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Simulation of the Quasi-Biennial Oscillations of the Zonal Wind in the Equatorial Stratosphere: Part II. Atmospheric General Circulation Models*

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Abstract—The problem of simulating quasi-biennial oscillations (QBOs) of zonal velocity in the equatorial stratosphere in atmospheric general circulation models is considered. In accordance with the results from Part I of this study on the basis of the models developed at the Institute of Numerical Mathematics of the Russian Academy of Sciences (INM RAS), the possibility of implementing (in these models) mechanisms of QBO excitation through both the interaction of planetary waves with the mean flow and breaking of short gravity waves is investigated. A new high-resolution $2° \times 2.5° \times 80$ version of the INM RAS model is designed, a climate simulation with the two $2° \times 2.5° \times 39$ and $2° \times 2.5° \times 80$ versions of the INM RAS model is briefly described, results of spectral analysis of equatorial wave activity are presented, and the QBO formation processes in these models are considered in detail. For the new $2° \times 2.5° \times 80$ model, realistic QBOs of zonal wind are obtained as the result of the action of both mechanisms.

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INTRODUCTION

This paper is the second part of a study that is devoted to quasi-biennial oscillations (QBOs) of zonal wind in the equatorial stratosphere and concerns the problems of modeling this climatic phenomenon. A comprehensive description of the QBOs and of their influence on the atmospheric general circulation is presented in Part I [1], where the importance of this atmospheric phenomenon for the Earth's climate and, as a consequence, the need for its simulation with modern general circulation models are shown. Part II is devoted to the simulation of the QBOs with atmospheric models developed at the Institute of Numerical Mathematics of the Russian Academy of Sciences and offers an analysis of results of numerical experiments on their reproduction.

It is noted in Part I that only a few present-day general circulation models are now capable of simulating the QBOs of the equatorial stratospheric zonal wind and other effects linked to these oscillations. Therefore, the major problem of the whole study is to construct atmospheric circulation models that would adequately reproduce the QBOs. The main difficulty in the solution of this problem lies in the implementation of a rather complicated mechanism of QBO formation: nonlinear interaction of the mean zonal flow with vertically propagating waves of different scales. The result of the analysis of the QBO generation mechanisms should be the formulation of necessary and sufficient conditions that general circulation models must satisfy for a simulation of this phenomenon. The solution of this problem was the subject of Part I, which considers the generation of zonal wind oscillations on the basis of simple low-parameter models.

Recall the content of Part I and the main results in brief. The interaction of equatorial waves with the mean flow in the equatorial stratosphere depends on the scale of wave perturbations. Therefore, two mechanisms of QBO formation were discussed: the interaction of long waves with the zonal flow and the breaking of short gravity waves. This separation is of particular importance for the development of general circulation models, because the generation of large-scale waves is an internal process, while gravity waves have a subgrid scale and parametrizations are used to take these waves into account.

QBO formation through the interaction of long planetary waves with the zonal flow in the equatorial stratosphere was studied in a simple model proposed by P. Plumb [2]. From numerical experiments, it was shown that this mechanism requires that models have a high vertical resolution, because the critical layers in which the main interaction occurs have a small vertical scale. This condition clearly becomes a necessary requirement for QBO simulation in more complicated

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general circulation models. It was shown that characteristics of an oscillatory process (period and amplitude) depend strongly on the wave parameters and on the parameters of the model itself. In this case, an oscillatory process happens in the region of parameters that differ slightly from realistic characteristics of equatorial planetary waves. It is logical to assume that the given dependence should also take place in global models; this type of wave should, however, be reproduced directly in them, and there may be more complicated dependences due to the influence of side processes disregarded in a low-parameter model. It is worth noting that, in addition to the propagation of large-scale equatorial waves in the stratosphere, the general circulation model must include a minimum set of other atmospheric processes that are necessary for driving the mechanism of QBO formation: the interaction of long waves with the mean flow occurs only in the presence of a certain diffusion process (its role is played by Newtonian cooling), and a change of the positive and negative phases of the cycle of zonal wind occurs through vertical mixing (vertical diffusion), which plays an important role when velocity gradients are large. The characteristics of oscillations are then dependent on the typical parameters of these processes. Provided that the processes described above do occur, it is possible to expect a simulation of the QBO of zonal wind through the interaction with long waves in general circulation models, but the conditions that are obtained can be insufficient. The results of experiments with the Plumb low-parameter model show that this mechanism in the global models is insufficient to drive realistic QBOs, because the realistic energy of long equatorial waves is deficient (it was overestimated in a simple model). Thus, it is necessary to take into account the entire spectrum of equatorial wave motions.

The generation of zonal velocity oscillations by the interaction of the mean flow with short gravity waves was described in Part I on the basis of a low-parameter model analogous to that of Plumb. For implementing the mechanism of the reversal of wind directions, the model included vertical diffusion, the magnitude of which determines the character of the solution obtained, and the interaction with gravity waves was provided via the Doppler-spread breaking of wave perturbations in the mean flow. As has already been noted, since the propagation processes of gravity waves in models with a rather coarse resolution have a subgrid scale, the interaction mechanism was prescribed in a simple model by a parametrization proposed by Hines and described in [3, 4]. The choice of this parametrization was motivated primarily by its use in the Institute of Numerical Mathematics of the Russian Academy of Sciences (INM RAS) general circulation model. From the results of numerical simulation, it was shown that the gravity-wave breaking mechanism on its own is capable of generating equatorial zonal velocity oscillations in the upper atmosphere. Realistic QBOs arise in a narrow range of the model parameters; the characteristics of the oscillation are very sensitive to both the parameters of the model itself and the side processes, which are disregarded in the model, so that the problem of implementing the given mechanism of QBO excitation in general circulation models is substantially complicated. However, for a small-scale wave breaking mechanism, it is possible to choose numerical characteristics of parametrization from a wide range of their values.

The role of small-scale wave activity seems to be very important, and mechanisms of its impact on the QBOs are not yet well understood. The results presented here demonstrate common features in the two mechanisms of QBO formation (a common scheme of vertical diffusion and of wind direction reversal and linear dependences of the oscillation period on major wave parameters). However, these processes cannot be combined in common terms, because one process will never account for the effects of the other. To obtain a more realistic pattern, a coupled low-parameter model was constructed in which the two mechanisms of QBO formation were combined: through the interaction of the mean flow with long waves and through the breaking of short gravity waves. Taken even in its simplified form, this model makes it possible to cover the entire spectrum of equatorial waves and to understand the relative role of different-scale processes in driving the QBOs. As a result of numerical experiments, a more realistic pattern of the QBOs of equatorial zonal velocity has been obtained with the mechanism of planetary wave absorption, which dominates in the lower stratosphere, and the gravity-wave breaking mechanism, which covers the upper layers [1]. Under the simultaneous action of these mechanisms, the propagation of gravity waves occurs against the background of zonal-velocity oscillations generated by long waves, with planetary waves playing the primary role in the formation of the period and asymmetry of the easterly and westerly phases of the QBO and gravity waves playing the secondary role by pumping additional energy into the oscillatory system.

