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Seasonal Changes in Stratospheric Circulation and Interactions between the Troposphere and the Stratosphere

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Abstract—Based on the data of ERA5 reanalysis, the dates of spring and autumn changes in the stratospheric circulation on isobaric surfaces of 30, 20, and 10 hPa in the latitude zone of 30–90° N in the period 1979–2020 have been obtained. Of the 42 cases of spring changes, 10 are early, 15 are middle, and 17 are late. The spread in the dates of spring changes on the surface of 10 hPa is 69 days. Most often, the spring changes of the circulation occurs from top to bottom; in some years, the delay of spring changes on the surface of 30 hPa relative to the surface of 10 hPa reaches 22–25 days. Autumn change takes place from the bottom up, and their terms at the 3 levels under consideration are close to each other. The relationship between the timing of the spring changes of the stratospheric circulation with solar activity and large sudden winter stratospheric warming is shown. An analysis of the fields of anomalies of daily temperature values and zonal wind velocity in the 1000-1 hPa layer in the period of January–May showed their significant spatiotemporal difference in the case of early and late spring changes. Thus, foci of positive anomalies of temperature and wind speed are formed initially in the upper stratosphere and then shifted from top to bottom. The interrelations between the layers of the atmosphere in different seasons are considered.

Keywords: stratospheric circulation, seasonal changes in circulation, solar activity, reanalysis data, temperature and wind speed anomalies, correlation

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INTRODUCTION

Much attention is still paid to the study of large-scale atmospheric processes that determine the general circulation and thermal regime of the troposphere and stratosphere and the nature of the interaction between atmospheric layers.

Thus, in (Guryanov et al., 2018), an analysis of wave activity and its changes in the troposphere and stratosphere of the Northern Hemisphere in winter in 1979–2016 was given, and a connection between wave periods averaged over the spectrum and the activity of sudden stratospheric warmings (SSWs) was revealed. According to modern concepts, most SSWs are formed as a result of the propagation of wave activity from the troposphere–lower stratosphere. However, as model calculations have shown, some SSWs can arise due to internal dynamic processes of nonlinear interaction of planetary waves with the average flow (Baldwin et al., 2019; Pogoreltsev et al., 2015). In (Perevedentsev et al., 2019), the spatiotemporal variability of air temperature and ozone mass fraction from ground level to an altitude of 64 km is considered using ERA-Interim reanalysis data for 1979–2016. An analysis of the results of modeling thermodynamic processes in the stratosphere using the Marchuk Institute of Computational Mathematics, Russian Academy of Sciences, climate model is presented in (Vargin and Volodin, 2016).

Research in the field of modeling the Arctic circumpolar vortex using empirical data and reanalysis data has made significant progress in understanding the influence of the stratospheric polar vortex on circulation processes in the troposphere (Baldwin et al., 2019; Kidston et al., 2015).

A special role in the processes of interaction between the troposphere and stratosphere is played by sudden stratospheric warmings (Baldwin et al., 2021), which lead to the degradation of the stratospheric polar vortex (main SSWs), causing its displacement or splitting into two smaller vortices (Ayarzagüena et al., 2019).

One of the most important features of stratospheric circulation (SC) is the presence of its seasonal changes: in the spring, the winter westerly cyclonic cir-

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culation turns into a summer anticyclonic circulation, and in the fall the process goes in the opposite direction—eastern flows are replaced by western ones. At the same time, the dates of change, especially in spring, experience a large interannual scatter. A number of works are devoted to the topic of seasonal changes of SCs (Bakulina et al., 2009; Perevedentsev et al., 1999; Tarasenko, 1988). In earlier works on the study of circulation processes in the stratosphere (Ped, 1973; Pchelko, 1959), it was shown that spring changes of the SC from winter to summer regime occurs from mid-March to the first 10 days of May. Taking into account the large interannual dispersion in the timing of the spring changes of SCs, it was proposed in (Bakulina and Ugryumov, 2008) to divide them into early, middle, and late. It was accepted that the date April 5 separates the dates of early and middle changes, and April 26 separates middle and late changes. The author's article (Perevedentsev et al., 1999) examined the nature of seasonal changes in circulation on isobaric surfaces of 30 and 10 hPa in 1977–1990 for latitude zones 70–50, 50–35, and 70–35° N.

Studies of spring and autumn changes in the SC are also of practical importance, since the timing of seasonal changes in circulation in the stratosphere is used in long-term weather forecasting in various regions of the Northern Hemisphere (NH) (Bakulina et al., 2009; Gechaite et al., 2016; Savenkova and Pogoreltsev, 2010).

The purpose of this work is to analyze the spring and autumn changes of the stratospheric circulation on isobaric surfaces of 30, 20, and 10 hPa in the latitude zone 30–90° N according to ERA5 reanalysis data for 1979–2020.

DATA AND ANALYSIS METHODS

Urgent data (0, 6, 12, and 18 h) were used as initial data about the geopotential fields of the Northern Hemisphere on isobaric surfaces of 10, 20, and 30 hPa at the nodes of a geographic grid of 2.5° latitude × 2.5° longitude for 1979–2020 presented in the ERA5 reanalysis (Hersbach et al., 2020). Based on the initial data, average daily values of geopotential at grid points and daily values of the zonal atmospheric circulation index of A.L. Katz (I_h) in the latitudinal zone 30–90° N were calculated according to the formula

$$I_3 = (H_1 - H_2)/(\varphi_2 - \varphi_1), \quad (1)$$

where H_1 and H_2 are values of absolute geopotentials averaged along boundary latitudes φ_1 and φ_2 of the considered zones.

