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Effects of solar activity variations on dynamical processes in the atmosphere: Analysis of empirical data and modeling

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Abstract. The effects of the 11-year, quasi-biennial, and 27-day cycles of solar activity on dynamical processes in the atmosphere are studied using empirical data and results of numerical model calculations. Estimates of changes during the 11-year solar cycle in the wind velocity, potential vorticity, geopotential and its large-scale zonal harmonics are obtained using the ERA-Interim reanalysis data. Features of the response of these atmospheric parameters to the solar cycle in some areas of the atmosphere are revealed for a whole year and depending on season. The results point to the existence of a reliable statistical relation of large-scale dynamical and thermodynamic processes in the troposphere and stratosphere to the 11-year solar cycle. Based on the results of 200-year measurements, the phase synchronization of decadal variations of the North Atlantic Oscillation index with the 11-year solar cycle have been found within time intervals alternating with 45–50-year periodicity. According to the ERA-Interim data, the quasi-biennial oscillation in the equatorial stratospheric zonal wind velocity is phase-synchronized at the stratopause level (~50 km) with the quasi-biennial variations of UV solar radiation. The proposed reason of the synchronization may be the the inhomogeneous heating of this layer due to the absorption of UV solar radiation by ozone, the meridional gradient of which changes in harmony with the quasi-biennial solar variations. The effect of the 27-day solar cycle on the characteristics of large-scale zonal wave harmonics of the geopotential in the Northern Hemisphere is analyzed using results of calculations by a 3-dimensional chemistry-climatic model. Noticeable correlations of the amplitude of the planetary wave components in winter in the Northern Hemisphere with the 27-day solar cycle have been found. The strongest response is obtained for perturbations with wave number 1 in the middle and high latitudes of the Northern Hemisphere.

1. Introduction

Solar radiation undergoes variations in a wide range of time scales from days to centuries [1]. A number of cycles are clearly manifested in its changes. These are the 11-year solar cycle, the variations with period of about 27 days (the 27-day cycle) associated with the rotation of the Sun around its own axis, and the quasi-biennial variations. The latter are noticeable in the phases of maximum and decrease of the 11-year cycle. The amplitude of the 11-year cycle at the 205 nm wavelength (range of effective photolysis of ozone) is about 4%, the amplitude of the 27-day cycle is about 2% [2], and the quasi-biennial variations are much weaker than the 11-year oscillations.

There are a lot of studies of the effects of the 11-year solar cycle on the earth's atmosphere and climate, including analysis of observational data and numerical simulations. A comprehensive overview of different aspects of the solar effects is given in [1], while references to more recent studies of the effect of the 11-year solar cycle on temperature and atmospheric circulation can be found in [3]. In general, there is a satisfactory agreement between the model results and the observations of the 11-year variations of atmospheric ozone and temperature in the tropical region. However, accordance is much worse in the middle and polar latitudes. The role of atmospheric dynamics in the atmospheric response to the 11-year solar cycle in the extra-tropical latitudes is not sufficiently clear.

The atmospheric response to the 27-day solar cycle was also studied in a large number of studies, and the main focus was on the response of ozone and temperature. A fairly detailed overview is given in [2], while the information about later works can be found in [4]. Model results for ozone and temperature are generally in satisfactory agreement with observations in the equatorial region. The response of atmospheric dynamics to the 27-day solar cycle are hardly studied. Here we can refer to the recent work [5].

The study of the influence of the quasi-biennial solar variations on the Earth's atmosphere is complicated by the presence of the strong inherent quasi-biennial oscillations in the atmosphere. The solar effect of the quasi-biennial scale was identified in the upper atmosphere [6], but it is almost impossible to detect the direct influence in the lower atmosphere layers. However, an indirect effect is possible, which consists in synchronizing of the inherent atmospheric oscillations with the solar quasi-biennial variations [7, 8].

This article is an overview of some results obtained at the A. M. Obukhov Institute of Atmospheric Physics, concerning the effects of solar activity variations on dynamical processes in the atmosphere of the three specified time scales. Some results were published [3, 9], but a considerable part is first represented.

