u'\phi')}{\partial\lambda} \\ \dfrac{2\Omega\sin 2\varphi}{S}\left[v'T' - \dfrac{1}{2\Omega a \sin 2\varphi}\dfrac{\partial(T'\phi')}{\partial\lambda}\right] \end{pmatrix}, \tag{1}$$

where S is the stability parameter, which is defined by the formula

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

u', v', T', ϕ' are the deviations from the zonal means of the zonal and meridional wind components, temperature and geopotential, respectively, $\hat{T}$ is the temperature averaged over the territory north from 20° N, k is the temperature conductivity coefficient, $H = 7$ km is the scale height, φ and λ are the latitude and longitude, respectively, Ω and a are the Earth's angular velocity and its radius, respectively, p is the air pressure at the given level, and $p_0 = 1000$ hPa.

One can show that these equations can be reduced to the two-dimensional EP vector, whose components describe the vortex momentum and heat transport by the planetary waves. In approximation of the linear optics, the three-dimensional EP vector is equal to the group velocity of the planetary waves multiplied by the wave energy density [18]. Three-dimensional EP fluxes describe the upward and downward propagation of the vortex energy. It should be noted that the vertical EP flux component F_z is associated not only with the vortex heat flux, but also with the longitudinal variability of the second term in (1), the contributions of which are compared with that of the first term. The same is true for the first and second terms of the zonal and meridional EP components. The two-dimensional EP vectors can not indicate any changes in the vertical propagation of planetary waves and their impact on the atmosphere dynamics.

The monthly mean NCEP/NCAR reanalysis data on meridional and zonal wind components (hereinafter, zonal and meridional wind) [12] were used for the computations at the standard levels 100, 70, 50, 30, 20, and 10 hPa for each month (November–March) in the period from 1958 to 2007. After determination of the EP fluxes, the flux deviations from the averages (i.e., anomalies) were computed for each level and month, i.e., seasonal cycle was eliminated. For the analysis, we used the empirical orthogonal functions (EOF) for the each standard level from 100 to 10 hPa.

RESULTS OF ANALYSIS

Unlike zonal wind in the stratosphere, which is nearly zonally-symmetric, planetary waves propagation from the troposphere to stratosphere and their impact on the zonal wind has large spatial and seasonal variability. The values of the vertical EP fluxes at 30 hPa averaged over December 1958–2006 and January 1959–2007 are shown in Fig. 1. The most significant penetration of the planetary waves from the troposphere to stratosphere (corresponding to the positive F_z values) is observed over Siberia, while the weak downward wave propagation occurs over the North Atlantic and southern Greenland (negative F_z) in December, which strengthens in January–February and weakens in March. The downward signal is small in comparison with the wave penetration from the troposphere to stratosphere, however, as shown below, it plays a major role in the stratosphere-troposphere interaction.

Interannual variability of the three-dimensional EP vectors also has longitudinal differences. For example, a significant strengthening of the wave penetration into the stratosphere over Eurasia and some weakening of the downward flux over the North Atlantic and Greenland were observed in December 1976 before stratospheric warming in January 1977. This created the “preconditions” [14, 16] for the strong stratospheric warming in January 1977. In December 1975, no wave activity strengthening was detected, but later, in January 1976, the jet current became stronger. The performed comparison of the meridional EP