The timing of seasonal changes in the stratospheric circulation was determined by the annual variation of the daily values of the zonal index I_h in the specified latitudinal zone. The date of the stable transition of the zonal index from positive values (winter westerly circulation) to negative values (summer eastern circulation) was taken as the date of spring circulation changes.

It should be noted that, during the spring changes, after the transition to the eastern circulation, a return to the western circulation is quite often observed, and then a repeated, now final, transition to the eastern circulation occurs. In such cases, the approach proposed in (Ped, 1973) was used. To determine the moment of changes, the intensity and duration of the eastern circulation after the initial transition was compared with the intensity and duration of the westerly circulation after the return. If the sum of negative daily values of the zonal Katz index after the initial change in circulation in absolute value turned out to be greater than the sum of positive values of the zonal index after the return, then the date of the initial transition to the eastern circulation was taken as the date of changes, and vice versa for the autumn changes of the stratospheric circulation. Estimating the intensity and duration of the return circulation allows, in our opinion, the most flexible and correct way to determine the dates of seasonal changes in the event of their unstable implementation (Perevedentsev et al., 1999).

Additionally, the vertical distribution in the layer from 1000 to 1 hPa of the anomaly of air temperature and zonal wind speed, calculated for early, middle, and late changes in the period from January 1 to May 31 for the latitude zone 60–90° N, was analyzed according to ERA5 reanalysis data (1979–2020). To assess the degree of interconnection in the temperature field between levels, correlation coefficients were calculated for the extratropical zone of the Northern Sea for different seasons of the year.

ANALYSIS RESULTS

A comparative analysis of dates of spring (DS) and autumn (DA) circulation changes in the stratosphere showed that, in the 10–30 hPa layer, the spring circulation changes most often occurs from top to bottom (in 29 cases out of 42), which is reflected in the average long-term dates: at the level of 10 hPa, adjustment is carried out on April 18; at the 20 hPa level it is on April 19; and, at the 30 hPa level, it is on April 23. Interannual variability in the dates of spring changes increases with altitude: the standard deviation (RMSD) is 15 days at 30 hPa, 17 days at 20 hPa, and 18 days at 10 hPa.

Table 1 presents the types and dates of spring changes of SCs on an isobaric surface of 10 hPa.

The timing of spring changes at the levels of 10 and 20 hPa is quite close to each other and, in 33 out of 42 cases, the difference in timing in modulus does not exceed 3 days. Linear correlation coefficient (r) between LW at levels 10 and 20 hPa is $r = 0.97$. The timing of spring changes at the levels of 10 and 30 hPa differs more; in some years the difference can reach 22–25 (1986, 2005, 2014, and 2017) and even 40 days

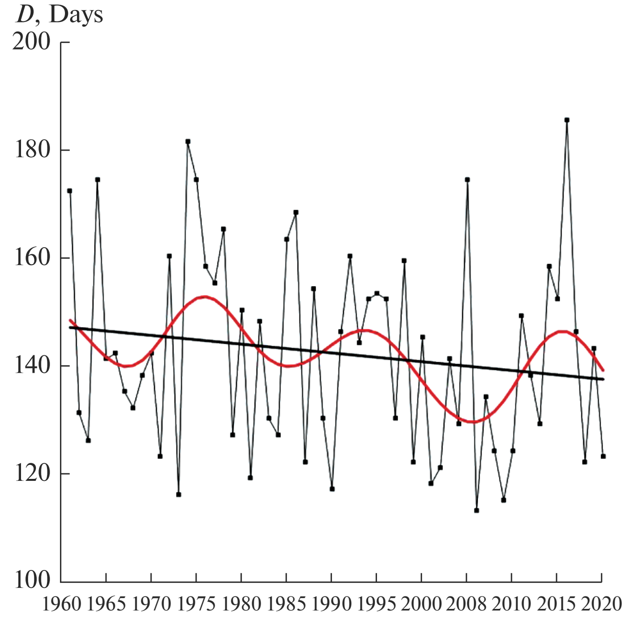

Fig. 1. Duration (in days) of the summer easterly circulation at 10 hPa.

(1992). During these years, the spring changes of circulation at the levels of 10 and 20 hPa occurred in the early stages (2nd 10 days of March to the 1st 10 days of April), and, at the level of 30 hPa, the winter circulation regime persisted for quite a long time. Later changes are carried out more synchronously at the levels under consideration; the difference in DS does not exceed 10 days. The linear correlation coefficient between the DS at the levels of 10 and 30 hPa is $r = 0.84$.

Table 1. Types and dates of spring changes of stratospheric circulation on the isobaric surface of 10 hPa in 1979–2020.

Type of change					
Early		Average		Late	
Year	Date	Year	Date	Year	Date
1982	April 5	1980	April 7	1979	May 3
1985	March 24	1983	April 24	1981	May 11
1986	March 21	1988	April 8	1984	May 4
1992	March 25	1989	April 25	1987	May 6
1994	April 2	1991	April 10	1990	May 11
1998	March 28	1993	April 16	1997	April 28
2005	March 13	1995	April 6	1999	May 3
2014	March 28	1996	April 10	2001	May 14
2015	April 3	2000	April 23	2002	May 7
2016	March 7	2003	April 16	2004	April 30
		2007	April 22	2006	May 12
		2011	April 7	2008	May 8
		2012	April 19	2009	May 10
		2017	April 8	2010	May 3
		2019	April 21	2013	May 2
				2018	May 6
				2020	May 2

The autumn changes of circulation in the 10–30 hPa layer occurs from bottom to top, which is reflected in the average long-term DA values: September 2 at the level of 30 hPa and September 4 at the levels of 20 and 10 hPa. Interannual variability in the dates of autumn changes decreases with altitude: The RMSD is 4 days at 30 hPa and 3 days at 20 and 10 hPa. The timing of autumn changes at three levels is close to each other; in all cases, the difference in modulo timing does not exceed 5 days. The linear correlation coefficient between DA at levels of 10 and 20 hPa is 0.87, at levels of 20 and 30 hPa $r = 0.94$, and at levels 10 and 30 hPa $r = 0.82$.