2. Data and analysis methods

The following empirical data are used.

1. Monthly (since the middle of the XVIII century) and annual (since 1700) means of the sunspot number from the Royal Observatory of Belgium (http://www.sidc.be/silso/citations).

2. Monthly mean data of measurements of the solar radio emission flux at 10.7 cm wavelength, $F_{10.7}$, since 1947 (https://www.ngdc.noaa.gov/stp/space-weather/solar-data/ and http://swc-legacy.nict.go.jp/sunspot/index_e.php).

3. Annual values of the integral index of solar activity, S_B, for 1881-2010, proposed in [10]. This index is a function of the area and brightness of active manifestations on the Sun, namely of sunspots, faculae, and light rings and is characterized by a strong 11-year cycle and distinct oscillations with period of about 45 years.

4. Monthly means of temperature, geopotential, wind velocity, and potential vorticity from the ERA-Interim reanalysis for 1979-2015 (http://apps.ecmwf.int/datasets/).

5. Monthly means of the North Atlantic Oscillation (NAO) index from the University of East Anglia for 1823–2017 (https://crudata.uea.ac.uk/cru/data/nao/).

6. Monthly mean surface air temperature in Central England since the middle of XVII century from the Met Office Hadley Centre (https://www.metoffice.gov.uk/hadobs/hadcet/data/download.html).

7. Results of satellite measurements of vertical ozone profiles by SBUV and SBUV 2 instruments since 1979 (ftp://toms.gsfc.nasa.gov/pub/sbuv).

8. Results of model calculations of the 27-day solar cycle effect on the Earth's atmosphere by the 3-dimensional chemistry-climate model, HAMMONIA, of the Max Planck Institute of Meteorology in Hamburg, Germany. The model and numerical experiments are described in [2]. The 27-day forcing was set at the upper boundary of the model (~250 km) as sinusoidal oscillations of the extra-atmospheric fluxes of spectral solar radiation in the range from extreme UV to IR region. The amplitude of the oscillations was estimated from observations.

Different methods are used for the analysis. Among them are the high-resolution cross-spectral analysis by the maximum entropy method [11], wavelet transform technique for a pair of signals (cross-wavelet analysis), and the multiple linear regression method.

The multiple linear regression model is used to identify the signal associated with the 11-year solar cycle in the data. The model is described in [3] and, in addition to the 11-year cycle, takes into account the linear trend, the annual cycle, the effects of the quasi-biennial oscillation, North Atlantic Oscillation, Southern Oscillation and products of the eruption of the Pinatubo volcano.

The cross-wavelet analysis identifies the local (in time) coherency, correlation, and phase shift [12, 13]. The local phase shift at a given frequency is defined as the minimum time shift between two signals, at which the best (modulo) correlation between the local (within the oscillation period) fragments of the wavelet transforms of the signals at this frequency is achieved. The local coherency is the local correlation coefficient at this shift. Thus, it characterizes the maximum (modulo) correlation obtained by adjustment of the local phases of the wavelet transforms. The local correlation is determined at a fixed time shift.

3. Results

The results obtained are presented according to the time scale of the solar oscillations.

3.1. *Effects of the 11-year solar cycle*

Figures 1–3 show the results obtained in the analysis of the ERA-Interim data by the multiple linear regression method. Figure 1 shows the changes in the zonal mean values of the geopotential height (GH) and the zonal wind velocity for the entire year as functions of latitude and pressure (altitude) under changes in solar activity during the 11-year cycle from minimum to maximum. The GH increases with increase in solar activity, and the strongest changes are characteristic of the Antarctic stratosphere (Fig. 1a). According to [3], the GH changes reach 200 gpm in spring in the upper stratosphere over Antarctica. The GH changes in the Arctic are statistically insignificant.

