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Climatic variability of the mean flow and stationary planetary waves in the NCEP/NCAR reanalysis data

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Abstract. NCEP/NCAR (National Center for Environmental Prediction – National Center for Atmospheric Research) data have been used to estimate the long-term variability of the mean flow, temperature, and Stationary Planetary Waves (SPW) in the troposphere and lower stratosphere. The results obtained show noticeable climatic variabilities in the intensity and position of the tropospheric jets that are caused by temperature changes in the lower atmosphere. As a result, we can expect that this variability of the mean flow will cause the changes in the SPW propagation conditions. The simulation of the SPW with zonal wave number $m=1$ (SPW1), performed with a linearized model using the mean flow distributions typical for the 1960s and for the beginning of 21st century, supports this assumption and shows that during the last 40 years the amplitude of the SPW1 in the stratosphere and mesosphere increased substantially. The analysis of the SPW amplitudes extracted from the geopotential height and zonal wind NCEP/NCAR data supports the results of simulation and shows that during the last years there exists an increase in the SPW1 activity in the lower stratosphere. These changes in the amplitudes are accompanied by increased interannual variability of the SPW1, as well. Analysis of the SPW2 activity shows that changes in its amplitude have a different sign in the northern winter hemisphere and at low latitudes in the southern summer hemisphere. The value of the SPW2 variability differs latitudinally and can be explained by nonlinear interference of the primary wave propagation from below and from secondary SPW2.

Keywords. Meteorology and atmospheric dynamics (Climatology, Middle atmosphere dynamics, Waves and tides, General circulation)

1 Introduction

The fundamental problem of the atmospheric dynamics, including seasonal, interannual, and climatic variability of the mean flow, temperature, and planetary wave activity within the troposphere and stratosphere, as well as possible effects within the middle atmosphere caused by these changes, becomes increasingly relevant for climate research. The reason for this is the need to study the impact of dynamical and photochemical processes on observed climatic changes in atmospheric temperature. Besides, there is growing evidence that an additional extended-range tropospheric forecast skill may also come from slow variations in the general circulation in the stratosphere (Baldwin and Dunkerton, 2001; Baldwin et al., 2003). According to the results obtained in recent studies of observational data, the lower stratospheric (Randel and Wu, 1999; Ramaswamy et al., 2001; Hu and Tung, 2002) and mesospheric temperatures (Beig et al., 2003; Golitsyn et al., 1996; Semenov, 2000) have been steadily decreasing during the past few decades. Significant trends are also observed in other tropo- and stratospheric fields and processes. For instance, a remarkable positive trend from the 1960s to the 1990s has been observed in the indices of the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and zonal-mean angular momentum (Hu and Tung, 2002; Hurrell, 1995; Thompson et al., 2000). Some model results and observational evidence support a possible explanation of the AO (or the Northern Hemisphere Annular mode – NAM) decadal variability by the internal coupling between the zonal flow and planetary waves (Limpasuvan and Hartmann, 1999, 2000; Thompson et al., 1998, 2000; Wallace, 2000). Fusco and Salby (1999) and Salby et al. (2000) found that on interannual time scales stratospheric ozone and temperature in the Arctic polar region in winter are regulated by the upward Eliassen-Palm (E-P) flux across the tropopause, and that these two parameters are strongly correlated. Similar correlations between the stratospheric temperature, NAM

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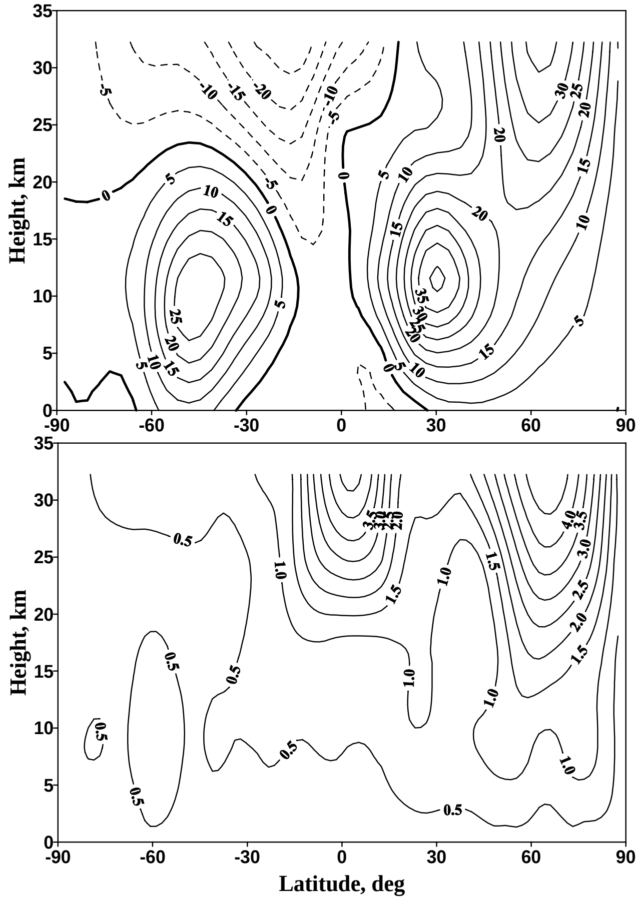

Fig. 1. Latitude-height sections of the zonal mean flow (upper panel) and their root-mean-square variability (lower panel) in January. Results obtained using data for the 1981–1991 time interval.

and zonal-mean angular momentum indices and E-P flux are seen in winter on interannual time scales (Hu and Tung, 2002). A strong longitudinal inhomogeneity of meteorological fields is one of the most characteristic properties of the stratospheric dynamics in winter. Simulations with linearized models show that SPW are very sensitive to the changes in zonal-mean flow in the troposphere (Nigam and Lindzen, 1989; Chen and Robinson, 1992). We may expect that decadal trends in the NAM and/or zonal-mean angular momentum indices have to be noticeable in the SPW amplitudes. The main purpose of the present paper is to estimate the climatic variability of the mean flow, temperature and SPW using the NCEP/NCAR reanalysis data. This observational study will be supported by numerical experiments with the linearized model of the SPW propagation (Pogoreltsev, 1999).