The connection between spring and autumn circulation changes in the stratosphere was also studied, but no significant correlation coefficients were found between the dates of spring and autumn circulation changes at the studied levels:

In the long-term course, there is a weak positive trend in the dates of spring changes (shift to later changes) and a weak negative trend in the dates of autumn changes (shift to earlier changes); at the level of 30 hPa, these trends are more pronounced.

In order to estimate the duration of the summer eastern circulation in the stratosphere at the level of 10 hPa over a long period, the dates of spring and autumn changes in the period 1961–2020 were calculated. Figure 1 shows the long-term variation in the duration of the summer eastern circulation, according to which there is a weak tendency for its reduction along a linear trend. The low-frequency component of this series (filtering oscillations with a period of less than 10 years) highlights quasi-20-year oscillations, possibly associated with solar activity.

It should be noted that in the considered stratosphere layer there is 30–10 hPa in the latitude zone 30–90° N. Cooling is observed in all seasons of the year at a rate of –0.34°C/10 years in summer; therefore, the "warm" period of the year is shortening, in contrast to the surface atmosphere, where the duration of the summer period is increasing in conditions of climate warming.

In order to assess the possible influence of solar activity on the nature of the seasonal changes of SCs, we jointly considered the long-term variation in the dates of spring changes of the stratospheric circulation at the level of 10 hPa (in days from the beginning of the year) (Fig. 2), in which, using the Potter filter, a low-frequency component with a period duration of more than 10 years (left scale) and solar activity indicators were identified: Wolf numbers (right scale).

The data analysis in Fig. 2 shows that there is an alternating relationship between the low-frequency component in the long-term variation of the timing of the spring changes of circulation in the middle stratosphere and solar activity. During the period of 1979–

2004, the maxima and minima of the low-frequency component of spring changes correspond to the maxima and minima in the long-term course of Wolf numbers: the linear correlation coefficient between the SC and solar activity indicators was $r = 0.70$. However, later the positive relationship changes to a negative one: periods of increased solar activity correspond to earlier spring changes of the stratospheric circulation and vice versa. The correlation coefficient for the period 2005–2020 was $r = -0.54$.

A similar alternating relationship has also been revealed between solar activity and the timing of the autumn circulation changes in the middle stratosphere. The correlation coefficient between the dates of autumn changes and Wolf numbers in the period 1979–1998 is negative and equal to $r = -0.35$, and in the period 1999–2020 the correlation becomes positive $r = 0.79$.

The timing of spring changes of the stratospheric circulation is influenced by winter stratospheric warming caused by the processes of dynamic interaction of the stratosphere with the troposphere (Bugaeva and Ryazanova, 1987). As is known, sudden stratospheric warmings (SSWs) occur in the stratosphere approximately twice every 3 years, leading to an increase in temperature and a change in the direction of circulation. In this work, only strong winter stratospheric warmings were taken into account, during which there was a change in the stratospheric circulation from western to eastern in the extratropical latitudes of the Northern Hemisphere and the average daily Katz zonal circulation indices at the level of 10 hPa in the latitude zone 30–90° N became negative. Accordingly, the date (in days from the beginning of the year) of the transition of the Katz index from positive to negative values was taken as the date of winter stratospheric warming.

As can be seen from Fig. 3, there is a tendency towards earlier spring changes in the presence of early winter and late (final) warmings.

The timing of the spring changes of circulation in the stratosphere is influenced not only by the timing of strong winter warmings, but also by their intensity. As a characteristic of the intensity of stratospheric warming, we used the modulus of the sum of negative daily values of the Katz index during the period of strong stratospheric warming. It was found that, with an increase in the intensity of winter stratospheric warming, the spring change occurs at a later date; the correlation coefficient between the intensity of stratospheric warming and the date of the spring change is $r = 0.65$ (Fig. 4). Using information about large SSWs from (Ageeva et al., 2017) is quite consistent with the result.

Strong winter warmings in the stratosphere do not occur every year; therefore, to assess the relationship between the timing of spring changes in the stratosphere and the characteristics of the stratospheric circulation in the previous winter period, linear correlation coefficients were calculated between the dates of spring changes and the average daily values of the Katz index in January–February. The best relationship is observed with the values of the Katz index on February 15; the greater the intensity of the zonal circulation on this day, the earlier the spring changes occurs in the middle stratosphere. The correlation coefficient was $r = -0.54$.