The main response of the zonal wind to the 11-year solar cycle is observed in the region of the Southern Hemisphere stratospheric circumpolar vortex, in the layer of the low-latitude stratopause, and in the neighbourhood of the upper-tropospheric subtropical jet streams (Fig. 1b). The wind velocity at the tropical stratopause (~1 hPa) increases with increase in solar activity. The changes in the wind velocity in the stratosphere of the southern polar region and in the subtropical jet streams occur approximately in anti-phase with the solar cycle.

Figure 2 shows the changes in potential vorticity (PV) in the isentropic coordinate system for the entire year and in September–November. The convenience of this representation is that in the adiabatic approximation and in the absence of dissipation, PV changes are due to horizontal advection on the isentropic surface [14]. The PV changes in Fig. 2 are characterized by alternation of negative and positive values with latitude. They are determined by features of the latitudinal structure of the

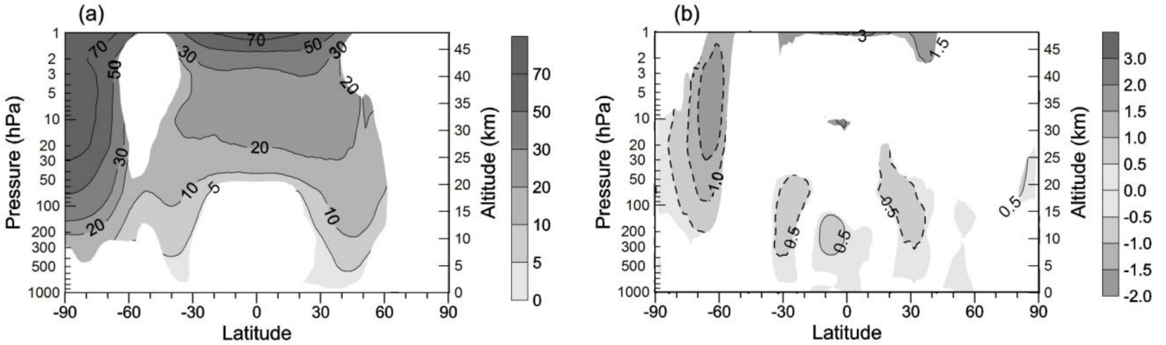

Figure 1. Changes in (a) the geopotential height (gpm) and (b) zonal wind velocity (m/s) from minimum to maximum of the 11-year solar cycle. Dashed contours correspond to negative values. Only statistically significant (at 95% level) changes are shown.

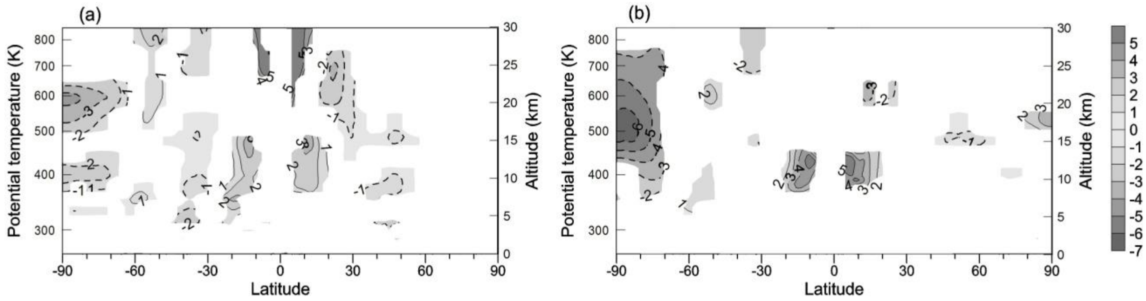

Figure 2. Changes in the potential vorticity (%) from minimum to maximum of the 11-year solar cycle. See explanation in Fig. 1.

zonal flow and correspond to the zones of the meridional shear of the flow velocity in the systems of high-latitude stratospheric and subtropical upper-tropospheric jet streams and the zonal flow in the tropical stratosphere and, as shown by a more detailed analysis, are mainly due to changes in the relative vortex. The strongest PV changes that are in phase with the solar cycle are characteristic of the tropical belt, while the anti-phase changes are characteristic of the lower stratosphere of Antarctica. The PV changes in the Antarctic stratosphere reach 6% in spring (Fig. 2b).