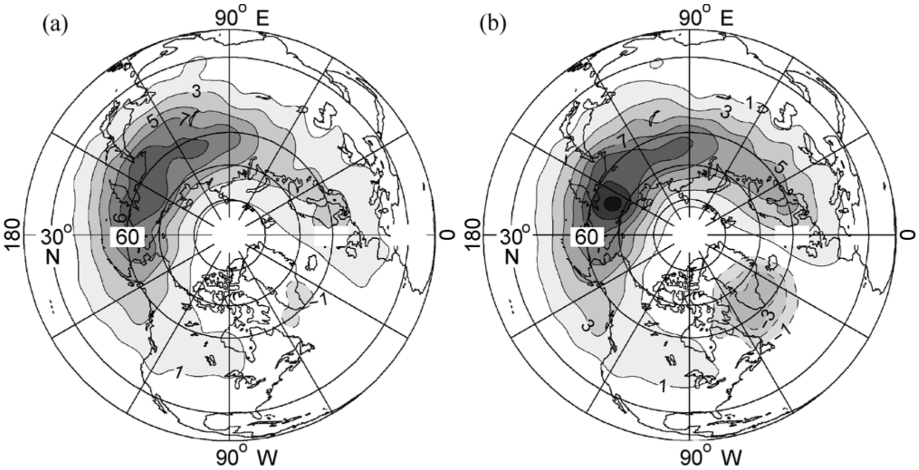

Fig. 1. The multi-years monthly means of the vertical 3D Eliassen–Palm fluxes at 30 hPa ($\times 10^{-5}$ m^2/s^2) in (a) December 1958–2006; (b) January 1959–2007. Dashed line contours their negative values.

flux component (no pictures provided in this paper) for the considered years in December also showed large longitudinal differences in the planetary wave horizontal propagation with the larger positive (poleward) F_y component over the northwestern Siberia and smaller negative (equatorward) F_y component over the Northern Europe in December 1976.

To study relations between the interannual variations of the wave activity and zonal circulation of the stratosphere, the EOFs of zonal wind and vertical component of the EP flux were computed for each month from November to March. The spatial structures of the first EOFs of the vertical EP fluxes and zonal wind at all the considered surfaces are similar, that is why in this paper we represent only results of computations for the 30 hPa level.

To reveal processes, which precede warming, we compared the vertical EP vector component and zonal wind in the lower stratosphere. Note that the EP flux value with a monthly lag (i.e., corresponding to the preceding month to the zonal wind change month) was used in our computations. Figure 2 shows the spatial patterns and their principal components of the first EOF modes of the vertical EP flux in December and zonal wind anomalies in January at 30 hPa. Spatial patterns of the first EOF (43% of contribution to the total variance) of the F_z anomalies allow seeing the clear wave with the wave number 1 along the longitude. Slightly negative F_z anomalies are observed over Iceland, while significant positive anomalies of the vertical EP flux component take place over the northern Siberia.

Figure 2c also illustrates the close correspondence between the coefficients of the first EOF of the vertical EP flux component (F_z) in December and zonal wind in January (the correlation coefficient –0.58). Positive peaks of the first EOF of F_z in December correspond well to the years with strong stratospheric warming in consecutive January in 1960, 1970, 1977, 1985, 1994, 1998, 2003, and 2006. This can mean that the strengthening of wave penetration into the stratosphere in December create conditions for stratospheric warming in subsequent January; this fact coheres well with the results presented in [15, 19], where the preceding (about 20–40 days) strengthening of the upward flux F_z before the stratospheric warming was noted. In the years with the strong polar jet current and cold stratospheric vortex in the Arctic, the negative F_z anomalies over the northern Siberia are negative, while the vortex heat transport with the planetary waves is directed from the high to mid-latitudes.

The question arises: does the situation remain the same in the mid- and late winter? In spite of that the spatial patterns of the first EOFs of the zonal wind anomalies are similar for each month during the wintertime, the correlation analysis did not reveal such relations between the F_z in January (February) and the zonal wind in February (March). Values of correlation between the coefficients of the first EOFs of the F_z modes and zonal wind anomalies at 30 hPa for each month for November–March are shown in the table. The estimation of the statistical significance was computed by the comparison of

$$\frac{r\sqrt{n-2}}{\sqrt{1-r^2}},$$

where r is the correlation coefficient, n is degree of freedom with the critical value of the Student t-test $t(n-2, 1-\alpha)$, where α is the confidence level.