It is currently accepted that the troposphere, stratosphere, and mesosphere form a single dynamic system, within which interaction occurs between layers through a wave mechanism, through which disturbances of meteorological fields caused by the barocli-

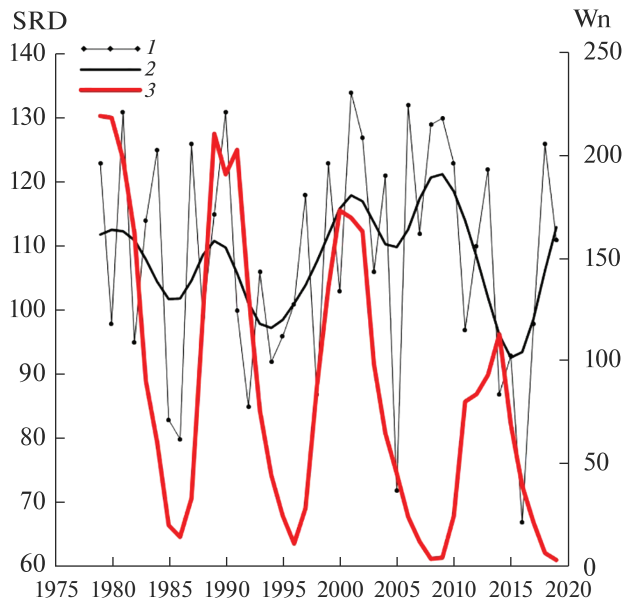

Fig. 2. Dates of spring changes of circulation in the stratosphere at the level of 10 hPa (SPR days from the beginning of the year) and Wolf numbers (Wn). (*1*) Initial series of spring changes dates, (*2*) low-frequency component with a period of more than 10 years of spring changes dates, and (*3*) Wolf numbers.

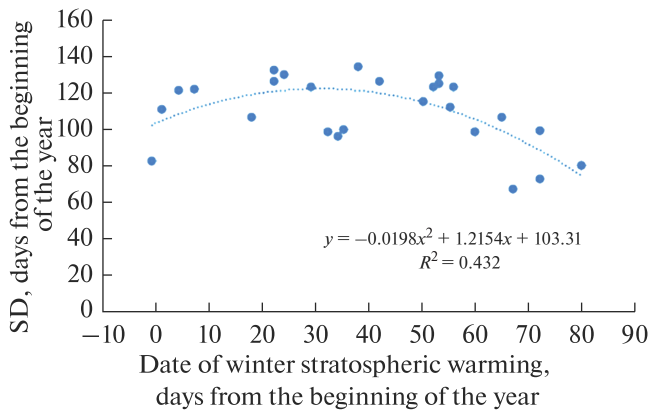

Fig. 3. Dependence of the date of spring changes of the stratospheric circulation on the date of winter stratospheric warming (10 hPa, 30–90° N).

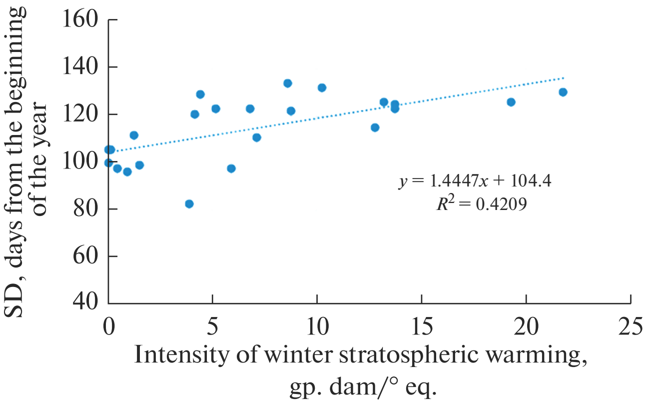

Fig. 4. Dependence of the date of spring changes of the circulation in the stratosphere on the intensity of winter stratospheric warming (10 hPa, 30–90° N).

nicity of the atmosphere and the inhomogeneous heating of the underlying surface and orography are transmitted from the troposphere to the stratosphere (Holton, 1979).

To assess the relationship between the dates of spring changes of the stratospheric circulation and near-surface air temperature, correlation coefficients were calculated between the dates of spring changes of the stratospheric circulation at the level of 10 hPa in latitudinal zone 30–90° N and average monthly values of surface air temperature at geographic grid nodes of 1° latitude × 1° longitude of the Northern Hemisphere. For a sample size of 42 years and a 95% confidence level, the linear correlation coefficient (r) was considered significant if $|r| > 0.31$.

An analysis of the spatial distribution of correlation coefficients showed that in January–March there are areas of significant correlation over the Pacific Ocean—a negative correlation in the eastern Pacific Ocean (off the coast of North America) and a positive correlation in the central and western parts of the Pacific Ocean. It should be noted that similar localization is observed in the Pacific Decadal Oscillation, which is characterized by an increase or decrease in water surface temperature in the Pacific Ocean north of 20° N with a period of 20–30 years. During the warm (positive) phase of the oscillation, cooling occurs in the western Pacific Ocean, warming occurs in the east, and the cold (negative) phase is characterized by an opposite temperature distribution. In most of the study period 1979–2010, the positive phase of the Pacific Oscillation prevailed, which may have affected the mechanism of formation of spring changes of the SC. The important role of the Pacific Decadal Oscillation in the dynamics of atmospheric and hydrological phenomena is indicated in (Mokhov, 2021).

A similar picture is observed over the Atlantic Ocean: a negative correlation in the western Atlantic Ocean (off the coast of North America) and a positive correlation in the eastern ocean. However, here the areas of significant correlation are significantly smaller in area than in the Pacific Ocean (possibly due to the smaller size of the Atlantic Ocean).

It is possible that the features of the distribution of surface temperature in January-March influence the occurrence of strong winter stratospheric warmings due to the wave interaction of the troposphere and stratosphere, which in turn influence the timing of spring changes of the stratospheric circulation, which requires special research.