2 NCEP/NCAR data and method of analysis

The data used for analysis are zonal wind, temperature, and geopotential height distributions in the tropo- and stratosphere for January during the entire NCEP/NCAR reanalysis time interval, i.e. since 1948 till 2006. The grid step is 2.5×2.5 degrees and temporal resolution is 6 h. All data are available at 8 isobaric surfaces: 1000, 500, 400, 300, 200, 100, 30, 10 hPa. As it is known (Nigam and Lindzen, 1989; Chen and Robinson, 1992), the most intensive SPW activity in the stratosphere is observed during the winter. In addition, the reanalysis data for the Northern Hemisphere are much more reliable than for the southern one (Kalnay et al., 1996; Kistler et al., 2001). Therefore, Northern Hemisphere winter data are chosen for analysis of possible climatic variabilities of the mean zonal characteristics and SPW.

The work method includes the decomposition of the longitudinal variations of the meteorological parameters for each time interval and each latitude into a mean zonal value and a superposition of 12 zonal harmonics. Amplitude and phase (position of a ridge) are calculated for each harmonic. Then the real and imaginary parts of the complex amplitude for each zonal harmonic are calculated at all latitudes and their monthly (January) average values are obtained. The method of averaging results in a filtering or, at least, the weakening of effects of travelling planetary waves with periods less than a month (for example, 16-, 10- and 5-days normal atmospheric modes). Further averaging is done within 11-year intervals (1948–1958, 1959–1969, 1970–1980, 1981–1991, 1992–2002) to avoid the influence of the 11-year solar activity cycle (Coughlin and Tung, 2004; Haigh, 2002), to estimate an interannual variability and to reduce the contribution of travelling planetary waves. NCEP/NCAR data are processed during all reanalysis time intervals, i.e. since 1948, for the estimation of mean zonal flow and temperature interannual variability. Preliminary results show that during the first decade of the reanalysis some of the basic features of the zonal mean flow in the equatorial stratosphere, like quasi-biennial oscillation (QBO), are not reproduced correctly. Probably, due to the lack of measurements, reanalysis data are less reliable before 1959 and the results of trend analyzes crossing these data have to be considered with special care (Kalnay et al., 1996; Kistler et al., 2001). Further study of a possible climatic variability is carried out using only NCEP/NCAR data since 1959.

3 Mean flow and temperature variability

Latitude-height distributions of the zonal mean wind and zonally averaged temperature are obtained for intervals 1959–1969, 1970–1980, 1981–1991 and 1992–2002 after averaging procedures. We use the log-isobaric height $z=-H\ln(p/1000)$ as a vertical coordinate, where p – pressure in hPa, H=7 km as a scale heigh. Standard deviations of

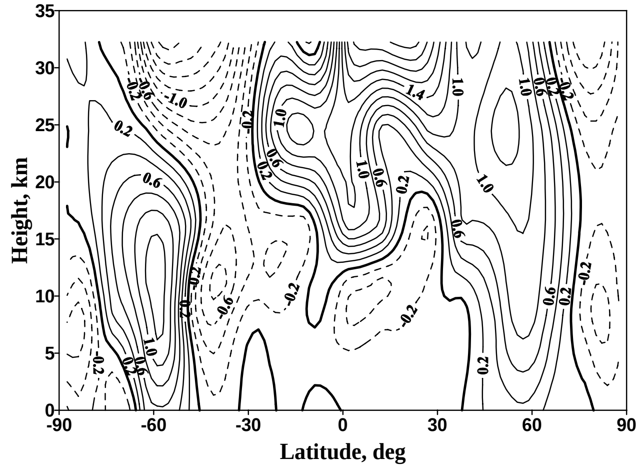

Fig. 2. The estimated linear rate of the mean zonal wind changes during 1959–2002, m/s/decade.

the atmospheric parameters are calculated to estimate their interannual variability inside the considered 11-year intervals. Figure 1 shows an example of the latitude-height sections of the mean zonal flow distribution (upper panel) and its standard deviation or interannual variability (lower panel) for the 1981-1991 time interval. The maximal interannual variability of the mean zonal flow is observed in the stratosphere at low and middle latitudes of the winter hemisphere. This can be explained by QBO effects at the low latitudes and by sudden stratospheric warmings and/or by stratospheric vacillations at the middle latitudes. Interannual variability of the mean zonal flow is significantly weaker in the troposphere than the stratosphere.

The linear rate of the mean zonal flow change is calculated using the least-squares method also, and Fig. 2 gives an example for the 1959–2002 period. This figure shows that mean zonal flow is accelerated in the higher middle latitudes of the troposphere on average. Note that mean zonal flow is decelerated (slowed down) at low latitudes of the winter hemisphere at 10–15 km heights. A comparison of the obtained rate of mean zonal flow change with the climatic distribution of tropospheric jet streams (Fig. 1 upper panel and Fig. 2) results in a clear view of a tropospheric jet maximum displacement in the winter hemisphere to the high latitudes that should affect conditions of SPW propagation from the troposphere into the stratosphere.