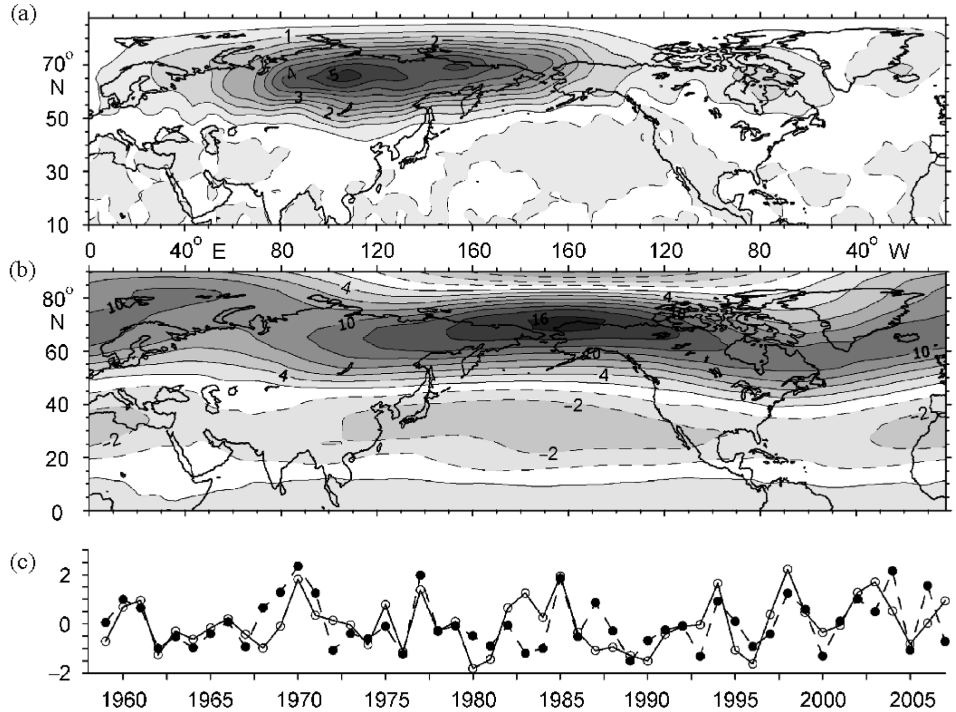

Fig. 2. First EOFs of (a) the vertical component of the EP flux ($\times 10^{-5}$ m^2/s^2) anomalies for December, (b) zonal wind anomalies (m/s) for January at 30 hPa, (c) principal components of the first EOF for the EP flux (arbitrary units). In panel (c), solid line is vertical component of EP flux; dashed line is zonal wind with reversed sign; marks at horizontal axis denote January.

Correlation between the coefficients of the first EOFs mode for the 3D EP flux vertical component and zonal wind at 30 hPa

Coefficients of the first EOF mode for the vertical component of EP flux	Coefficients of the first EOF mode anomalies of zonal wind				
	November	December	January	February	March
November	**–0.44**	**–0.47**	**–0.26**	–0.05	0.15
December	–0.06	**–0.29**	**–0.58**	**–0.27**	–0.04
January	0.03	–0.09	–0.12	0.04	0.12
February	0.16	**0.21**	**0.47**	**0.38**	0.06
March	**0.26**	**0.32**	0.14	**0.35**	–0.13

Note: for November, December, February, and March 1958–2007 and January 1959–2004, bold values are statistically significant on the 95% level of confidence.

It can be seen in the table that the interaction between the vertically propagating quasi-stationary waves and zonal circulation of the stratosphere has significant intraseasonal differences. Thus, the correlations are negative in early winter (November, December); meanwhile the simultaneous correlations, for example, between F_z in December and zonal wind in December equals to –0.29, i.e., essentially less by its absolute value than that between F_z in December and zonal wind in January (–0.58). This can imply that the deceleration (acceleration) of polar jet is associated with the strengthening (weakening) of the planetary wave penetration from the troposphere to the stratosphere over the northern Eurasia (Fig. 2) in the preceding month. The situation strikingly changes in late winter (February–March): correlation becomes positive and now the zonal wind structure in the preceding month defines F_z in the next month, for example, the correlation coefficient between zonal wind in January and F_z in February equals to 0.47.