It is known that seasonal changes in the SC are accompanied by thermobaric transformations in the atmosphere. In order to identify spatiotemporal differences in the fields of air temperature and zonal wind speed for the latitude zone 60–90° N and layers of the atmosphere (1000-1 hPa) according to the ERA5 reanalysis data, anomalies of the average daily air temperature (Δt) and zonal wind speed (Δu) have been calculated for three types of seasonal changes in the SC: early, middle, and late. The period January–May (from January 1 to May 31) was considered as a time interval. The climate norm was calculated for 1991–2020.

Let us consider the dynamics of anomalies of average daily air temperatures in the 1000-1 hPa layer in the period January 1–May 31 over a 42-year period (1979–2020) in the latitude zone 60–90° N. In the case of early changes in the 300-1 hPa layer, from the 65th day from the beginning of the year to the end of May, a heat anomaly occurs, with a maximum Δt = +9°C in the 30-4 hPa layer in the last days of March (Fig. 5a). In the case of average changes, the field of temperature anomalies is positive (Δt reach up to 3°C) throughout the entire atmosphere from 1000 to 1 hPa in the period of 60–150 days. In this case, the maximum values of Δt are observed in the 10-1 hPa layer. With the late changes of the SC, an extensive center of negative temperatures is formed in the period 60–120 days from the beginning of the year (with a maximum Δt = –7°C above the level of 10 hPa on the 85th day from the beginning of the year). A positive temperature anomaly occurs only in the 10-1 hPa layer (Δt = 2°C) from 95 days from the beginning of the year (Fig. 5b). The contrast in the temperature field during the early and late changes of the SC should be noted. If in the first case a vast area of positive temperature anomalies is formed, then in the second there are negative ones. In their structure, hot and cold centers have similar features. Thus, in the case of early changes of the SC, a region of elevated temperatures (heat) is formed in a vast altitudinal–time zone, and, in the case of late changes, a region of cold ones is formed. In this case, there is a shift in the zones of heat and cold over time from higher to lower levels.

An analysis of calculated daily anomalies of zonal circulation Δu (m/s) for spring changes of different dates of the SC shows their significant difference. In

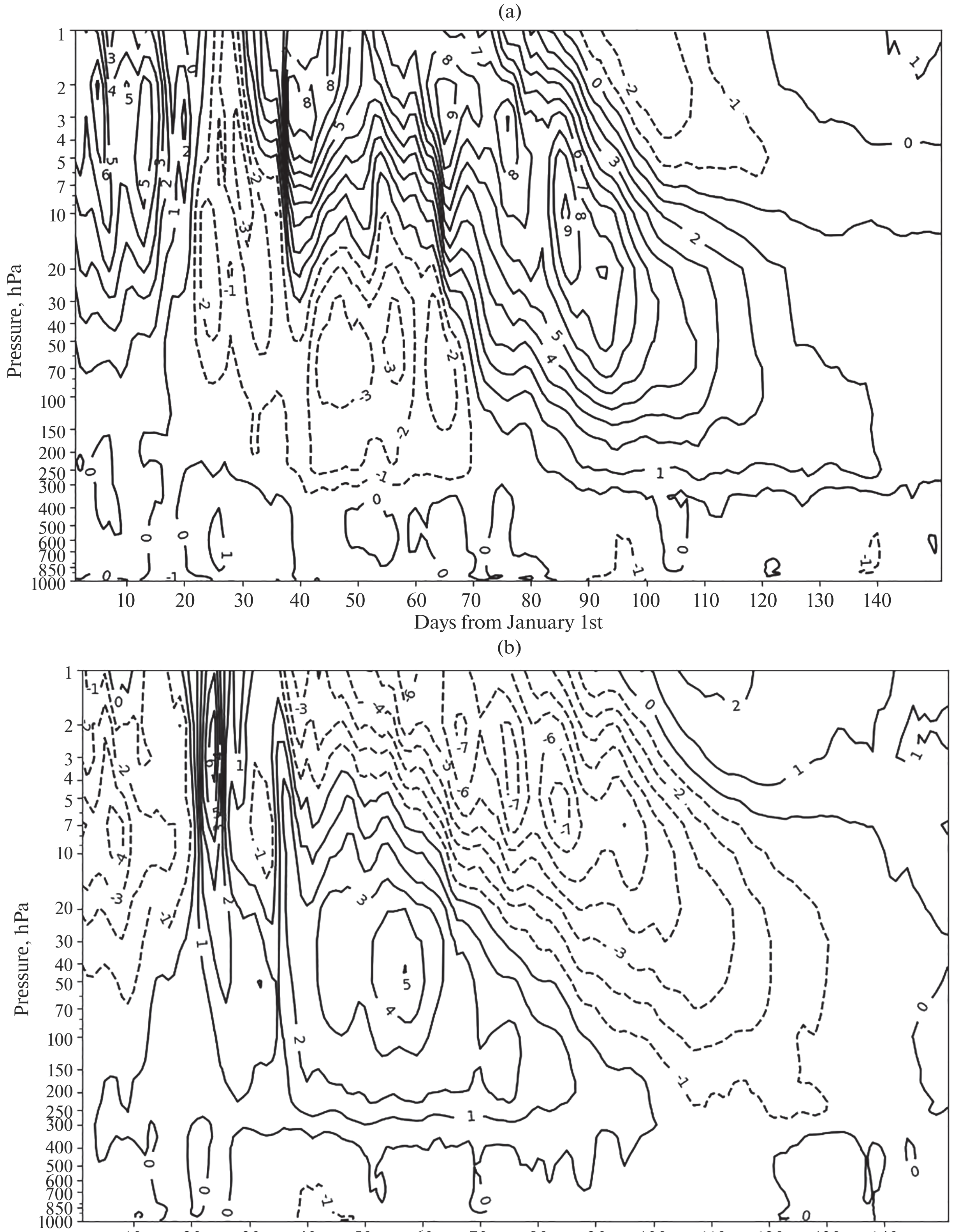

Fig. 5. Distribution of temperature anomalies (°C) in the 1000-1 hPa layer during the period January–May (1979–2020): (a) early changes of the SC; (b) late changes of the SC.