To prove this presumption we performed a similar analysis of the temperature change rate during 1959–2002. Figure 3 gives an example of the latitude-height section of the temperature distribution (upper panel) and its interannual variability (lower panel) for the 1981–1991 time interval. According to the lower panel of Fig. 3, significant interannual temperature variability is observed only in the stratosphere of the winter hemisphere at high latitudes. The possible explanation is the sudden stratospheric warming events and/or stratospheric vacillations. Note that interannual temperature variability is insignificant at the low latitudes; that means the choice of an 11-year interval as the averaging period was correct because 11-year solar cycle effects are suppressed in the tropo- and stratospheric temperature.

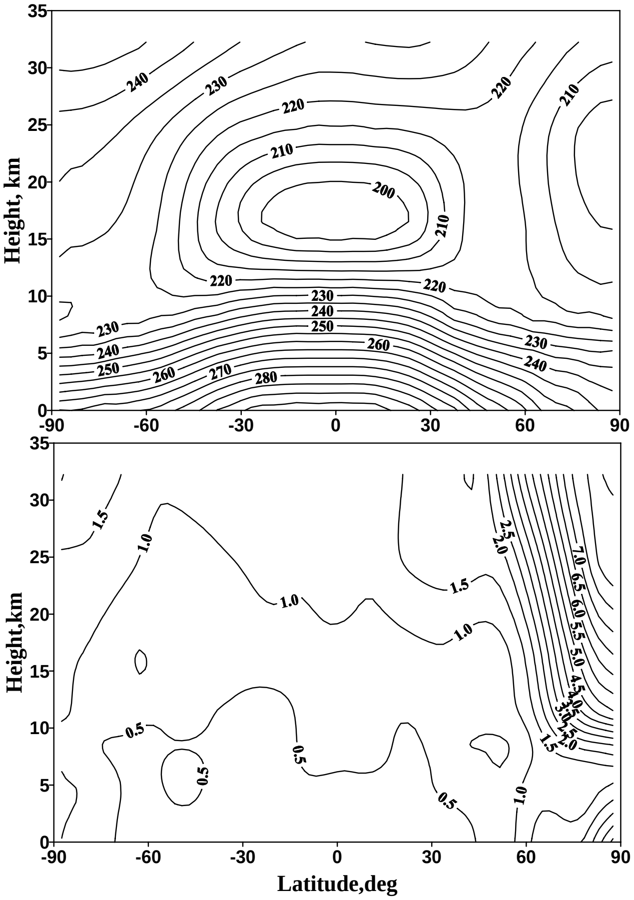

Fig. 3. Latitude-height sections of the zonally averaged temperature (upper panel) and their root-mean-square variability (lower panel) in January. Results obtained using 1981–1991 time interval.

To estimate climatic temperature changes, the linear rate of temperature change in the tropo- and stratosphere is calculated using the least-squares method and averaged temperature distributions for consecutive 11-year time intervals. Figure 4 shows a linear rate of temperature change obtained during 1959–2002 and a cooling of the stratospheric middle latitudes and equatorial belt. On the other hand, middle and high latitudes in both hemispheres of the stratosphere are heated up appreciably. Also note that the rate of temperature change in the winter hemisphere at heights of about 10 km has various signs at low (heating) and high (cooling) latitudes. Comparing the linear rate of the temperature change with climatic temperature distribution (Fig. 3 upper panel and Fig. 4) we confirm an increase in the absolute value of the latitudinal gradient of the zonally averaged temperature in the troposphere at middle latitudes. This should lead to

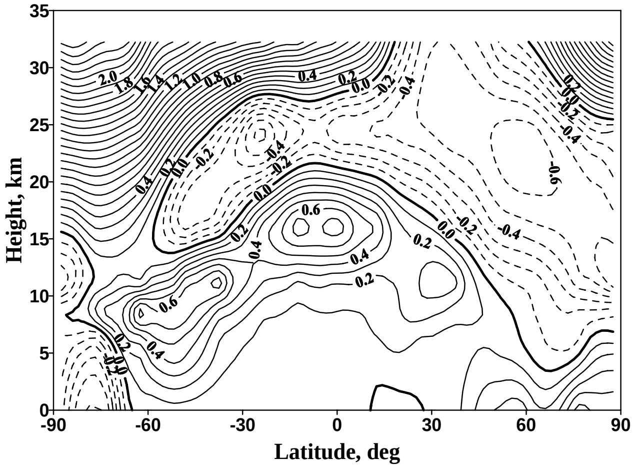

Fig. 4. The estimated linear rate of the zonally averaged temperature changes during 1959–2002, K/decade.

the tropospheric jet stream strengthening in the winter hemisphere.

Linear rates of variations and standard deviations of the discussed parameters for corresponding coefficients of linear dependences are calculated to estimate the statistical significance of the trends obtained. Processing is done using the least-squares method and the monthly averaged temperature and mean zonal flow distributions for January of every year from 1959 up to 2002. The temperature and mean zonal flow variation rates (not shown) do not differ significantly from the parameter distributions obtained according to that averaged over the 11-year intervals (Figs. 2 and 4). Figure 5 shows ratios of linear rate absolute values to corresponding standard deviations for zonal wind (upper panel) and temperature (lower panel). When the time period length includes 44 points the trends obtained are statistically significant with a probability of more than 95% by a t-test, if the above mentioned ratio exceeds 2 (Bendat and Piersol, 1986). Analysis of Fig. 5 makes the impossibility of statistically significant conclusions about trends on the basis of the 44 years worth of data only in the winter hemisphere at high latitudes clear. A possible reason for the latter is a strong interannual variability caused by a SPW-mean flow interactions.