Figure 3 shows the F_z anomalies in January and February averaged over the years with warm and cold stratospheric vortexes. Separation of the years with cold and warm vortexes was performed in accordance with minima and maxima of the first EOF of zonal wind anomalies at 30 hPa for the corresponding month.

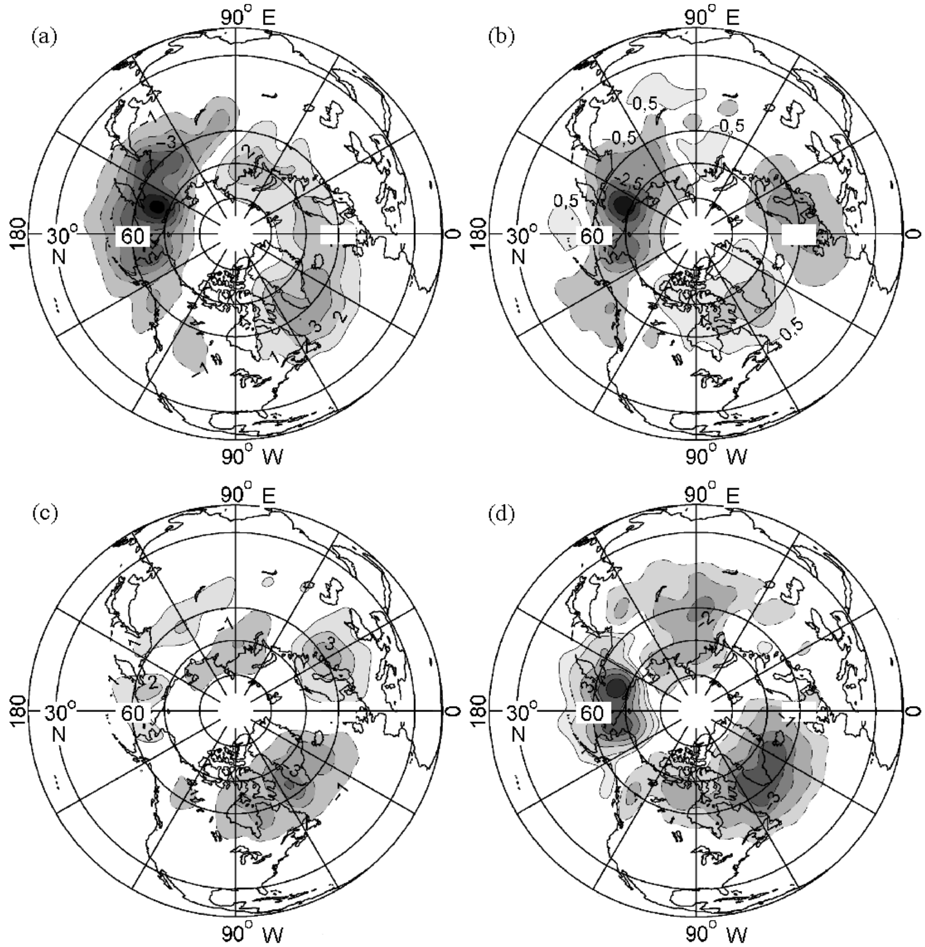

Fig. 3. Anomalies of the EP flux vertical component ($\times 10^{-5}$ m^2/s^2) for (a, b) warm and (c, d) cold stratospheric vortexes in (a, c) January and (b, d) February. Negative anomalies are marked by dashed contours.