Figure 3 shows the changes in the amplitudes of the 1st and 2nd harmonics of the GH during the solar cycle for one season (March–May). They indicate that the large-scale wave structure of the geopotential changes during the 11-year solar cycle. For example, an increase in the amplitudes of the components with wave numbers 1 and 2 in certain areas of the polar stratosphere and troposphere in March–May has been revealed, which reflect the increase in wave activity with the increase in solar activity (Fig. 3).

The results shown point to a reliable statistical relationship between the large-scale dynamical processes in the troposphere and stratosphere and the 11-year solar cycle.

The NAO index and Central England temperature, together with the sunspot number, are analyzed by the cross-wavelet method. Figures 4a and 4c show the distributions (spectra) of the local coherency between the NAO index and temperature, respectively, with the sunspot number as functions of time and period of variations. The main feature of the spectra is the alternating quasiperiodic changes in the coherency at the solar cycle period. The averaged period of the changes is about 50 years.

Figure 4b shows the local correlation spectrum between the NAO index and the sunspot number at the 7-year lag of the NAO index relative to the sunspot number. Note two features of the spectrum. First, mostly negative values of the local correlation manifest themselves at the period of the solar cycle. Second, the periodic modulation of the local correlation with the same aforementioned period of

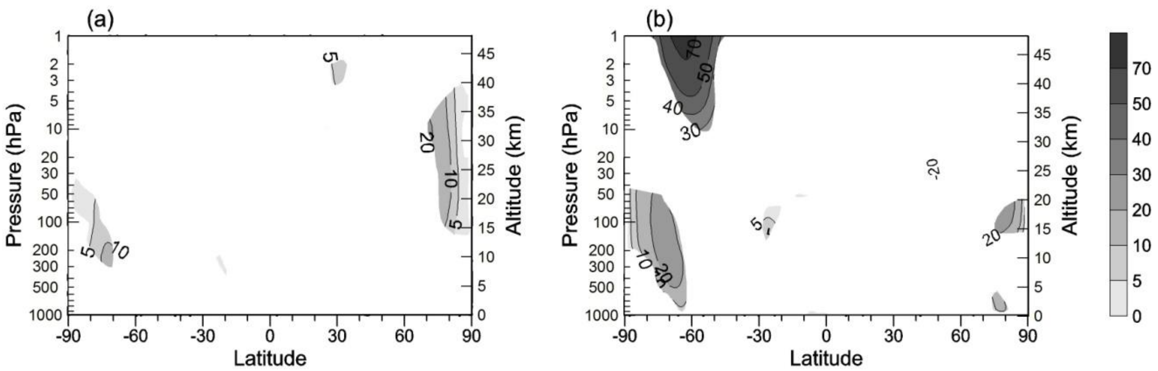

Figure 3. Changes in the amplitudes of (a) the 1st and (b) the 2nd zonal harmonics of the geopotential height (gpm) from minimum to maximum of the 11-year solar cycle. See explanation in Fig. 1.