Despite the high statistical significance of the results obtained from the climatic trends estimation based on the NCEP/NCAR data, it is necessary to remember that the reanalysis data grow substantially out of the numerical modelling. It is especially important over areas where observations are sparse and/or in the stratosphere at low latitudes, where artificial trends have been produced by model assimilation of satellite observations since 1979 (Pawson and Fiorino, 1999). A comparison of temperatures and also comparison of the trends based on NCEP/NCAR data reanalysis and observed climatic trends of temperature was carried out for both satellite and for ground–based measurements (Sterin, 1999; Santer et al., 1999; Rubinstein and Sterin, 2002; Khan et al., 2003). The main results of the above-mentioned comparisons for our analysis are the signs' coincidence of the temperature trends calculated from NCEP/NCAR with observations (Khan et al., 2003) and the quantitative coincidence over areas well provided with measurements. Therefore, it is necessary to be cautious about the temperature trend modulus at the high stratospheric latitudes but the latitudinal temperature gradient increasing at the middle latitudes in the troposphere of the Northern Hemisphere can be considered to be reliable.

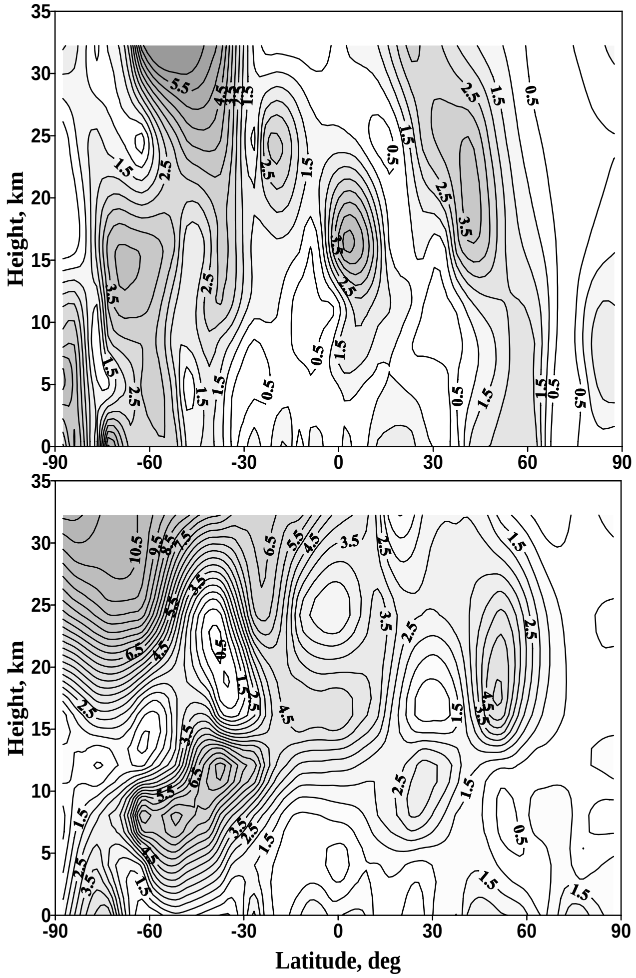

Fig. 5. Ratio of linear rate absolute values to the corresponding standard deviations for zonal wind (upper panel) and temperature (lower panel).

4 SPW1 modelling results

The structure of the SPW1 is numerically simulated on the basis of the tropospheric wind characteristics' distributions for 1960 and 2000. The purpose of the simulations is to estimate the possible influence of the zonal mean flow change

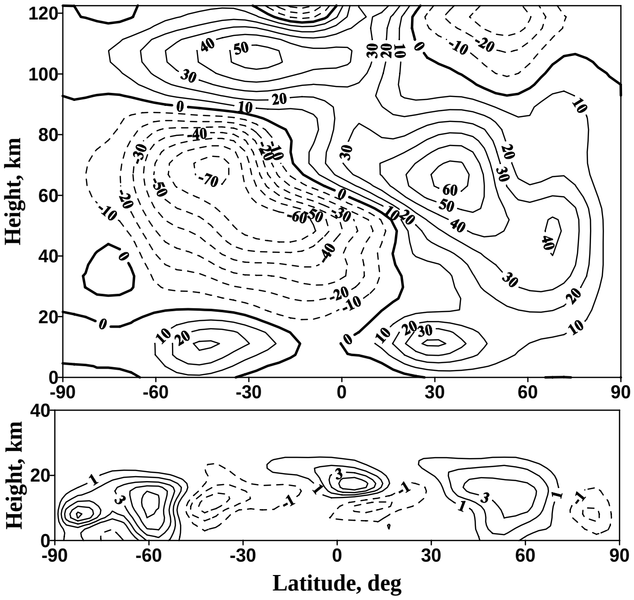

Fig. 6. Latitude-height sections of the zonal mean flow calculated for January 1960 (upper panel) and estimated zonal flow changes in the troposphere during 40 years (lower panel).

in the troposphere on propagation conditions of planetary waves. These parameters are processed from climatic distributions of the zonal mean flow (averaged over all considered time intervals 1959–2002), which are modified in the troposphere according to the linear rate of zonal flow climatic change shown in Fig. 4. In the lower and upper stratosphere, mesosphere and lower thermosphere, CIRA-86 empirical model (Fleming et al., 1988) data are used as a background wind in January. In the transition zone (14–28 km), the background wind obtained from NCEP/NCAR data is combined linearly with a wind from the CIRA-86 model. Figure 6 shows the background wind for conditions in 1960, resulting after linear merging procedure. Changes in the background wind from 1960 till 2000 are shown in Fig. 6b. The tropospheric jet stream position is displaced towards high latitudes in the winter hemisphere during the last 40 years. The displacement resulted in the formation of the strengthened westerly winds' (directed to the east) connecting the tropospheric jet stream with the stratospheric jet in the winter hemisphere: 20 m/s value isoline stretches to the stratosphere.