An analogous problem of QBO simulation in simple models through gravity waves and the combined action of large- and small-scale equatorial waves is discussed in [5, 6]. Unfortunately, we had not been aware of these results when Part I of our work [1] was published. In [5, 6], somewhat different models of wave interaction with the mean flow were used. The main goal in the research is a study of wave characteristics and the conditions that are necessary for QBO generation, the possibility of replenishing a deficit in energy of planetary waves through gravity waves is shown, and the role of planetary waves in the formation of the oscillation in the lower stratosphere and of gravity waves in the upper stratosphere is distinguished. Similar results were obtained in our work, with emphasis, however, on the formation of the oscillation period and on its dependence on the characteristics of different-scale waves and on the key role of planetary waves in the formation of the period, findings which are missing in [5, 6].

These conclusions are quite significant for further investigation, because all physical processes that play an important role in the dynamics of the equatorial stratosphere should be described realistically in studying the QBOs and in constructing comprehensive general circulation models. On the basis of the results of a simple coupled model, it is possible not only to highlight the role of each mechanism, but also to examine synchronization processes of various periodic events arising in the equatorial dynamics of the atmosphere. An ideal global general circulation model must reflect the interaction of the entire spectrum of equatorial waves with the stratospheric zonal wind.

As was noted above, the primary goal of Part II of our study is to develop an atmospheric general circulation model that would reproduce realistic QBOs of zonal wind in the equatorial stratosphere. To solve this problem, we used the INM RAS troposphere–stratosphere–mesosphere model with a spatial horizontal resolution of $2° \times 2.5°$ and a rather coarse vertical resolution of 39 levels. With standard parameters, this model fails to reproduce the QBOs in the equatorial stratosphere, producing a negative shift of the zonal velocity in the lower stratosphere, but it simulates semiannual oscillations in the equatorial upper stratosphere and mesosphere.

In view of the fact that the two selected mechanisms exciting an equatorial zonal velocity oscillation are naturally separated in global models, the problem of assessing the degree of implementation of each mechanism in the INM RAS general circulation model emerges. As for the mechanism whereby the velocity oscillations are driven by gravity-wave breaking, the results and technique of studying a low-parameter model can be directly extended to the INM RAS general circulation model, because it uses the same Hines parametrization to describe the effect of gravity waves in the upper atmosphere.

One key feature of the interaction of long equatorial waves with the mean flow in the stratosphere is that much of the momentum transfer from a wave to the zonal flow occurs in a narrow region of critical levels, where the velocity of the flow itself is close to the phase velocity of an individual wave; as a result, the wave in this zone is completely absorbed quite rapidly. The generation and propagation of long planetary waves are determined by solving the dynamic equations of the model itself as a whole; it is important to stress that wave parameters are not prescribed externally, and, for detecting and describing the characteristics of each wave, spectral analysis of numerical modeling results is needed, which by itself is a laborious task. The extent to which these waves can interact with the mean flow is even more difficult to assess; however, it can be expected that the mechanism of QBO formation must work if the requirements formulated in Part I are fulfilled and several oppositely directed planetary waves with realistic characteristics are present. One of the conditions necessary for driving this mechanism was the construction of a new general circulation model with a high vertical resolution in the stratosphere. (The results of Part I show that an adequate simulation of critical-level absorption of long waves requires a resolution with a step less than 500 m). To solve this problem, the authors developed a new INM RAS atmospheric general circulation model with a resolution of $2° \times 2.5° \times 80$. The basis was the original model in which the vertical grid was modified: the number of levels was increased to 80, and the grid spacing in the stratosphere was approximately 0.5 km. This modification was carried out not only for the equatorial zone of interest, but also for the entire atmosphere, which should, in principle, improve the general performance of the model.

Emphasis in our study was placed on the simulation of the QBO in the models presented here. Relying on the results of Part I, with a switch to the simulation of the QBO with general circulation models, we tried to answer the following questions in Part II.

1. On the basis of studying two mechanisms of QBO excitation and conditions for their implementation, the task of preliminarily investigating general circulation models for their ability to reproduce both types of interaction of the equatorial waves with the mean flow in the stratosphere arises. As was noted above, an accurate assessment of the degree of wave interaction with the zonal flow is rather hard to obtain in global atmospheric models; however, a general description both of climate with the two INM RAS models with resolution $2° \times 2.5° \times 39$ and $2° \times 2.5° \times 80$ and, particularly, of equatorial processes will give a fairly comprehensive pattern of the large-scale and equatorial wave dynamics in the stratosphere. Such a description is most important in the context that wind oscillations driven by both mechanisms are very sensitive to external processes; this applies particularly to the gravity-wave breaking mechanism, which is naturally included in the general circulation model through the Hines parametrization. A brief description and overview of the climate of both versions of the INM RAS models from the results of control runs are presented in Section 1.

2. For a more detailed analysis of the equatorial dynamics and mechanisms of QBO formation in the models, it is necessary to analyze wave activity in the equatorial stratosphere and to assess the degree of wave interaction with the zonal flow. A detailed

description of equatorial processes and preliminary results of spectral analysis in this region for the control runs with both versions of the models can be found in Section 2.

3. For the reasons described above, it is hard to expect that the implementation of the mechanism of interaction of long waves with the mean flow is possible in the $2° \times 2.5° \times 39$ version of the general circulation model with coarse resolution; under these conditions, however, the question arises as to whether zonal velocity oscillations can be excited by gravity-wave breaking prescribed by the Hines parametrization, because an important positive result has been obtained in the low-parameter model. Since we expect that the wave mechanism in this version of the model should actually be specified only by the breaking of small-scale waves, it is of some interest to compare the relationships obtained for the sensitivity of characteristics of the zonal flow to variations in the model parameters. It should be emphasized that vertical diffusion in the upper stratosphere in the INM RAS general circulation models is described by the same parametrization with a dimensionless coefficient, which makes it possible to govern one more important process that influences QBO formation. An investigation of the $2° \times 2.5° \times 39$ version of the INM RAS general circulation model is presented in Section 3.

