Dynamics and energy of the intraseasonal atmospheric processes according to ground-based and aerological measurements

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Intraseasonal oscillations are studied based on experimental observations at the network of stations of atmospheric monitoring and aerological observations in several industrial regions of Tatarstan during the period of 1996–2003. Simultaneously, we measured near-surface concentrations of aerosol, trace gas atmospheric admixtures, and meteorological parameters. Long-term measurement series have made it possible to perform reliable empirical studies of intraseasonal atmospheric wave processes through estimation of their energy balance at several altitudes, and to investigate the relationships between wave parameters. Eastward propagating waves and perturbations with opposite velocities show significant differences both in the spatial dependences and in the energy characteristics.

Introduction

Knowledge of the regularities in the development of intraseasonal atmospheric processes in the ground layer helps to more efficiently solve the problems of prediction of meteorological and ecological state of environment, and more precisely estimate the anthropogenic influence on it.

Recently, many different models have been developed to treat atmospheric variations, having characteristic spatial scales of a few thousand kilometers and periods from 2 to 60 days.[1,2] The planetary waves determine the dynamical interaction between the troposphere and other atmospheric layers.[3] Most of the experimental observations concerns the Rossby waves in the troposphere and stratosphere,[4] ozonosphere,[5] and other regions of the atmosphere. Normal-mode Rossby waves represent westward moving planetary waves being free oscillations of the atmosphere. Also, there are evidences of the existence of planetary wave processes propagating eastward. For instance, the satellite stratospheric data[6,7] prove the existence of Kelvin waves. Ivanov[8] used aerological and meteorological data to study the eastward moving variations with periods 30–50 days at midlatitudes, and showed their interrelation with the wave processes in the tropics.

The atmospheric wave processes may be one of the causes for spatiotemporal admixture variations. In their turn, the admixtures may serve indicators of wave motions.[9–11] The most well studied aspect of the atmospheric admixture inhomogeneities is the spatiotemporal variations of ozone, and to a lower degree the variations of other trace gas admixtures.[10,13,14] Periods of 8–18 days represent variations of admixture concentration due to large-scale synoptic processes.[15] Periods of 1 to 7 days are usually characterized by local short-period processes, including local synoptic-scale processes, caused both by local characteristics of terrain and cyclonic and anticyclonic activity, among others.[14] Influence of synoptic processes on the variations of characteristics of submicron aerosol has been demonstrated in Ref. 16. Isakov et al.[11] studied long-period variations of optical and microphysical parameters of near-surface aerosol.

Experimental data and methods of the study

In Ref. 12 it was shown that the variations of near-surface concentration of atmospheric admixtures in two industrial regions of Tatarstan are determined to a large degree by intraseasonal processes with periods of 2 to 64 days. For studying synoptic and intraseasonal processes in the ground layer, we use data of network of stations in Almetyevsk (53°N, 51°E), Zelenodolsk (54°N, 49°E), Aznakaevo (53°N, 51°E), and Kazan (56°N, 49°E). Simultaneous measurements of CO, NO, NO_2, H_2S, and SO_2 concentration are being performed at the height of 2.4 m above the ground. At the stations, the temperature, relative humidity, pressure, and wind speed and direction are measured. The distance between the sites is from 50 to 310 km.

To study atmospheric wave variations, based on the time series of atmospheric parameters and admixtures, we used original methods. Methods of wavelet and mutual wavelet analysis, developed by the authors, make it possible to study the parameters of atmospheric wave processes, based on synchronous time series measured at spaced observation points.[9,12] Events of intraseasonal variations were identified taking into account only those periodic variations that showed more than 80% significance of amplitude and phase wavelet spectrum. Experimental distributions of horizontal phase velocities and spatial scales of wave processes are determined.

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This paper, extends the studies first presented in Ref. 12, investigates the regularities of the intraseasonal processes based on the array of data on the waves obtained in Ref. 12. The altitude structure of the ground layer was studied using radiosonde data obtained at Kazan station in 1998–2002.

Incorporation of data on vertical profiles of atmospheric parameters in the work makes it possible to complement the study of horizontal spatial coherence of the fields of atmospheric parameters and admixtures.