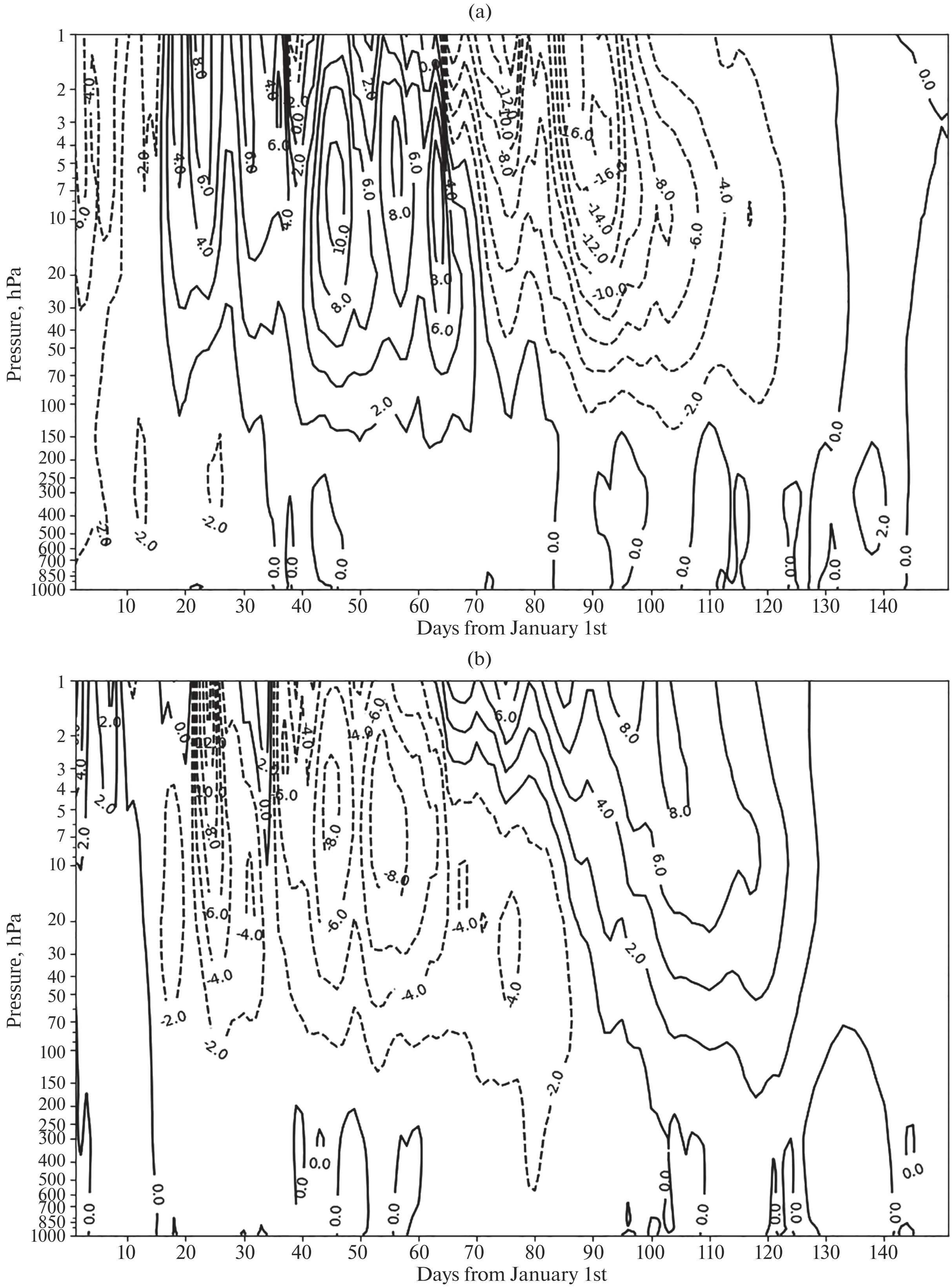

Fig. 6. Distribution of wind speed anomalies (m/s) in the 1000-1 hPa layer during the period January–May (1979–2020): (a) early changes of the SC, (b) late changes of the SC, and (c) difference between composites of late and early changes (areas with a significance of 95% or more are highlighted by dots).

(c)