According to this classification, warm stratospheric vortices were observed in January 1960, 1968, 1970, 1971, 1977, 1985, 1987, and 2002 and in February 1966, 1973, 1979, 1980, 1984, 1989, 1999, and 2001. Cold stratospheric vortices were observed in January 1962, 1964, 1967, 1972, 1976, 1983, 1989, 1993, 1996, 1997, and 2000 and in February 1959, 1964, 1967, 1974, 1976, 1986, 1988, 1996, and 2000.

It is known that the planetary waves can not propagate in the easterly jet currents [8]; they are either absorbed, or reflected from critical line (i.e., the line, where the zonal wind speed is zero). In the years with warm vortex, when significant weakening of the polar jet current or even change in its direction are observed in stratosphere (the lower stratosphere is “locked”), no planetary waves propagation from the troposphere to stratosphere and vice versa happens. This fact is confirmed also by significant negative anomalies of F_z over the north of Eurasia and positive anomalies over the North Atlantic. Similar patterns also are typical for February.

In the years with the cold stratospheric polar vortex, the structure of the F_z anomalies is opposite. In these years, stationary planetary just slightly penetrate into the stratosphere over the northern Eurasia in December and cause formation of the strong polar jet current. In January and especially in February, significant negative and quite small positive anomalies of the downward flux are observed over the North Atlantic and Eurasia, respectively. These findings give evidences of strong relations between the planetary wave penetration from the troposphere over northern Eurasia and the downward propagation of a wave signal over North Atlantic and prove existence of so-called “stratospheric bridge,” which links the northeastern part of Eurasia and the North Atlantic in the years with the strong polar jet current [5].

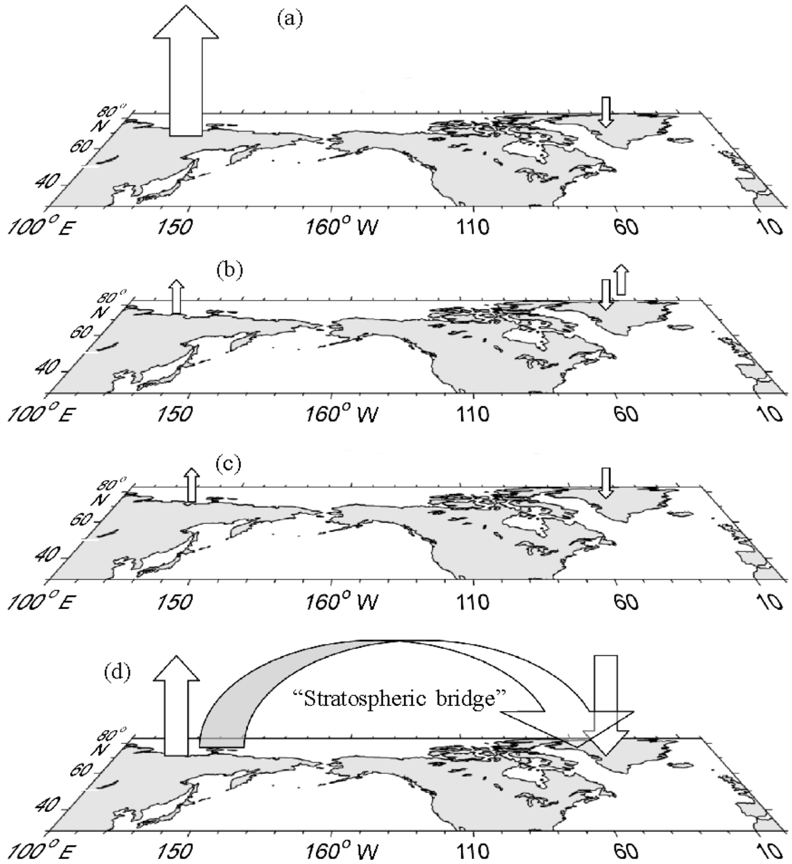

Fig. 4. Scheme of the upward and downward propagation of the wave signal for the warm stratospheric vortex in December and January (panels (a) and (b), respectively). The same is shown for cold stratospheric vortex ((c) and (d)). Arrows show the directions and power of the wave signal at 30 hPa.