The altitude structure of intraseasonal variations in the ground layer

Figure 1 presents the wavelet spectra of intensity of synoptic-scale temperature variations at several altitude levels, obtained using aerological data for 2002. It is seen that almost simultaneously the spectra exhibit maxima at all altitudes in the range from 10 to 5500 m. The coefficient of correlation between the matrices of amplitudes of wavelet spectra for close altitudes such as 100 and 600 m or 2000 and 4000 m is 0.8; for spatially resolved altitudes 600 and 4000 m, it is 0.2. This is because the intraseasonal variations have small but significant altitude phase shift. Analysis of phase wavelet spectra at different altitudes shows 90% significant linear dependence of the phase of significant periodic variations with altitude.

It is found that these spectra based on the aerological data are similar to the spectra of temperature, pressure, wind velocity, and relative humidity, obtained from independent observations at the network of monitoring stations in the ground layer. The amplitudes and periods of intraseasonal variations and their localization coincide with the analogous parameters of surface processes. That is, as expected, the planetary waves manifest themselves almost simultaneously in the ground layer and in the troposphere up to 5500-m heights. The radiosonde data were also used to construct the wavelet spectra of pressure, relative humidity, and zonal and meridional components of wind velocity.

The array of wave processes, obtained using data of ground-based atmospheric monitoring stations was compiled via selection of events of existence of spatially coherent quasi-periodic variations simultaneously at two sites, Zelenodolsk–Almetyevsk (1996–1999) or Zelenodolsk–Aznakaevo (2002). It is noteworthy that the selection was made using independent measurements of meteorological parameters and admixtures.[12] The ground-based daily data on temperature, wind velocity, pressure, and relative humidity, measured at the site of radiosonde launch in 2002 (Kazan), were used as time series for

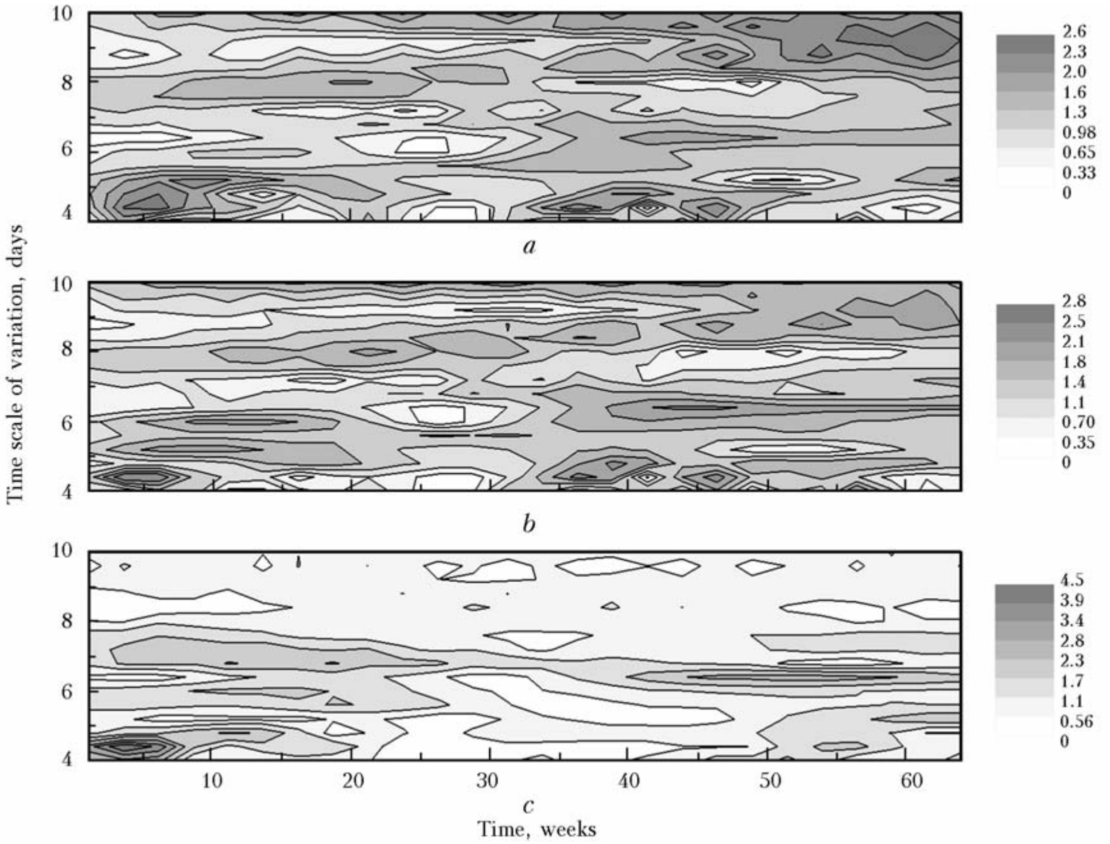

Fig. 1. Wavelet spectra of intensity of periodic variations of temperature T at altitude levels 100 (*a*), 600 (*b*), and 4000 m (*c*) (Kazan, 2002). Scale represents the intensity of temperature variations, K.