Linearized model of the planetary waves' global structure is used to simulate SPW1 propagation with specified background zonal flow distribution. To simulate the SPW in the middle atmosphere, a steady-state, 2-D, linearized model of global-scale waves has been used (Pogoreltsev and Sukhanova, 1993; Pogoreltsev, 1996, 1999, 2001). The model horizontal domain is an area from the South Pole to the North Pole and the vertical domain is from the surface up to the height of about 165 km (log-pressure height 140 km). The vertical resolution in the log-pressure coordinate is $\delta z = H/4$, where $H = 7$ km is the scale height. A set of hydro-thermodynamics equations is linearized relative to the zonally averaged state. The SPW is introduced into the model at the lower boundary ($z=0$) as an amplitude and phase of geopotential height perturbations with a zonal wave number of $m=1$ at the 1000 hPa level, extracted from NCEP/NCAR data (see Fig. 7).

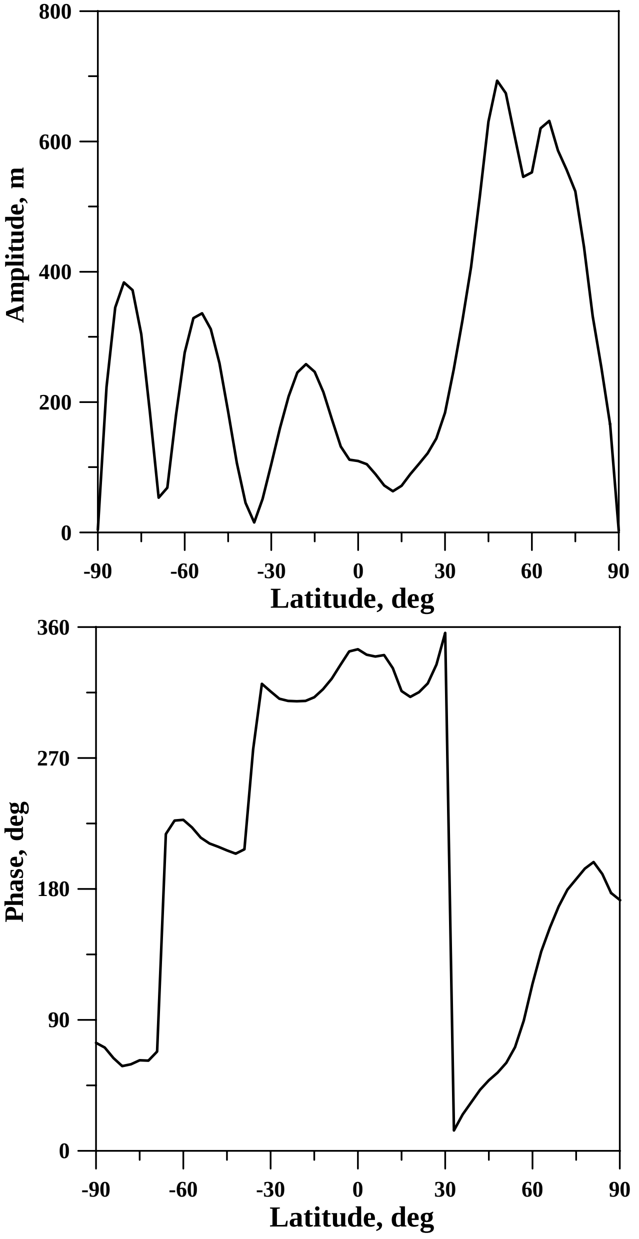

Fig. 7. Climatic distribution of the SPW1 amplitude, *m* (upper panel) and phase, deg (lower panel) in geopotential height.

The amplitude of the SPW in the stratosphere and mesosphere depends mainly on background zonal wind distribution. The boundary-value problem formulation and the

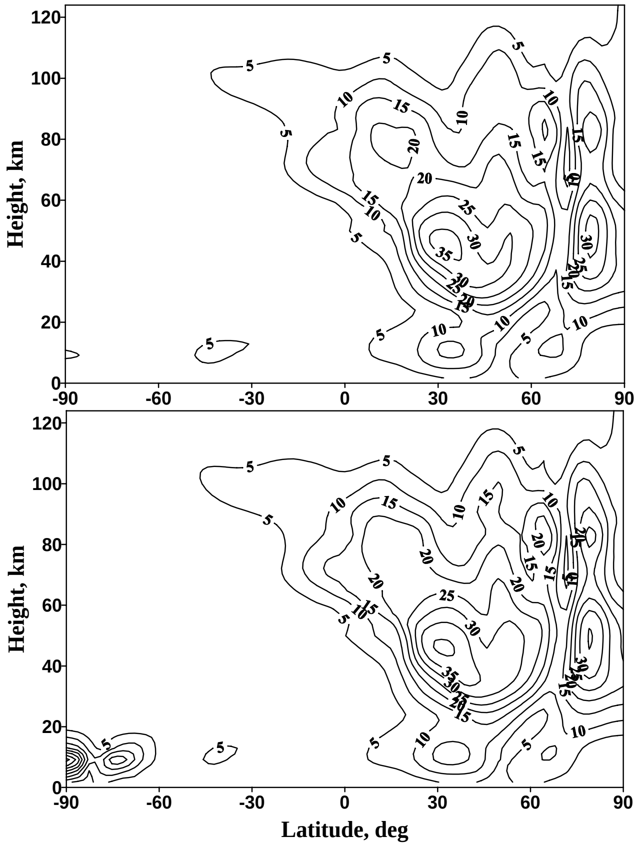

Fig. 8. SPW1 amplitude in zonal wind (m/s) calculated using zonal mean flow for January 1960 (upper panel) and January 2000 (lower panel).