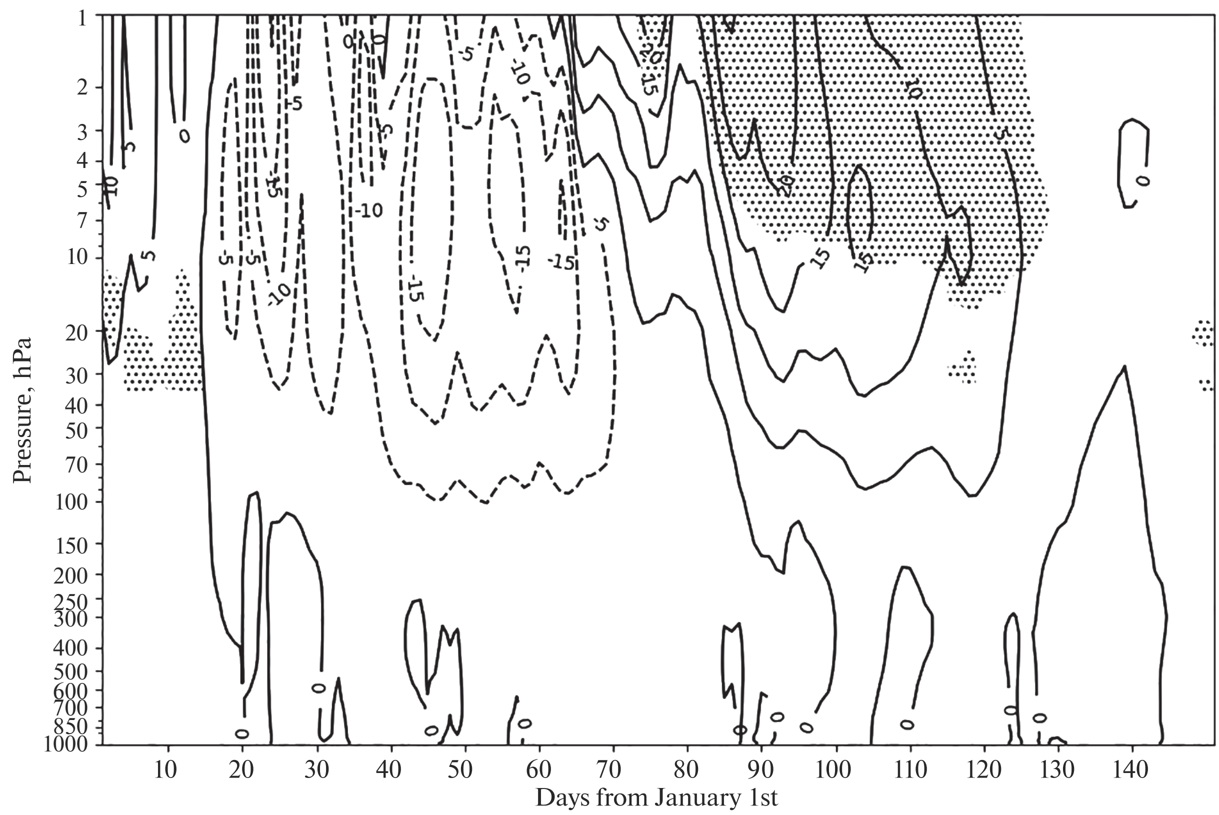

Fig. 6. (Contd.)

the case of early changes in the latitudinal zone 60–89° N, in the 50-1 hPa layer in February, a center of positive zonal velocity anomalies is formed. In early April, Δu reaches –16 m/s in the 20-7 hPa layer (Fig. 6a). In the case of an average changes over time, no spatio-temporal contrasts are observed in the zonal wind speed field. Only in the 10-1 hPa layer is there a change in the sign of the anomalies in the Δu value. However, starting from March, a zone of negative anomalies appears in the 5-1 hPa layer, which in the period 100–130 days from the beginning of the year also appears in the 100-1 hPa layer ($\Delta u = -4$ m/s). With late changes of the SC in the thickness of 100-1 hPa, a distribution pattern of Δu is formed that is opposite the situation in the case of early changes. Thus, in the period of 20–80 days, centers of negative u anomalies predominate in the stratosphere, reaching values of –8 m/s at the level of 10 hPa. However, starting from 70 days from the beginning of the year, starting from the upper levels (from 1 hPa) with a delay at lower levels, an area with positive values of Δu is formed, reaching 8 m/s at the level of 4 hPa (Fig. 6b). Figure 6c shows the differences between the composites of late (Fig. 6b) and early (Fig. 6a) changes. Areas of significant (t-test, 95%) differences are indicated by dots. The main areas of significant differences correspond to their positive values, which corresponds to positive Δu for late changes and negative Δu for early changes in the upper (mid-March to April) and middle (first half of January) stratosphere. The first can be explained by the restoration of westerly circulation after the main SSWs in January–February.

To assess the degree of vertical connectivity between atmospheric layers, correlation coefficients were calculated (r) between the temperature of neighboring levels for the extratropical zone of the Northern Territory from ground level to 80 km for all months of all seasons: winter, spring, summer, and autumn. As can be seen from Fig. 7, in the spring months the correlation between neighboring levels in the 0–26 km layer is close ($r > 0.8$) and there are high values of r in the 50–80 km layer ($r > 0.9$); however, in the 26–43 km layer, where spring changes occurs, connections between neighboring levels weaken, especially in May. At the level of 36 km, the value of r in May decreases to a value of 0.39. It should be noted that in all summer months in the layer of 26–43 km there is a decrease in r (in June at the level of 40 km $r = 0.4$). The spring and summer vertical profiles of the r value are externally similar, especially for May and June. In the autumn period, connections in the temperature field weaken below the stratopause (in November