third reference point in the study of phase velocities and wavelengths of intraseasonal oscillations. All the wave oscillations detected in meteorological parameters for the same year across Zelenodolsk–Aznakaevo database were also obtained simultaneously for Aznakaevo–Kazan base, and the periods, phase speeds, and wavelengths of each oscillation coincided within the accuracy of the method.[9,12]

Thus, it can be concluded that both temporal and spatial scales of intraseasonal oscillations manifest themselves simultaneously in alterations of pressure, relative humidity, and wind velocity components in all tropospheric layers. Seemingly, they determine also the intraseasonal oscillations of the surface admixtures.

Dynamics of intensity of intraseasonal oscillations

The long-term observation series were used to estimate the contribution of intraseasonal processes to the total variance of atmospheric admixtures in Tatarstan. The minutely data were used to estimate the variance of admixtures within each calendar season in 1996 to 2003. Then the series were filtered by the method of running average, and subtraction was applied to remove the variations with periods longer than 3 months and shorter than 1 days. The resulting series were used to estimate the variance of intraseasonal variations. The variances obtained were averaged over stations operated in each measurement season. Figure 2 presents the estimates of the fraction of variance due to intraseasonal variations in the total variance of the aerosol mass concentration.

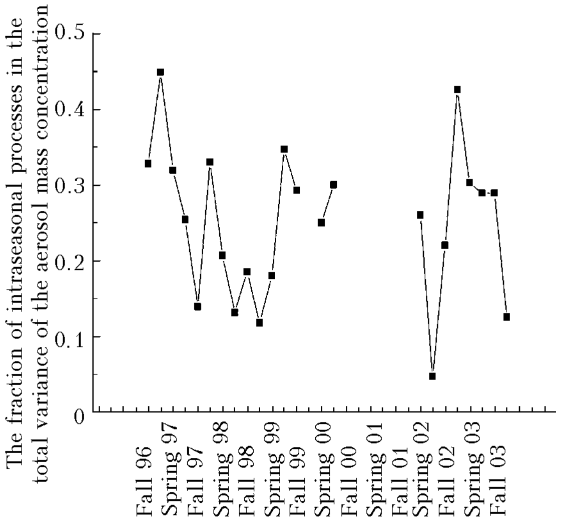

Fig. 2. Estimates of contribution of intraseasonal variations to the variance of the aerosol mass concentration.

It is seen that, on average, it is 20–30% of the total variance and reaches 45% in certain seasons. For trace gas constituents, similar regularities are observed. Such an approach takes into account the contributions of all intraseasonal processes, both anthropogenically induced and caused by variations of meteorological parameters, that change the admixture concentrations in the atmosphere. When we consider only periodic and spatially coherent processes which, as shown in Ref. 12, are almost simultaneously observed both in meteorological parameters, i.e., wind velocity, temperature, and relative humidity, and in the mass concentration of aerosol and trace gas constituents, it is possible to partially filter out the anthropogenic intraseasonal factors.

We have averaged the amplitudes of all wave variations revealed over calendar seasons. Variations of all meteorological parameters, with the exception of relative humidity, and admixture concentrations have maximum amplitudes in winter, consistent with the conclusion drawn in Refs. 8 and 17 that the maximum amplitudes take place in winter, based on observations of intraseasonal variations in the troposphere associated with Kelvin waves. Maximum amplitudes of Rossby waves in winter are inferred from satellite data in Refs. 4 and 5. The total number of the wave variations found is also larger in winter, the fact also deduced from observations of planetary variations of the stratosphere and mesosphere.[3]

Spatial characteristics of waves as functions of variability period

All wave perturbations determined fell into two groups according to the sign. Mainly the variations, caused by westward (eastward) propagating waves, have the periods 3–10 days (8–58 days). We studied the parameters of wave variations as functions of period of the processes (Fig. 3).