method of solution are described in details by Pogoreltsev and Sukhanova (1993). At the lower boundary (z=0) the climatic distributions of the amplitude and phase SPW1 in geopotential height are defined so that the lower boundary condition remains constant, and all changes in the stratosphere, mesosphere, and lower thermosphere are caused by the change in the wave propagation conditions due to tropospheric zonal wind variations. Figure 8 shows the results of the calculations the background conditions for 1960 and 2000 as latitude-height zonal wind amplitude distributions. Comparison of the results for these conditions in 1960 and 2000 indicates noticeable SPW1 amplitude strengthening in the stratosphere of the winter hemisphere. As a consequence, the SPW1 amplitude at the mesospheric high latitudes is also increased. It is necessary to note that a significant increase in the SPW1 amplitude in the stratosphere should affect the background temperature and zonal flow distributions. Although a feedback mechanism is not included in our simple linearized model, there is still an opportunity for estimation of the SPW influence on zonal fields with the aid of calculations of the following parameters: E-P flux divergence, nonlinear heat and residual circulation divergence, that will be assumed in future works.

In general, there is a possibility to perform the simulation of SPW2 propagation from the troposphere into the stratosphere and mesosphere under different background conditions using the linearized model. However, our experience shows that amplitudes of the secondary stationary wave with zonal wave number m=2, arising from the nonlinear self-interaction of the primary SPW1 in the stratosphere, are comparable with the amplitudes of the primary SPW2 propagating from below (Pogoreltsev, 2001). Thus, to simulate SPW2 propagation in the middle atmosphere, a nonlinear model of the general circulation should be used. Nevertheless, some results of data analysis on SPW2 climatic variability will be presented in the following section.

5 Observed climatic variability of the SPW

Results of simulation of SPW1 propagation with the background zonal wind distributions for 1960 and 2000 assume SPW1 activity strengthening in the stratosphere. It needs to be confirmed in the accessible NCEP/NCAR data. For this purpose, monthly mean amplitude and phase values of a zonal harmonic with m=1 are calculated for January, for all years, i.e. from 1959 to 2002. The averaging procedure is carried out for the intervals 1959–1980 and 1981–2002, i.e. not for 11 years (as in the analysis of mean zonal characteristics variability), but during 22-year intervals, to avoid the influence of a strong interannual SPW variability in the stratosphere, for example, caused by a sudden stratospheric warming development. Figure 9 shows latitude-height sections of amplitudes of the zonal wind disturbances for SPW1 and its root-mean-square interannual variabilities obtained after averaging of the 1959–1980 and 1981–2002 time intervals, respectively. Comparison of the left and right panels of Fig. 9 indicates, noticeably, an increase in amplitudes and their root-mean-square variability values in the stratosphere of the winter hemisphere during the last years that is in good agreement with predicted SPW1 propagation simulations. Also, SPW1 is displaced a little aside towards high latitudes and the additional maximum of the root-mean-square deviation of the amplitude appears at the low latitudes. Probably, this maximum occurrence is caused by an increased number of satellite observations at low latitudes in the stratosphere which were assimilated in the NCEP/NCAR model.

To estimate the linear rate of the SPW changes in the lower stratosphere, the analysis of the SPW1 and SPW2 is performed using the geopotential height NCEP/NCAR data. Figures 10 and 11 show the latitudinal distributions of the estimated linear rates, their standard deviations (SD), and relations of the linear rates to these deviations (t-test used as before) for amplitudes of SPW1 and SPW2 in the geopotential height at 30 hPa level. Amplitudes of SPW1 and SPW2 are averaged over three winter months (December, January, February). One can see from Fig. 10 that changes in the SPW1 amplitudes are statistically significant at middle