4. The new $2° \times 2.5° \times 80$ version of the INM RAS MODEL is designed to solve the main task: simulating realistic QBOs. With a positive answer to the question posed in item 2 on the propagation and interaction of planetary waves with the mean flow at the equator, one can expect that both mechanisms of QBO generation are implemented in the given model. The need emerges for a study of their combined action in the general circulation model and for a comparison of the results with those from the corresponding section of Part I. Note that the available means of modification and adjustment of the model consist, as before, of changing the characteristics of the Hines parametrization; at the same time, the parametrization provides the possibility of changing the level of vertical diffusion, a necessary and an important external process in both mechanisms. Results of numerical experiments on the simulation of QBOs in the $2° \times 2.5° \times 80$ version of the INM RAS model are described in Section 4.

Should the problem of QBO simulation be resolved positively, a number of practical questions emerge that concern the degree of realism of this oscillation, its influence on other processes in the atmosphere as a whole, and the sensitivity of oscillation characteristics to parameter variations. A discussion of the experimental results with both versions of the model and conclusions can be found in the last section.

1. GENERAL DESCRIPTION OF THE INM RAS $2° \times 2.5° \times 39$ AND $2° \times 2° \times 80$ GENERAL CIRCULATION MODELS

The most comprehensive description of the basic equations of the INM RAS general circulation model, its structure, and its algorithm can be found in [7]. The original version considered there had a horizontal resolution of 4° in latitude and 5° in longitude and 21 vertical levels in σ-coordinates up to the upper boundary at 10 mb. An extended version of the INM RAS model, with the same horizontal resolution but with 39 vertical levels in σ-coordinates and spanning the troposphere–stratosphere–mesosphere system, is described in detail in [8]. This model is used as the basis for constructing the $2° \times 2.5° \times 39$ and $2° \times 2.5° \times 80$ versions considered here. The $2° \times 2.5° \times 39$ model corresponds mainly to a description presented in [8]; the basic modification is the improvement of the model's horizontal resolution (the new version has 2° in latitude and 2.5° in longitude). The vertical resolution was held unchanged: 39 vertical levels in σ-coordinates up to the upper boundary at 0.003 mb, with a distance between levels in the upper stratosphere and mesosphere of about 3 km. The new version of the model has 80 vertical levels in σ-coordinates up to the same upper boundary at 0.003 mb, and the distance between levels in the stratosphere was decreased to about 0.5 km, in agreement with the condition necessary for the mechanism of the interaction of planetary waves with the zonal flow (see Part I [1]). The vertical resolution of the troposphere and upper mesosphere remained unchanged; the horizontal resolution was 2° in latitude and 2.5° in longitude.

The main addition to the original version of the INM RAS general circulation model [7] is the parametrization of small-scale gravity wave forcing, along with an improvement in resolution. This process is separated into two independent parts: orographic and nonorographic gravity-wave drag. The former is described by the parametrization proposed by Palmer [9]. As was noted above, the nonorographic wave drag, which determines the effect of gravity waves in the upper atmosphere, is calculated through the Hines parametrization. The main aspects of the Doppler-spread parametrization of the interaction between short waves and the mean flow proposed by Hines are described in detail in our paper [1] and in papers of the author himself [3, 4]. For the $4° \times 5° \times 39$ version of the INM RAS model, the application of this parametrization is described in [8]. In the new $2° \times 2.5° \times 39$ and $2° \times 2.5° \times 80$ versions, this parametrization is held virtually unchanged.

As has already been noted, one particularly important process in the general circulation model is the vertical diffusion in the stratosphere, which is described by the gravity-wave drag parametrization caused by the turbulence resulting from gravity-wave breaking (a description of the calculation can be found in [3]). This process influences the dynamics of horizontal velocity in the model and is an essential part of both mechanisms of QBO excitation [1]. The final magnitude of vertical diffusion depends on gravity-wave forcing. This causes nonlinear feedback between the two important processes in particular models. Note that some important results on the sensitivity of the original version of the model to gravity-wave drag parameters are presented in [8], where it is shown that it is these parameters that can determine the dynamics of the equatorial stratospheric. These results will be given more attention below.

We now turn to a brief description of the climate of the $2° \times 2.5° \times 39$ and $2° \times 2.5° \times 80$ models and consider the aspects that are important for the task of simulating the mechanisms of QBO formation in more detail. It should be noted that both models were used in multisequenced MPI versions. All numerical runs were conducted on the INM RAS 32-processor cluster and on a cluster system of the Moscow Institute of Physics and Technology (136 nodes with 4 processors each, a total of 544 processors, 4 × Intel Xeon EM64T 3.0 GHz node configuration, 4 GB RAM per node, peak performance of 6.5 Tflops).

A detailed discussion of the simulation of climate in the INM RAS $4° \times 5° \times 39$ atmospheric model was presented in [8]. Note that, in general, the climate of the versions used here differs slightly from the results obtained in [8]. Due to the adjustment of the parametrization of deep convection, a better simulation of the propagation of stationary waves into the winter stratosphere has been achieved. The amplitude of stationary waves in the stratosphere has become close to that which is observed. Moreover, zonal winds in the stratosphere and mesosphere have somewhat changed due to the adjustment of the parametrizations of orographic gravity-wave drag.

Control numerical experiments were conducted with both versions to simulate the present-day climate for a period of 20 years for the $2° \times 2.5° \times 39$ version and 30 years for the $2° \times 2.5° \times 80$ version. For the lower boundary conditions, the climatic annual cycles of sea surface temperature and sea-ice extent were specified. The distribution of radiatively active gases in the atmosphere corresponded to the end of the 20th century and was prescribed according to observations. Consider some of the basic results from the simulation of climate with these models.

Figure 1 shows the zonal temperature in January and July averaged over time for each month of the study periods from the data of the two models and observations [10]. In general, both models adequately reproduce the observed temperature distribution, and the gradient is well simulated in the upper troposphere. Common shortcomings are an overestimation of temperature near the stratopauses, particularly in high latitudes, and an underestimation of the temperature difference between the winter and summer hemispheres in the upper mesosphere. The climate in both versions of the model is nearly the same, but it should be noted that the $2° \times 2.5° \times 80$ model simulates the temperature at the tropopause level much better, where the improvement of vertical resolution exerts the greatest effect.