For eastward propagating waves, the periods always exceed 8 days, phase velocity practically always does not depend on period, and the wavelength grows with the increasing period. This agrees with theoretical dependences for Kelvin waves: their minimum period is 7.6 days for latitude of our stations.[2] The Kelvin waves move with constant phase velocity, not experiencing dispersion. Their dispersion relationship is expressed by the simple formula $\omega = kC$, where k is the horizontal wave number, and C is the phase speed of the wave. These results confirm the assumption that eastward propagating perturbations of atmospheric parameters and admixtures can be caused by Kelvin waves. Recently, detailed studies have been performed by different methods at various altitude levels, and they demonstrated the presence of Kelvin waves at midlatitudes, e.g., in total ozone[7,17] and in the troposphere over Europe and Asia, based on radiosonde and ground-based meteorological observations.[8]

Average phase velocities of westward propagating waves decrease with growing period. The amplitudes of temperature are maximum for periods of up to 10 days, and somewhat decrease for longer periods.

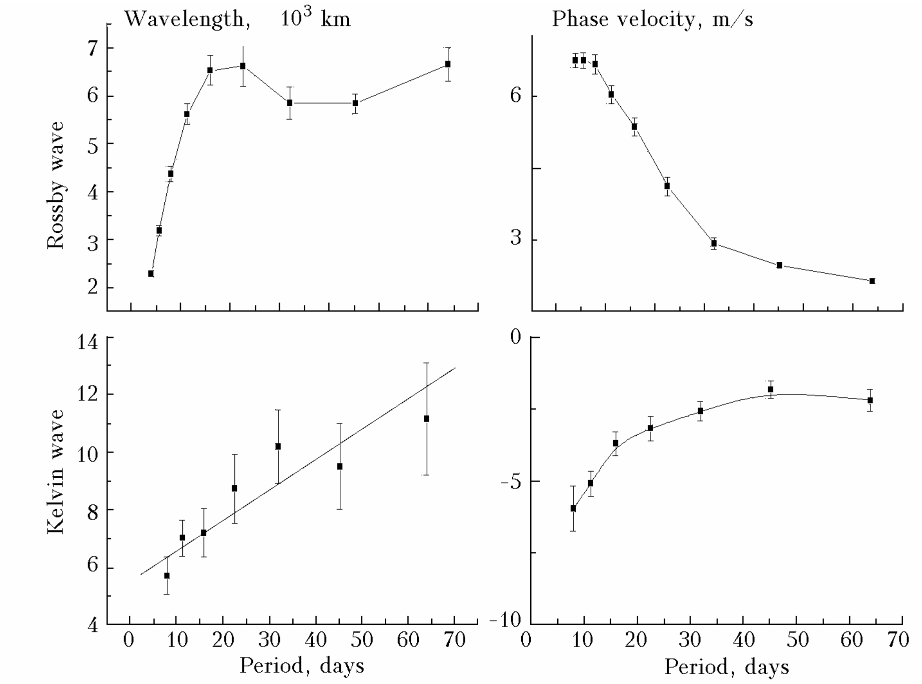

Fig. 3. Parameters of intraseasonal waves versus the period of process.

On the contrary, the amplitudes of wind velocity and admixtures are larger for wavelengths longer than 10 days. The phase velocities and wavelengths of eastward moving waves well correspond to both observed and theoretically calculated values for intraseasonal variations in the stratosphere and troposphere.[1,3] The dependences, we have obtained ourselves, well agree with the parameters of Rossby waves with large wave numbers.[1,2]

For westward propagating waves, there is a tendency toward increase of phase velocity in fall–winter period. The wavelength, on average, is shorter in summer and fall, apparently because the short-wave mode of Rossby waves is exhibited in these seasons. For all parameters, with the exception of aerosol mass concentration, westward propagating waves are mostly observed in winter, primarily because of significance of variations, as we simply cannot detect the waves at small aerosol concentration. Phase velocities of eastward moving waves are constant throughout the year. The seasonal dependence of these wavelengths is opposite to that of the westward propagating waves: maximum (minimum) wavelengths are observed in summer (winter). For all parameters, with the exception of NO_2 and SO_2 concentrations, the number of eastward moving waves is maximum in fall, primarily because of significance of variations: wave processes at small concentration of these admixtures are not detected.