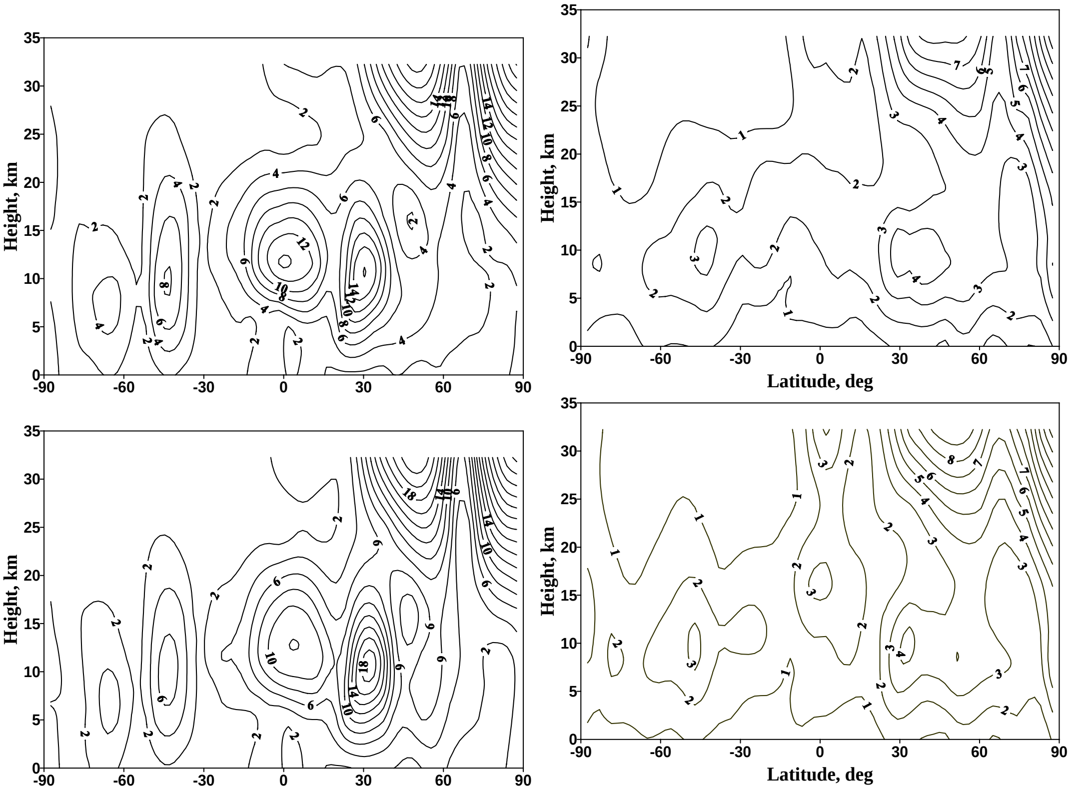

Fig. 9. Amplitudes of SPW1 in zonal wind averaged over January 1959–1980 (left upper panel) and over January 1981-2002 (right upper panel). Contour interval is 2 m/s. Lower panels show root-mean-square variability of SPW1 amplitudes, m/s, respectively.

latitudes of the Northern Hemisphere in winter. In the case of SPW2 (see Fig. 11), there are statistically significant changes in the amplitude at middle latitudes of the Northern Hemisphere and at low latitudes in summer (Southern Hemisphere). At the high latitudes in winter the statistical significance is lower in both cases (SPW1 and SPW2) mainly due to a strong interannual variability. In general, the linear rates of the SPW2 amplitude changes are smaller in comparison with that of SPW1.

The corresponding long-term changes in SPW1 amplitudes in the geopotential height at 30 hPa level for the 62.5 N latitude and SPW2 amplitudes at 42.5 N and 17.5 S latitudes are shown in Figs. 12 and 13, respectively. Figure 12 shows a clear positive trend of the SPW1 amplitude in the geopotential height at the 30 hPa level, at 62.5 N latitude. The value of linear growth is about 100 m during the time interval from 1959 till 2006. A strong variability of the SPW1 amplitude should be noted especially during the last years of 1960s and 1980s. Much more intense variability is observed around 1980–1990. On the another side, Fig. 13 shows a negative trend in the SPW2 amplitude in the geopotential height during 50 years at the 30 hPa level, at 42.5 N latitude and a positive trend at 17.5 S latitude. The magnitude of decrease is about 30 m and it is characterized by a strong variability. Although the positive change in the summer hemisphere has a

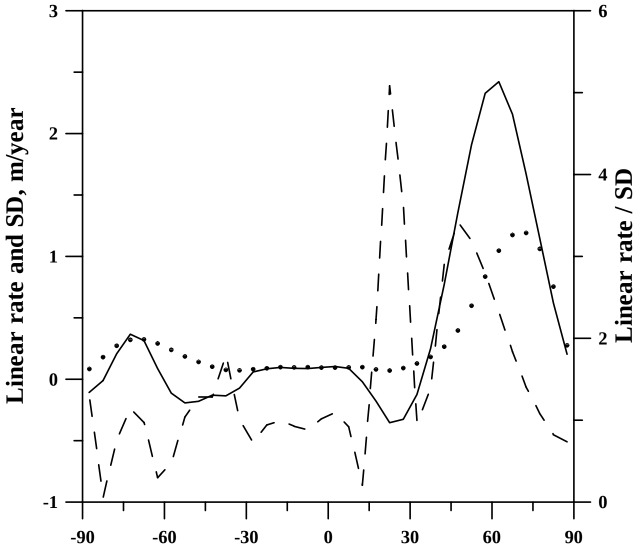

Fig. 10. The estimated linear rate (solid line), its standard deviation (dotted line), and absolute value of their relation (dashed line), for the amplitude of SPW1 in the geopotential height at the 30 hPa level.

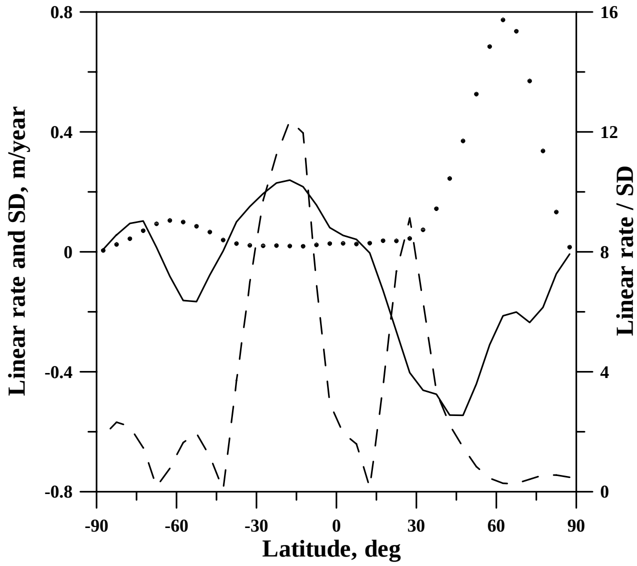

Fig. 11. The same as in Fig. 10, but for the SPW2.