DISCUSSION AND CONCLUSIONS

Results presented here show that the downward wave signal is most clearly observed in the lower stratosphere over the North Atlantic in January–February. The previous studies [7, 13, 15, 19] could not directly reveal the downward wave signal, because they used for the analysis the Eliassen–Palm fluxes averaged over the zone and did not take into account the longitudinal peculiarities of the planetary wave propagation. In general, the presented results of the analysis of interannual variations of three-dimensional Eliassen–Palm fluxes cohere well with results of previous studies. In particular, results shown in Fig. 2 cohere with the results presented in [15, 19], which allow concluding that strengthening of the upward zonal mean F_z flux in polar region occurs 20–40 days prior to stratospheric warming. In addition, antiphase relations between the upward F_z fluxes in the early (November–December) and mid- to late (January–March) winter are shown (see the table), that correspond well to the results of analysis of the zonal averages of the EP fluxes [13].

Figure 4 illustrates the scheme of the spatiotemporal interaction of the vertically propagating planetary waves and zonal wind in the stratosphere. Two scenarios were revealed, which describe interaction between the planetary waves and zonal wind of the stratosphere for the warm and cold stratospheric vortexes. If the strengthening of the planetary wave penetration from the troposphere to the stratosphere (so-called "pumping" of the vortex energy) is observed in November–December, then it results in the stratospheric warming in January. The analysis of the three-dimensional Eliassen–Palm fluxes allowed not only to diagnose the wave activity variations preceding the stratospheric warming, but also to specify the region, which plays a decisive role in this process. Strengthening jet current over the northeastern part of Eurasia leads to the stratospheric warming. The significant weakening (and even a reverse) of polar jet occurs during such a stratospheric warming. While the planetary waves can not propagate in the easterly current, the "blocking" of the stratosphere takes place in the month with the stratospheric warming (Figs. 3a, 3b). In the following months, the polar jet current is restored due to the relaxation to the radiation equilibrium [8].

If the wave flux from the troposphere to the stratosphere is weak in November–December, then the polar vortex in January is strong. Meanwhile, the significant negative F_z anomalies observed in January and February over the North Atlantic (Figs. 3c, 3d) give evidence of the wave signal downward propagation in the given region. The prominent "stratospheric bridge" is formed under these conditions. A possible explanation of this "bridge" can be a refraction of planetary waves from the strong polar jet current [5].

Thus, the planetary waves affect the zonal flow in the lower stratosphere in early winter, while the structure of the zonal wind influences on the propagation of planetary waves in mid- to late winter, i.e., the antiphase interaction between the fluxes are observed in early (November–December), in mid- and late (January–March) winter. This fact is also confirmed by the analysis of the two-dimensional Eliassen–Palm fluxes [13].

It should be noted that no long-term trends of the wave penetration to stratosphere in the wintertime in 1958–2006 were detected in contrast with the analysis of the vertical EP flux averaged over the territory north from 50° N [11]. The mentioned difference between the results can be caused by way of the spatial and temporal averaging used by Hu and Tung [11].

Identification of the upward and downward propagation of the wave signal is very important for enhancement of the long-range forecasting based on the use of characteristics of the stratosphere [2, 3]. Revealing the downward flux from the stratosphere to troposphere over the North Atlantic can explain that the total ozone content over England in January is a good predictor of abnormal Februaries in the Western Siberia [2]. This phenomena can be associated with the influence of the vortex transport of stratospheric ozone on the total ozone content over the North Atlantic. Further studies are necessary for understanding the Arctic Oscillation relations both with SST anomalies of the extratropical North Pacific and North Atlantic [1] and the interaction of the Aleutian and Icelandic cyclones in the troposphere [9, 10] in order to identify the upward and downward wave signals propagation in the troposphere and stratosphere.

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