Energy of intraseasonal variations

Little attention has yet been paid to the experimental study of planetary waves, especially to the energy characteristics of the waves in the ground layer, where the energy of different waves can strongly differ from model representations in view of influence of underlying surface and turbulent processes. An objective characteristic of the differences between the wave types may be energy composition of an oscillation.[1] We studied the interrelations among different kinds of energy in the planetary (2–64-day period) waves.

The energy density was calculated directly from experimental data using the formula for kinetic energy of horizontal component of motion:

$$E_p = \bar{\rho}\frac{|V_x|^2 + |V_y|^2}{2},$$

where V_x and V_y are perturbations of zonal and meridional components of wind velocity; and $\bar{\rho}$ is the average air density.

The energy, associated with fluctuations of entropy (thermobaric energy):

$$E_\tau = |p - c^2\rho^2|\frac{g}{2\kappa^2 R\bar{p}(\gamma_a - \gamma)},$$

where R is the universal gas constant; c is the adiabatic sound speed; γ is the lapse rate; γ_a is the adiabatic temperature gradient; $\bar{p}$ is the pressure, p is the pressure perturbation in the wave, $\kappa = c_V/c_P$ is the ratio of specific heat capacities of air at constant volume and constant pressure, and g is the acceleration due to gravity.[1]

We have studied all the detected waves with periods from 2 to 64 days. The density of kinetic energy was calculated at three different altitudes using radiosonde data. The calculated results on the mean density are presented in the Table.

Table. Average energy density in synoptic and intraseasonal waves

Energy density, J/m^3	Westward propagating waves	Eastward propagating waves
Kinetic energy at height, m		
10	0.072	0.055
50	0.194	0.194
100	0.267	0.203
Thermobaric energy	0.311	0.207

Evidently, the kinetic energy of eastward propagating waves at height 100 m is approximately equal to potential energy, while for westward moving waves it is 46% of the total energy. The Rossby radius for the latitude 56° is about 2 thousand km; consequently, all the detected modes are comparable with Rossby radius, and relationship of energy densities should be approximately identical.

Average kinetic energy density for westward propagating waves is constant, while the thermobaric energy density increases with growing wavelength. Kinetic energy density for eastward moving waves slowly grows with wavelength. The thermobaric energy density of these wavelengths has a tendency to decrease, though insignificantly, with growing wavelength. These dependences are presented in Fig. 4.

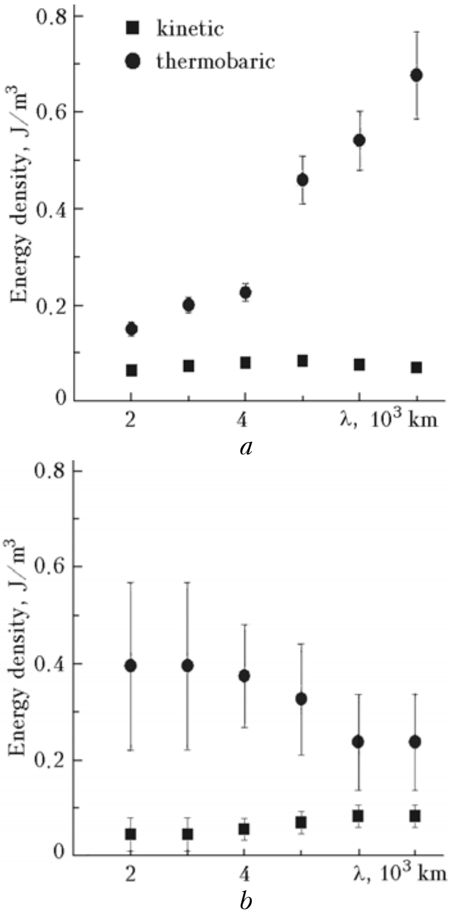

Fig. 4. Average energy density at height 10 m for westward (*a*) and eastward (*b*) propagating waves versus spatial scale.

Thus, eastward and westward moving perturbations show significant difference both in the spatial dependences and in the energy characteristics of waves.

Conclusion

In this paper, we have demonstrated that the intraseasonal atmospheric processes manifest themselves in the troposphere at altitudes from 2 to 5500 m, and typically have altitude phase shift. They make a significant contribution to the variance of the surface admixtures. The eastward and westward moving perturbations have significant differences in dependences of spatial and energy characteristics on the wave timescales. Study of relationships for periods and phase velocities of these variations allows us to hypothesize that westward (eastward) propagating perturbations of parameters and admixtures are associated with Rossby (Kelvin) waves.

Acknowledgments

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