The time-averaged zonal winds from both models and observations in January and July are shown in Fig. 2. Both models correctly reproduce basic features of the zonal wind in the atmosphere. The easterly and westerly wind maxima in the model agree with observations, and the midlatitude velocity gradients and the equatorial reversal of the mean-velocity directions are well simulated. One common shortcoming is the lower position of the maximum easterly and, particularly, westerly winds in the models in comparison with observations, which may point to a slight overestimation of the nonorographic gravity-wave drag. The basic velocity maxima are generally underestimated, yet they are reproduced much better in the $2° \times 2.5° \times 80$ version of the model, and the stratospheric zonal velocity in this version is closer to the observed velocity than that in the $2° \times 2.5° \times 39$ version. There is no large difference in the results of the two models, but some improvement of the simulation of zonal wind at the tropopause level can be seen in the $2° \times 2.5° \times 80$ model, where an individual maximum of the easterly wind is actually observed at 30° in the Southern Hemisphere in July.

On the whole, it can be concluded that both models simulate the climatic features of the atmosphere quite successfully, yet there are common problems. The improvement of the vertical resolution in the model has positively affected the simulation of the climate features at the tropopause level in the lower stratosphere. This result is most important in the context that the main sources of equatorial wave activity are located in this region. Thus, the general climatic background of wave dynamics is simulated better in the $2° \times 2.5° \times 80$ model.

Note that stratospheric and mesospheric wind speeds at all latitudes are sensitive to adjustments of the Hines gravity-wave drag parametrization; therefore, it makes sense in our task to vary the parameters only in the narrow equatorial region where zonal wind QBOs should be generated. In the control experiments for climate determination, the following values of gravity-wave drag parameters were used in both models (for all latitudes): $\Phi_1 = 0.3$ (statistical coefficient of the total rms deviation of horizontal velocity), $\Phi_2 = 1.5$ (statistical coefficient of the rms deviation in one out of 12 directions), $\sigma_0^2 = 1.75$ m^2/s^2 (the total rms deviation at the source level of gravity waves), $m_{\min} = 10^{-4}$ m^{-1} (minimum vertical wave number at the source level of

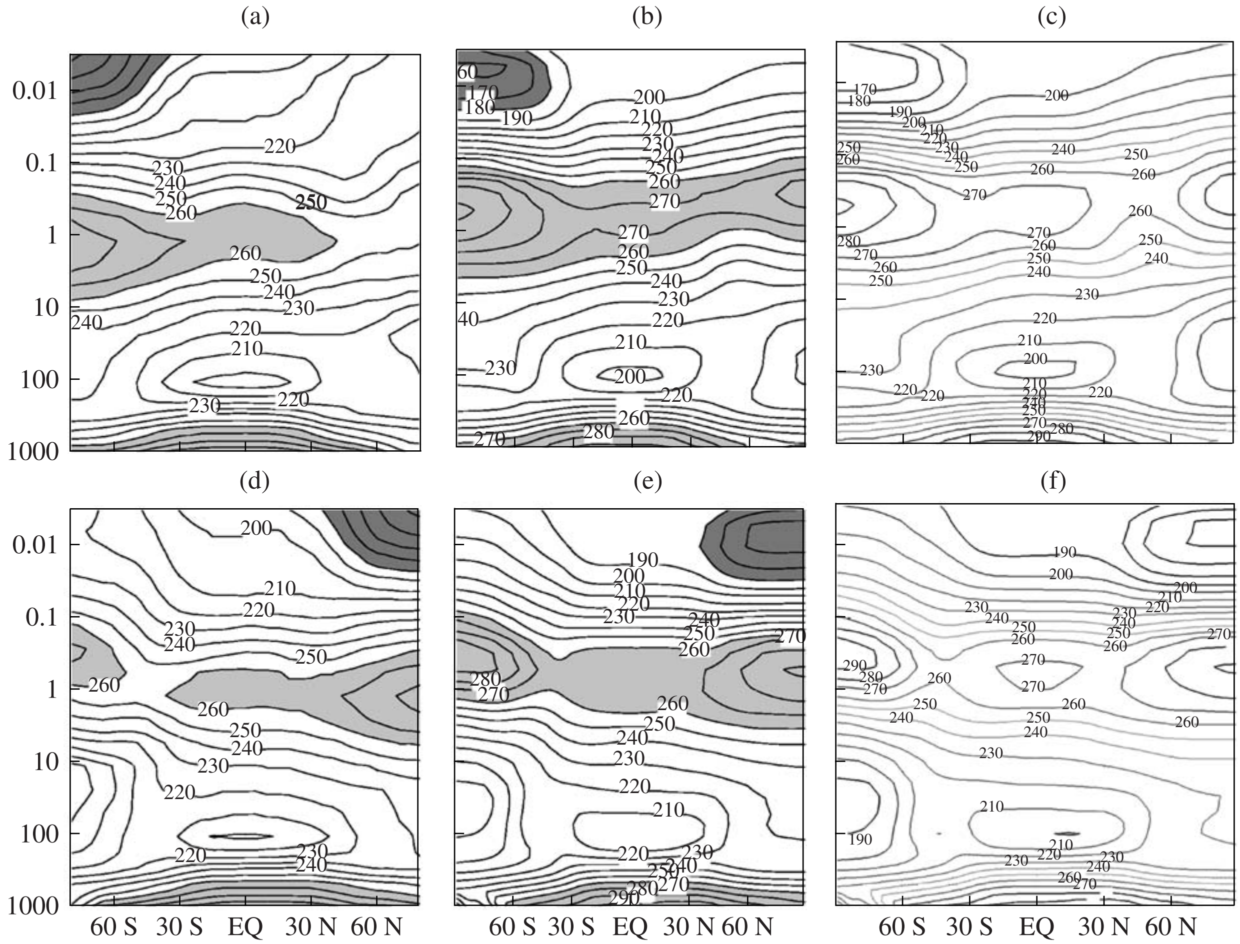

Fig. 1. Zonally averaged temperature (K) in (a)–(c) January and (d)–(f) July from (a) and (d) observations and from INM RAS general circulation models with resolution (b) and (e) $2° \times 2.5° \times 39$ and (c) and (f) $2° \times 2.5° \times 80$.

waves), $h = 2.5 \times 10^{-5}$ m^{-1} (horizontal wave number), $\Phi_6 = 0.25$ (vertical diffusivity), the wave source was assumed to be at the 500-mb level, and the vertical spectrum was assumed to be linear for all versions of the model. Note that these parameters are the basic characteristics of the Hines parametrization [1, 3, 4, 8].