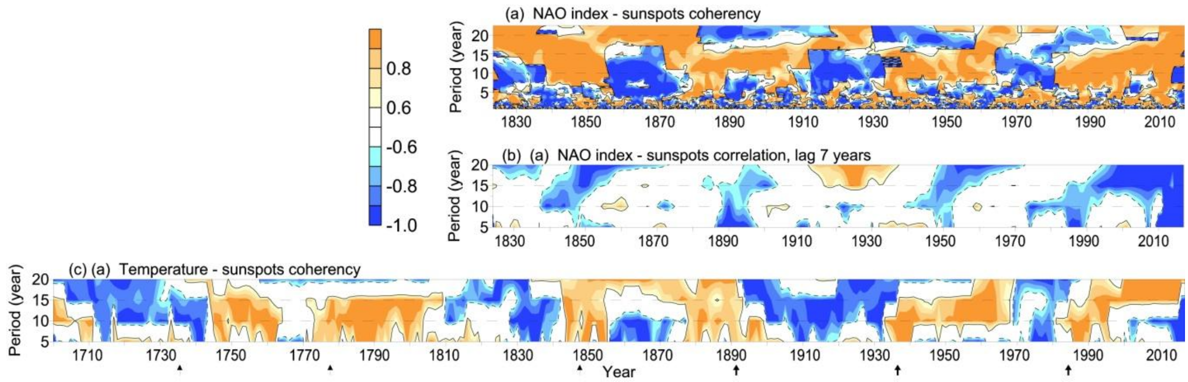

Figure 4. (a) Spectrum of the local coherency between the NAO index and the sunspot number; (b) spectrum of the local correlation of the NAO index with the sunspot number at the 70year lag; (c) spectrum of the local coherency between Central England temperature and the sunspot number.

about 50 years is evident.

The three bold arrows in Fig. 4 correspond to the maxima of oscillations of the Loginov's index with period of about 45 years [10]. They are extended to earlier dates by the thin arrows, which correspond to the maxima of multi-decadal variations of the sunspot number. These variations are obtained by smoothing the sunspot number series by the Kaiser-Bessel filter with a cutoff frequency of 0.05 year^{-1} [15] and reflect groups of solar cycles with enhanced amplitudes. Combining all the maxima, we see in Fig. 4c that five of the six maxima fall into intervals of positive coherence or directly precede them.

The results show that the decadal variability of the NAO and Central England temperature are synchronized with the 11-year solar cycle during certain time intervals. Their relationship with the solar cycle within these intervals varies approximately from in-phase to anti-phase. The multidecadal modulation of the relationship is probably due to the multidecadal variations of solar activity.

3.2. Effect of the quasi-biennial variations of UV solar radiation

The quasi-biennial oscillation (QBO) is the dominant component of the variability of the zonal wind velocity in the equatorial stratosphere [14]. The phase of the wind QBO propagates downwards. In [8, 9, 16], on the basis of various data, the presence of a rather high coherency of the QBO in the equatorial stratospheric wind with the quasi-biennial solar variations was shown.

We applied the cross-spectral method to the mutual analysis of the zonal wind velocity over the equator drom ERA-Interim and the solar activity index, $F_{10.7}$. Figure 5 shows the phase lag of the wind velocity QBO relative to the quasi-biennial variations of the $F_{10.7}$ index. It can be seen that the wind velocity oscillations in the vicinity of the stratopause (~50 km) are synchronized with the solar variations with the phase lag that is close to zero.

It is known that the ozone heating function is maximal in the neighbourhood of the stratopause [17]. The zonal wind velocity, u, is related to the meridional distribution of temperature, T, by the thermal wind equation, which is modified at the equator to the form: $u_z \sim -T_{yy}$ [8, 18], according to which the vertical shear of the wind velocity depends on the curvature of the meridional temperature distribution.

We estimate the degree of the curvature of the meridional ozone distribution (O_3) from SBUV/SBUV 2 data as the average concentration gradient of O_3 in the direction of the poles obtained by averaging the gradients in the northern and southern vicinities of the equator. The phase lag of the quasi-biennial variations of this gradient relative to the variations of the $F_{10.7}$ is shows in Fig. 5. Its value in the vicinity of the stratopause is such that the variations of the O_3 meridional gradient occur approximately in anti-phase with the solar variations (which corresponds to the near-zero phase lag in Fig. 5) and therefore in anti-phase with the wind velocity QBO.