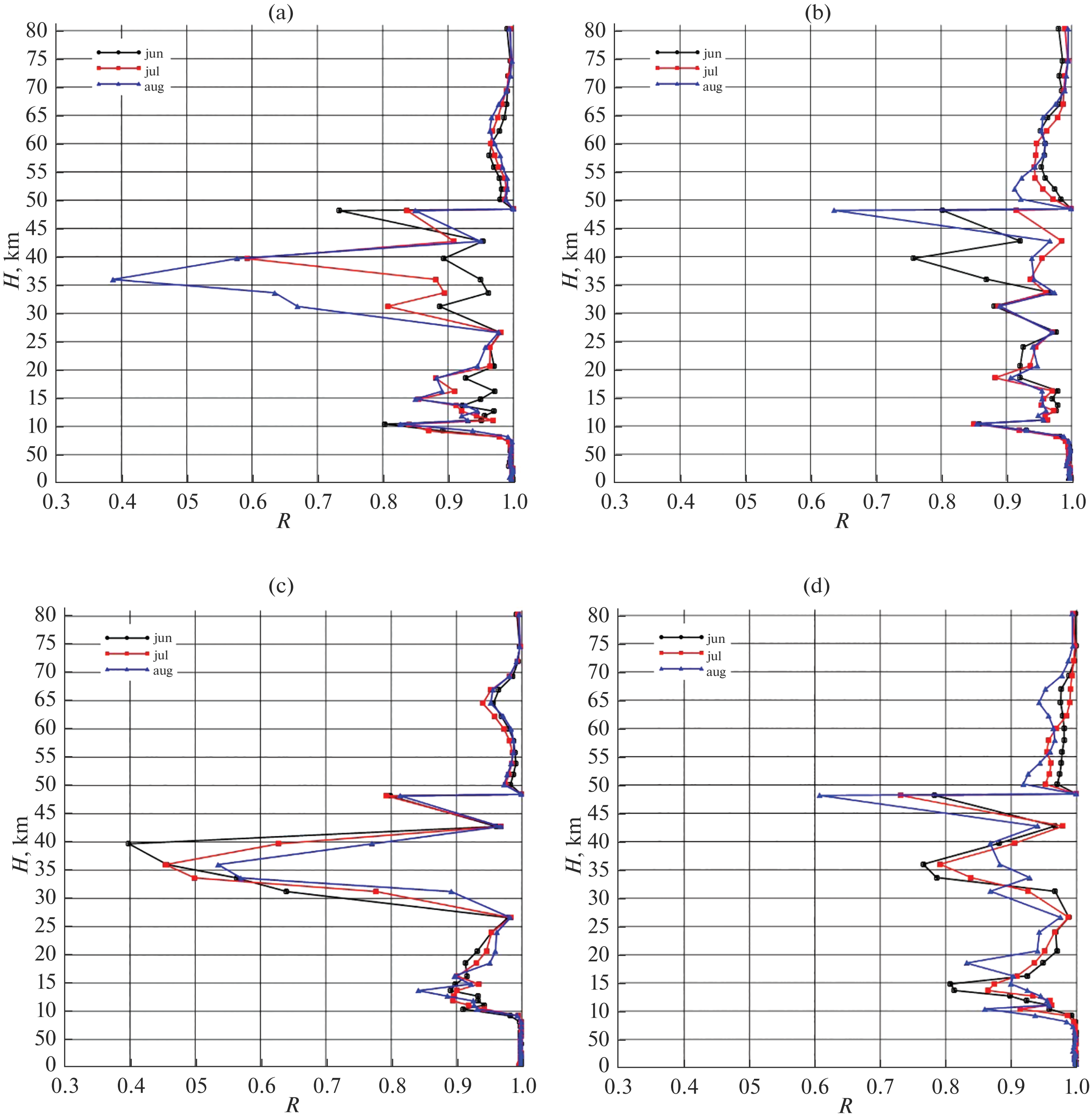

Fig. 7. Profile of the correlation coefficient of temperature of neighboring levels in the extratropical zone of the North Sea.

$r \sim 0.6$ at 47 km level). The connections between neighboring levels from 10 to 45 km are quite close (r varies from 0.76 to 0.98). The structure of connections is more complex in the 10–30 km layer, since the autumn changes of the SC begins from below. In the winter months the picture is most uniform. The correlation coefficients between adjacent levels are high ($r > 0.8$) and only below the stratopause in December does r decrease to 0.64. Correlation connections are significant, because in all cases $r > 0.3$ (with a given sample size, all coefficients are significant, with a 95% probability $r \geq 0.31$).

In general, as can be seen from Fig. 7, the spring period is distinguished by the most complex structure of connections in the temperature field between neighboring levels, which is associated with changes in stratospheric circulation.

Consideration for the r profiles calculated between the 1000 hPa level and all overlying ones in the extratropical zone shows a weakening of connections in the temperature field between levels with height. During the transition of the tropopause, r becomes negative, which indicates the opposite nature of the processes in the troposphere and stratosphere. In September, $r = -0.8$ at an altitude of 25 km.

CONCLUSIONS

Based on reanalysis data for the period 1979–2020, quantitative indicators of seasonal changes of stratospheric circulation on isobaric surfaces of 30, 20, and 10 hPa in the latitude zone 30–90° N were obtained. It is shown that the spring changes of circulation most often occurs from top to bottom, which is reflected in the average long-term values of the dates of changes: April 18 at 10 hPa, April 19 at 20 hPa, and April 23 at 30 hPa. The autumn changes of circulation in the stratosphere occurs from bottom to top: the average long-term date of autumn changes at the level of 30 hPa is September 2, at the level of 20 and 10 hPa on September 4. A correlation dependence of the dates of late spring changes on the presence of large SSWs has been revealed. It is shown that in the period 1979–2004, the maximums and minimums of spring changes correspond to the maximums and minimums in the long-term course of Wolf numbers. The differences between daily anomalies in the temperature and zonal wind fields during the periods of early and late changes are considered. An analysis of vertical correlations in the air temperature field showed that in the spring their structure is more complex, which is apparently due to the process of spring changes of the SC.

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CONFLICT OF INTEREST

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

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