2. RESULTS OF CONTROL EXPERIMENTS ON THE SIMULATION OF EQUATORIAL ZONAL WIND AND AN ANALYSIS OF WAVE DYNAMICS IN THE INM RAS $2° \times 2.5° \times 39$ AND $2° \times 2.5° \times 80$ GENERAL CIRCULATION MODELS

Consider results of the control experiments with both versions of the model in the region of equatorial dynamics. The time behaviors of the equatorial zonal wind velocity in both models are shown in comparison with each other in Fig. 3, and the annual mean cycle of the equatorial zonal velocity from the models and from the NCEP/NCAR reanalysis data [11] (only in the lower atmosphere) is presented in Fig. 4. For the$2° \times 2.5° \times 39$ model, the zonal wind in the layer between 10 and 100 mb is dominated by oscillations of a 1-year period with the mean value significantly shifted toward negative velocities (easterlies) and with a ~5 m/s amplitude, in contrast to the QBO with a mean period of about 28 months and amplitudes of ~35 m/s. The oscillations in this version resemble the observed ones, particularly those obtained in our study with low-parameter models [1]: in all cases, the propagation of the westerlies and easterlies occurs from above downward, and the maxima of the amplitude of wind-velocity oscillations are in the upper stratosphere at heights around 10 mb and with a magnitude of about 30 m/s, which is also close to the observed value. Thus, it can be argued that the model with a coarse vertical resolution of $2° \times 2.5° \times 39$ produces a mechanism of excitation of zonal velocity oscillations in the equatorial stratosphere, but they are far in period from the real QBOs. On the basis of the arguments outlined above, it can be assumed that, of the two mechanisms of QBO excitation, gravity-wave breaking specified by the Hines parametrization is

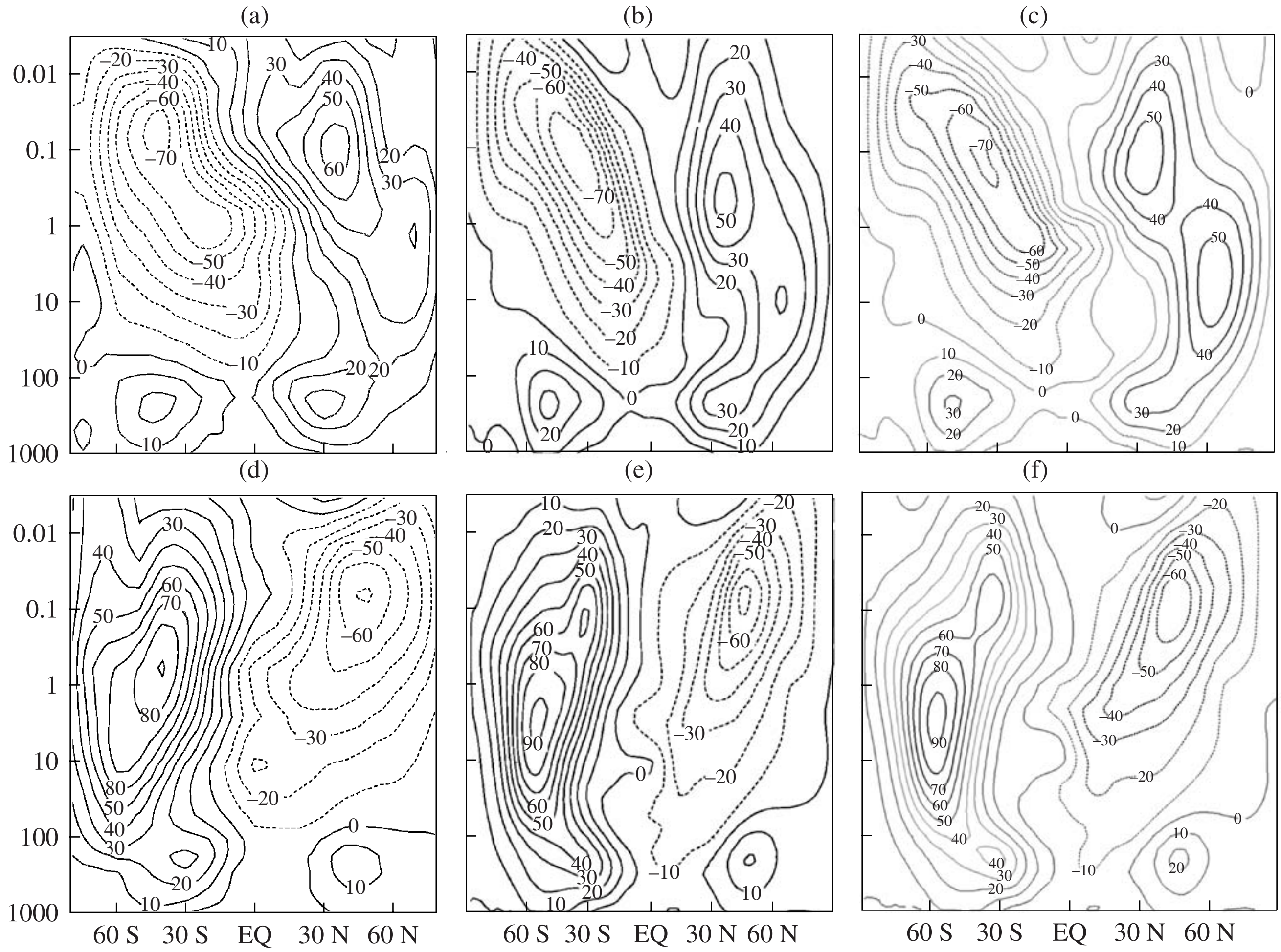

Fig. 2. Zonally averaged zonal wind velocity (m/s) in (a)–(c) January and (d)–(f) July from (a) and (d) observations and (b) and (e) $2° \times 2.5° \times 39$ and (c) and (f) $2° \times 2.5° \times 80$ models.

realized in this model, because the interaction of long waves with the mean flow at critical levels in this version with a coarse vertical resolution is hardly possible; however, for the exact answer to this question, a comprehensive analysis of wave activity in the model is required.

We now consider results of the $2° \times 2.5° \times 80$ model: in Fig. 3b we can see a completely different pattern in the equatorial dynamics of the stratosphere and mesosphere. In the 10–100-mb layer, the annual cycle has a small amplitude, but biennial oscillations with the mean value shifted toward easterly winds are discernible. In fact, the maximum of a positive oscillation phase is a zero velocity, which disagrees with the real values of QBO amplitudes; however, it can be concluded that both mechanisms of the excitation of zonal wind oscillations are realized in this model. With constant adjustments of the Hines parametrization, a quasi-biennial oscillation period has been obtained, which points to an earlier assumed simulation of the interaction between planetary waves and the mean flow.