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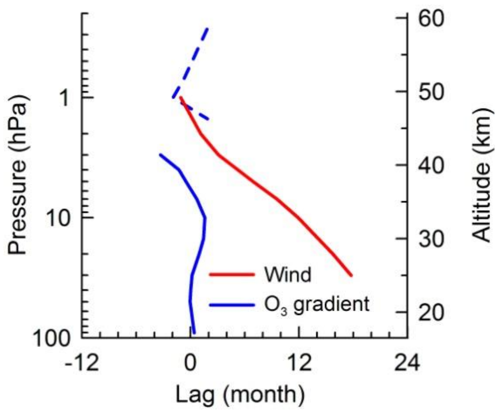

Figure 5. Time lags of the quasi-biennial variations of the equatorial zonal wind velocity and the meridional ozone ratio gradient averaged for 0°–10°N and 0°–10°S latitude belts relative to the quasi-biennial variations of the $F_{10.7}$ index. Dashed parts of the curves correspond to variations shifted by half period relative to the actual variations.

The results are consistent with the results of the earlier studies [8, 9, 16]. If the revealed correspondence of the phases of the quasi-biennial variations of solar activity, zonal wind velocity, and ozone meridional profile in the vicinity of the equatorial stratopause is not accidental, it points to synchronization of these variations. To test this assumption, numerical experiments with an atmospheric model reproducing the QBO in the equatorial stratospheric wind are needed.

3.3. Effects of the 27-day cycle

The effect of the 27-day solar cycle on the atmosphere is studied using results of calculations by the 3-dimensional chemistry-climatic model HAMMONIA. In this paper, we use for the analysis the zonal mean values of the geopotential (geopotential height – GH) and amplitudes and phases of zonal harmonics of the geopotential (GH). The amplitudes and phases (phase is defined as the longitude of the harmonic maximum) were calculated for each latitude, altitude, and date by decomposing the geopotential (GH) field into a Fourier series along the latitudinal circle. The time series of the GH and the series of the amplitudes and phases of its zonal harmonics were smoothed by a 35-day rectangular

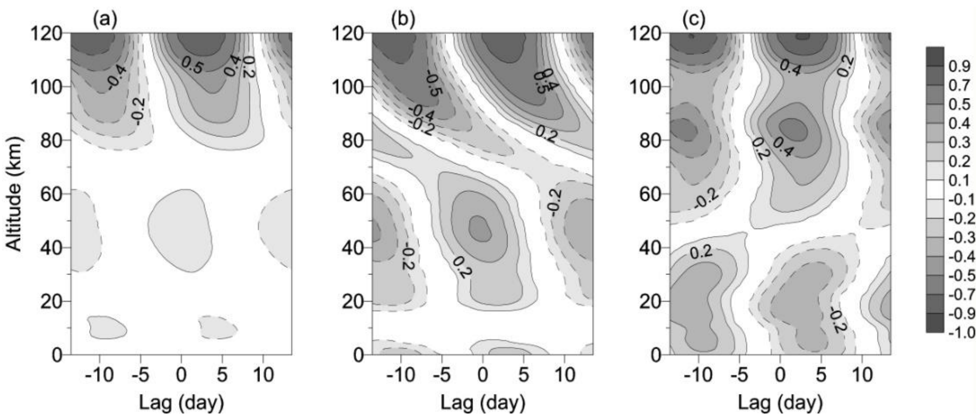

Figure 6. Coefficients of correlation between the geopotential at 50ºN and the 27-day forcing (a) for the entire year and in (b) winter and (c) summer as functions of altitude and time shift. Only values statistically significant at 95% level are shown.