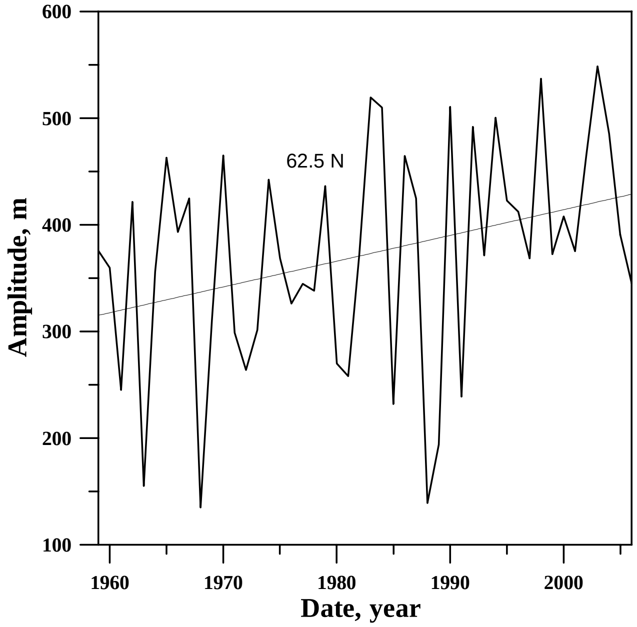

Fig. 12. The long-term change in SPW1 amplitudes in the geopotential height at the 30 hPa level and at 62.5 N latitudes. The estimated linear rate is also shown.

value of about 10 m, this trend is clearly recognizable due to a weak variability of SPW2 amplitude. Interannual variability of SPW2 is more complicated and this can be explained by interference of the primary wave propagating from below and the secondary SPW2 arising from a nonlinear self-interaction of SPW1. The changes in the SPW2 amplitude have a different sign in the winter (northern) hemisphere and at low latitudes in the summer (southern) hemisphere.

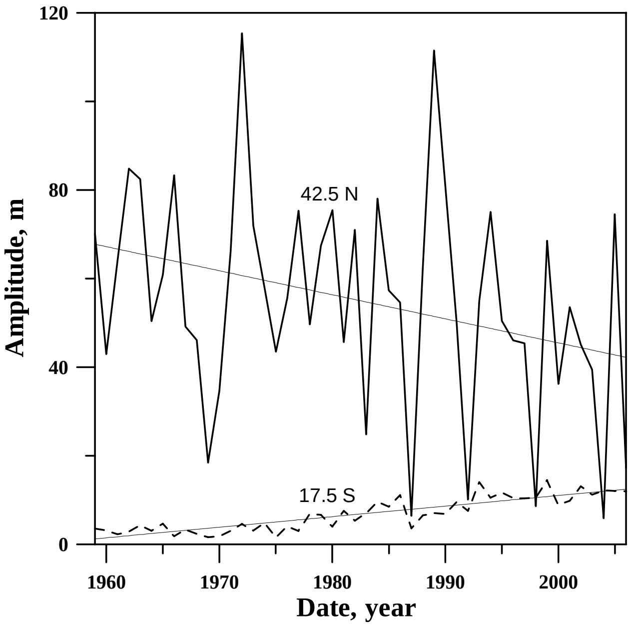

Fig. 13. The same as in Fig. 12, but for the SPW2 at 42.5 N latitudes (solide line) and 17.5 S latitudes (dashed line).

6 Conclusions

The main aims of the work are the analysis of the long-term changes in the zonally averaged temperature, wind, geopotential height and wave activity of the SPW1 during the last decades using NCEP/NCAR assimilated fields from 1959 to 2002, a simulation of the SPW propagation on the basis of the observed changes in the zonal-mean wind in the troposphere as an input parameter for the linearized model of planetary waves and, finally, the comparison of observed and simulated changes in SPW. The importance of our research includes a scientific explanation requirement of observed climatic temperature trends in the middle atmosphere, i.e. numerical estimations of temperature variations and circulation parameters of the middle atmosphere which are connected to the apparent changes of the SPW propagation conditions from the lower atmosphere (intensity and position of tropospheric jet streams). The results obtained show changes in the intensity and position of the tropospheric jet streams maxima and significant temperature changes in the lower atmosphere which have opposite signs at low and high latitudes. Simulations of the SPW1 propagation made for climatic zonal wind distributions characteristic for 1960 and 2000 show that SPW1 propagation conditions are, on average, improved during the last 40 years. Finally, the SPW1 amplitude is significantly strengthened in the strato- and mesosphere.

The analysis of zonal wind perturbations amplitudes for SPW1 in the NCEP/NCAR data indicates an intensification in the SPW1 activity in the lower stratosphere during the last years, which is also accompanied by an observed increase in the interannual variability of the wave amplitude.

It should be noted that the SPW1 amplitude increase in the lower stratosphere may lead to the fundamental change in the stratosphere dynamic mode, i.e. to transition from a steady-state regime under small SPW1 amplitudes to quasi-periodical and/or even chaotic oscillations (the so-called vacillations) at a critical value of the SPW1 amplitude (Holton and Mass, 1976; Haynes, 2005), and the results obtained show that there exists such a tendency during the last several decades.

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