From the data of the control run for the $2° \times 2.5° \times 80$ model, the quasi-biennial oscillations of zonal velocity were observed in the stratosphere in a latitudinal zone from about 10° S to 10° N, with maximum amplitudes of zonal velocity for both directions being observed at the equator and decreasing rather rapidly toward the mean value as it gets further from the equator. In both hemispheres, starting at the 15° latitude, the biennial cycle is not observed and the mean latitudinal annual cycle of zonal velocity begins to form. These results are entirely consistent with observations and have been obtained for all experiments with the $2° \times 2.5° \times 80$ model, which is evidence of the occurrence of the equatorial trap of the QBO in a narrow region.

Note that, in agreement with observations, a semiannual harmonic is clearly seen in the mesosphere at heights of 1–10 mb in both models. However, the characteristic maxima in the new $2° \times 2.5° \times 80$ version

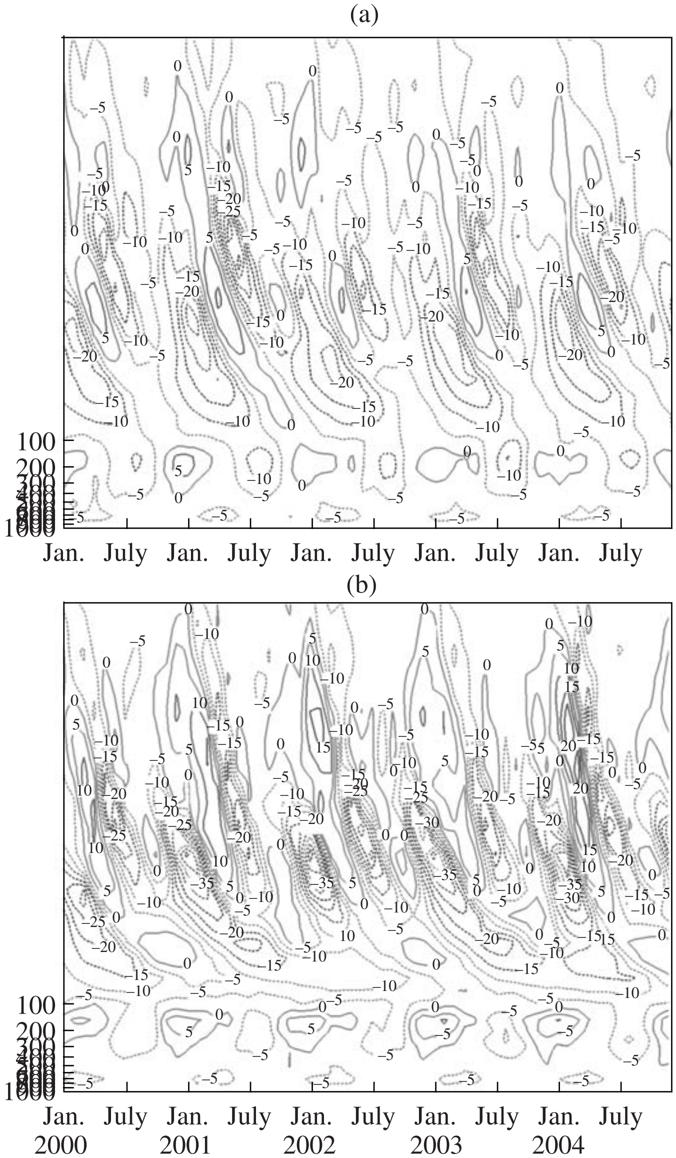

Fig. 3. Mean zonal equatorial wind (m/s) from control experiments for (a) $2° \times 2.5° \times 39$ and (b) $2° \times 2.5° \times 80$ models for five years in the altitude zone from 1000 to 0.003 mb. The contour interval is 5 m/s, and easterly winds (negative direction) are dashed.

are well overestimated relative to the semiannual harmonic in $2° \times 2.5° \times 39$, especially the easterly wind maximum, which is practically absent in the 39-level model. This is particularly clear from a comparison of the annual mean cycle of the equatorial zonal velocity in both models. As can be seen from Fig. 4, a well-pronounced semiannual harmonic in the $2° \times 2.5° \times 80$ version extends through the entire mesosphere and starts at higher levels than weaker semiannual oscillations in the $2° \times 2.5° \times 39$ version. It is these results of the new 80-level model that are most consistent with the actually observed mesospheric and stratospheric semiannual oscillations. Such records can be indicative of both a significant improvement in the simulation of wave dynamics in the entire equatorial atmosphere and the amplification of the energy of waves themselves. This can be judged from a comparison of the annual mean cycle of zonal velocity in the experiments and observations. Both models adequately reproduce the annual cycle of zonal velocity in the troposphere, but they underestimate the dynamics of the tropopause with height. In the new version of the model, the records of the mean velocity have been significantly improved above the tropopause, where an evident annual cycle is absent and the mean zonal velocity is comparable to the observed one, but there is a considerable increase in the winter maximum of easterly winds around the tropopause itself. This is probably the result of enhanced convective processes, which eventually leads to an increased energy of wave perturbations and to the response in the upper layers.

Thus, even from the preliminary data describing the climatology of the INM RAS general circulation models with resolutions $2° \times 2.5° \times 39$ and $2° \times 2.5° \times 80$ in the equatorial atmosphere, it can be concluded that the implementation of the mechanism of the excitation of zonal wind oscillations through short gravity wave breaking (given by the Hines parametrization) is possible in both versions, but the new version, which has good vertical resolution, also simulates the interaction of long waves with the mean flow. This process reflects the internal dynamics of the model, and it is hard to distinguish the process from the control results or to govern it by varying some parameters.