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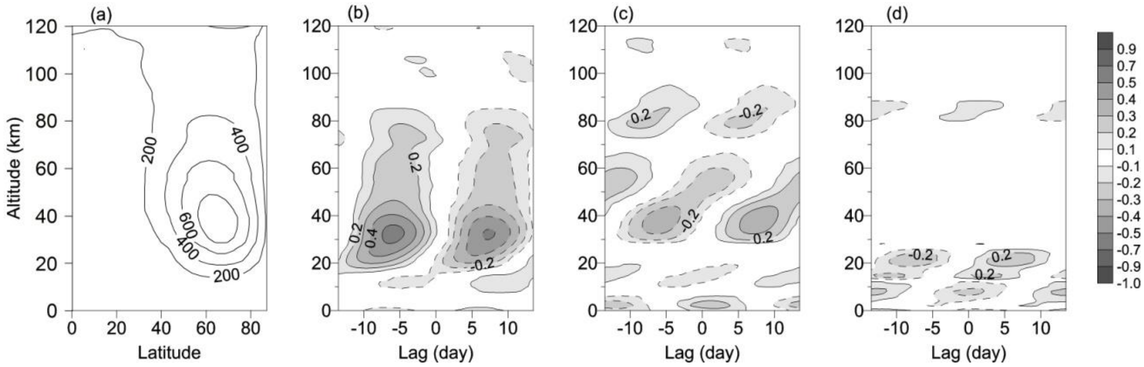

Figure 7. (a) Latitude-altitude distribution of the amplitude of the 1st zonal harmonic of the geopotential height (gpm) in winter. (b–c) Coefficients of correlation between the amplitude of the 1st zonal harmonic of the geopotential at 50ºN and the 27-day forcing in (b) winter and (c) summer as functions of altitude and time shift. (d) Coefficient of correlation between the phase of the 1st harmonic of the geopotential at 50ºN in winter and the 27-day forcing as function of altitude and time shift.

filter, similar to [2]. The smoothed series are then subtracted from the original series. The resulting series contain variations of monthly and intra-monthly scales.

Figure 6 shows the correlation coefficients between the geopotential at 50ºN and the 27-day forcing for the entire year as well as for the winter and summer seasons, as functions of altitude and time shift. Positive values of the shift correspond to the lag, and negative values correspond to the advance of the geopotential changes relative to the forcing. According to Fig. 6, the response of the geopotential in the thermosphere (above ~100 km) to the solar cycle is weakly dependent on the season, but the stratospheric-tropospheric responses in winter and summer are fundamentally different. The geopotential variations in the stratosphere and troposphere occur in winter in phase with the 27-day solar cycle, while the variations in summer are close to anti-phase behaviour, lagging relative to it by a few days.

Figure 7a shows the distribution of the amplitude of the 1st zonal harmonic of the GH in winter. It is characterized by a maximum of ~800 gpm in the vicinity of 65°N at altitude of about 40 km. Figures 7b and 7c show the correlation coefficients between the amplitude of the 1st harmonic of the geopotential at 50ºN in winter and summer and the 27-day forcing. The relationship of the wave amplitude with the solar forcing in winter is manifested most closely in the stratosphere near the 30 km altitude (the correlation coefficient is ~0.5). Stratospheric variations of the amplitude with period of ~27 days, as follows from Fig. 7b, are approximately orthogonal to the forcing, so that, for example, the increase in solar radiation flux is followed by the decrease in the wave amplitude in a quarter of the period (~7 days).

The relationship of the 1st harmonic of the geopotential with the 27-day solar cycle in the summer period is much weaker (Fig. 7c). The maximum correlation of ~0.3 is in the neighbourhood of the 40 km altitude, with the phase relation between the harmonic amplitude and the 27-day forcing opposite to that obtained for the winter period.

Figure 7d shows the correlation coefficient between the phase (longitude of maximum) of the 1st harmonic of the geopotential at 50ºN in winter and the 27-day forcing. The relationship of the harmonic phase with the 27-day cycle is rather weak and manifests itself mainly in the lower stratosphere. Longitudinal displacements of the phase of the wave (e.g., of the trough) due to the 27-day forcing are about 30º of longitude. From comparison of Figs 7b and 7d, it follows that the amplification of the quasi-stationary planetary wave in the lower stratosphere (~20 km) due to the 27-day solar forcing is accompanied by the wave displacement in the longitude direction to the west, and the weakening of the wave is accompanied by the displacement to the east.