To resolve the problems indicated above, a preliminary spectral analysis of wave processes in the equatorial atmosphere has been performed for different periods of the computation runs from the results of the control experiments with both versions of the INM RAS general circulation models. A comprehensive analysis requires a separate publication; however, preliminary data show that both models simulate the formation of long-period waves traveling eastward in the troposphere (at about 200–100 mb), and the maximum energy is accounted for by a wave with a period of about 20 days and horizontal wave number 1, which corresponds to the observed equatorial Kelvin wave. The wave energy is higher in the 80-level model (amplitude values of the deviation of zonal velocity in this version are on the order of 2.5 m/s, while in the 39-level model they are about 1 m/s). The wave activity in the $2° \times 2.5° \times 80$ model is also higher in general, and there are other waves with lower energies, including those in the east–west direction (a numerical analogue of a Rossby-gravity wave with a period of 5–7 days and amplitude of ~1 m/s). The vertical structure of the wave spectrum leads to the conclusion that the waves are absorbed at some height above 100 mb and are not found in the upper layers, depending on the magnitude of the background mean flow. For a demonstration of the absorption of long-period waves by the mean flow

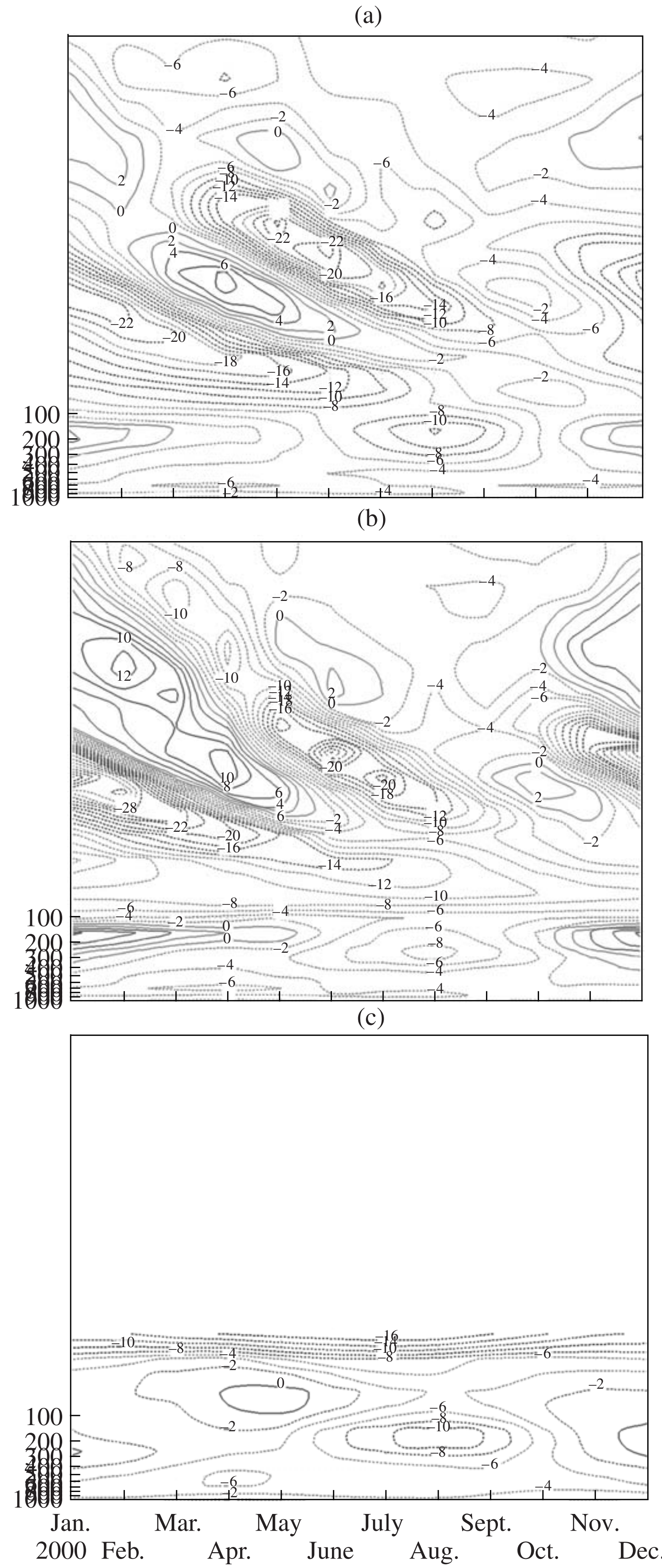

Fig. 4. Annual mean variation of equatorial zonal wind (m/s) from control experiments for (a) 2° × 2.5° × 39 and (b) 2° × 2.5° × 80 models in the altitude zone from 1000 to 0.003 mb and (c) NCEP/NCAR reanalysis data in the altitude zone from 1000 to 10 mb. The contour interval is 2 m/s, and easterly winds (negative direction) are dashed.