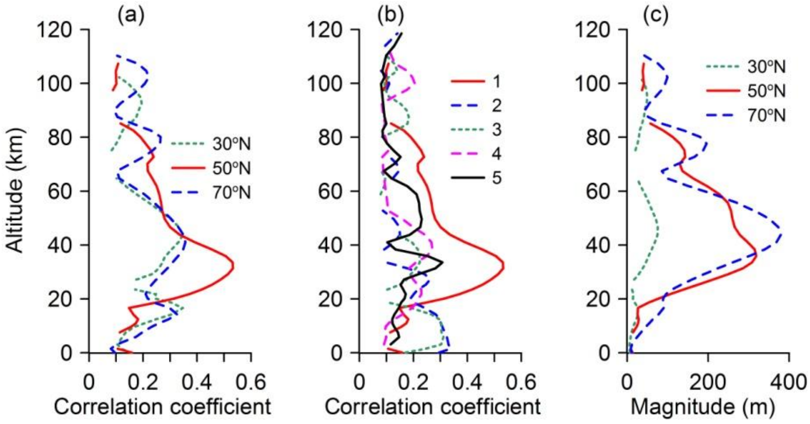

Figure 8. (a–b) Altitude distributions of the maximum coefficients of correlation (a) between the amplitudes of the 1st zonal harmonic of the geopotential at 30ºN, 50ºN, and 70ºN in winter and the 27-day forcing and (b) between the amplitudes of the zonal harmonics of the geopotential with wave numbers 1–5 at 50ºN in winter and the 27-day forcing. (c) Altitude distribution of the magnitude of the 27-day oscillations in the amplitude of the 1st zonal harmonic of the geopotential at 30ºN, 50ºN, and 70ºN in winter.

Figure 8a shows altitude profiles of the maximum (modulo) correlation coefficients (CCs) between the amplitudes of the 1st zonal harmonics of the geopotential at 30º, 50º, and 70ºN in winter and the 27-day forcing. The maximum CC is determined within the time shift between the correlated values by half-period (13.5 days) in one and the other directions. The absolute CC maximum of ~0.5 is noted at 50ºN near the 30 km altitude (compare with Fig. 7b). In the subtropical and polar latitudes, the CC reaches ~0.3 near the 40 km altitude.

Figure 8b shows the maximum (modulo) CCs between the amplitudes of the zonal harmonics of the geopotential with wave numbers 1–5 at 50ºN in winter and the 27-day forcing. From comparison of profiles it follows that the influence of the solar cycle on large-scale disturbances in the stratosphere is mainly expressed in the effect on the planetary component with wave number 1. The response to the solar forcing in the troposphere is manifested in components with zonal wave numbers 2 and 3. The largest response to the solar forcing is obtained for disturbances with wave number 1 in the middle and high latitudes (Fig. 8c). The magnitude of the oscillations is ~300 gpm in the middle and upper stratosphere.

The results point to the possibility of the effect of the 27-day solar cycle on large-scale wave activity in the atmosphere in winter in the middle and polar latitudes of the Northern Hemisphere.

4. Discussion of the results and conclusions

The results presented indicate the presence of statistical relationships of a number of atmospheric circulation parameters with variations of solar activity on the three time scales: the 11-year solar cycle, the quasi-biennial variations, and the 27-day (rotational) cycle. The effects of the 11-year and 27-day solar cycles are manifested not only through effects on the chemical composition and basic thermodynamic and dynamical parameters of the atmosphere [2. 3] but also in the form of the response of planetary waves to the forcing.

One possible mechanisms of the influence of solar activity oscillations on the Earth's atmosphere can be synchronization of the inherent atmospheric variability of the corresponding time scale by solar oscillations. Indications of this have been obtained for the QBO in the equatorial stratosphere and for the decadal variability of the NAO and Central England temperature.

The analysis of long series of the NAO index and the temperature show that the nature of the relationship of these parameters with the 11-year solar cycle changes on the multidecadal time scale.

Changes on this scale cannot be detected in relatively short data from ERA-Interim reanalysis or ozone observations. However, we cannot rule them out. Therefore, the results on the 11-year solar cycle effect retrieved from the reanalysis should not be extended to the preceding period of time.

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