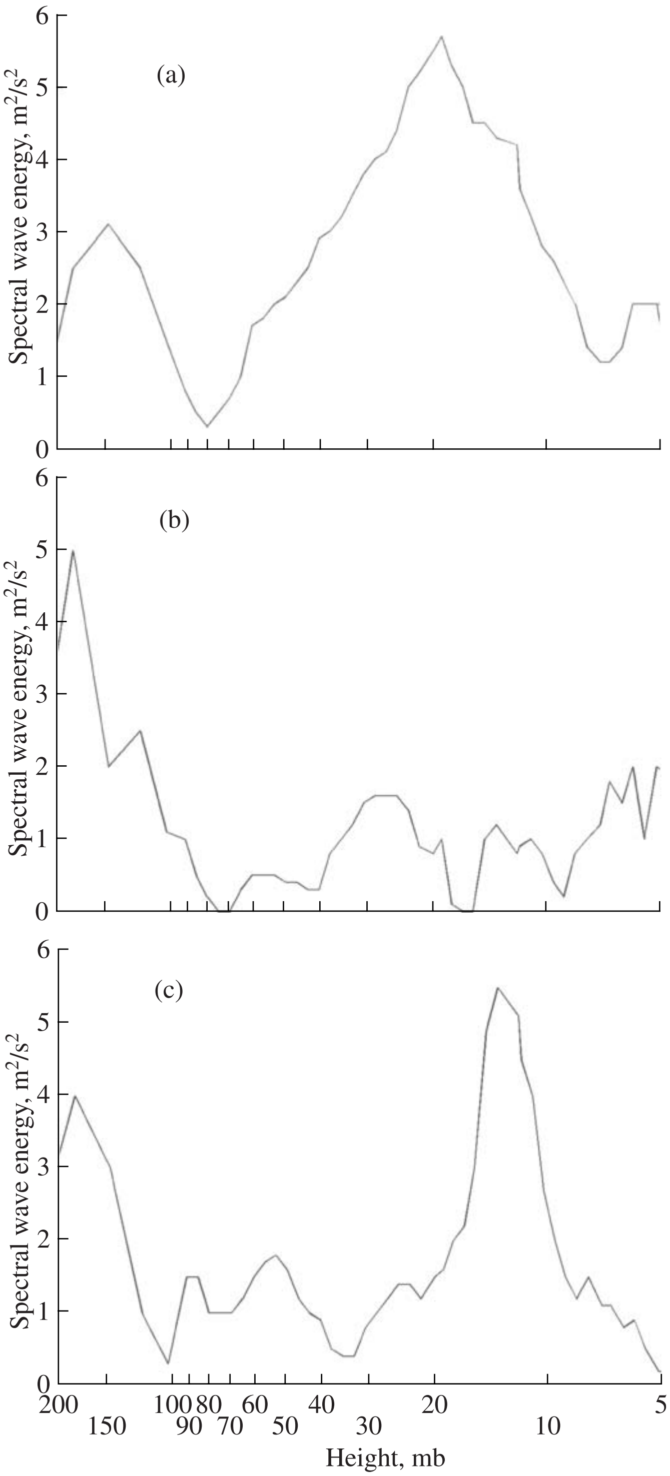

Fig. 5. Vertical distribution of the energy of waves resulting from spectral analysis of the control experiment with the $2° \times 2.5° \times 80$ model: (a) wave in the east direction ($k = 1$, $T \sim 18$–25 days) from data for January–February; (b) wave in the east direction ($k = 1$, $T \sim 15$–20 days) for June–July; and (c) wave in the east–west direction ($k = 1$, $T \sim 12$–18 days) for June–July of the first year of the run.

in the $2° \times 2.5° \times 80$ model, the vertical distribution of spectral energy maxima of the identified waves in the stratospheric region for different periods is plotted in Fig. 5. The panels show the characteristics of clearly defined waves of a particular frequency from the entire spectrum at different heights; if the energy is less than 1 m^2/s^2, the wave is assumed to be no longer observed (the peak is strongly smeared in the spectrum or remains from other waves). Consider the results of spectral analysis of zonal velocity for the first two months (January and February) of the control run with the $2° \times 2.5° \times 80$ model. As can be seen from Fig. 3b, a strong easterly mean flow dominates in the stratospheric region starting at ~80 mb, which changes rapidly to easterly flow in the upper layers. In the easterly background flow, Kelvin waves are observed in the atmosphere, which transfer energy and momentum upward, where they are absorbed at the critical level. Figure 5 shows the height dependence of the energy of a wave from the $2° \times 2.5° \times 80$ model in the west–east direction with horizontal wave number $k = 1$ and a period of 20 days (a model analogue of a Kelvin wave). As is evident from the figure, in the lower layers at the tropopause level, there is some wave activity in this range of frequencies (as well as at other frequencies) which vanishes by the 80-mb level, where a region of strong easterly winds begins. Sources of planetary equatorial waves are located in this zone, because a steady spectral peak corresponding to the Kelvin wave starts from this level with a rather rapidly increasing energy (in response to the density decrease), the maximum of which is observed at the level of the easterly wind maximum. The wave energy reaches values comparable to or even greater than the observed ones. In the upper layers, the energy falls off sharply, particularly from the ~10-mb level, above which a reversal of the direction of the mean flow begins. Such a decrease in energy to a negligible value (the peak is no longer discernible in this region) points to the complete absorption of the wave in a narrow layer and to momentum transfer to the newly formed westerly mean flow. Above this level, the spectral pattern changes abruptly and the previously identifiable wave is no longer observed.

To support these conclusions, we consider results from a spectral analysis of zonal velocity in the control experiment with the $2° \times 2.5° \times 80$ model for June and July of the first year of the run. It is seen from Fig. 3b that the easterly phase of the mean flow in this region dominates in the lower stratosphere from ~200 to ~20 mb; above this, there is a shift toward weak westerly winds (relative to the negative mean zonal velocity in the stratosphere). In this situation, wave activity in the eastern direction must dominate in the lower layers and these waves must be absorbed in the region of the mean flow's reversal. In the zone of westerly winds, there may be westward propagation of waves, which are absorbed at higher levels. Consider the height distribution of the energy of a modeled Kelvin wave with a period of about 20 days and horizontal wave number 1 obtained from spectral analysis for the given interval (Fig. 5b). As is seen from a comparison with Fig. 5a, analogous wave activity is observed in the tropopause region, but long-period westerly waves disappear at 80 mb. From this source region of stratospheric waves, along with the start of the easterly phase of the mean flow, a stable Kelvin wave is observed; however, its energy does not reach large values and decreases sharply to zero at 20 mb. Thus, the Kelvin wave is absorbed at the critical level at a reversal of the mean flow's direction, not propagating above and transferring its energy and momentum to the westerly wind (cf. Fig. 3b). The distribution of the energy of a wave observed in the spectrum in the east–west direction for the same period of observations is shown in Fig. 5c. A sharp spectral peak with high energy is clearly seen in the analysis of waves with wave number 1 and over a period of about 15 days. In the lower stratosphere with the predominance of the easterly mean flow, the waves in this direction are weak, but when the mean wind changes direction, the waves that carry momentum and energy westward have a high energy (at 20 to 10 mb). Above 10 mb, the westward-propagating wave (which could be called a numerical analogue of an oppositely directed Kelvin wave) is absorbed abruptly, and the reversal of the mean wind toward easterlies takes place.

Note that, for this period of investigation, westward wave activity occurs in the region of the mean westerly flow for the horizontal wave number 4 and for a period of about 5 days, which is in full agreement with observed mixed Rossby–gravity waves. The energies of the modeled waves are also comparable to the observed values, but they are somewhat higher than those of observed Kelvin waves.

Such a pattern is not obtained in the $2° \times 2.5° \times 39$ model, where a weak wave spectrum is gradually smoothed in the upper layers. These results are strongly suggestive of the implementation of the interaction between planetary waves with the mean flow and their absorption at critical levels; they also support the conclusion that the 80-level model slightly overestimates wave energy. To obtain a more realistic pattern, additional processing of the factors that determine wave energy (heat convection, etc.) is needed in the model.

Thus, a high-resolution model satisfies the conditions for the implementation of both interaction types; therefore, the combined action of the two QBO generation mechanisms described in Part I takes place in the $2° \times 2.5° \times 80$ version, in agreement with Section 3 of [1]. For the $2° \times 2.5° \times 39$ model, it makes sense to consider the generation of zonal wind oscillations through the interaction of short waves (cf. the results of Section 2 in Part I [1]). Recall that, according to conclusions of Part I, the results of this mechanism are affected by side processes at the equator. From the results produced by both versions of the model, it follows that the annual cycle at the tropopause (at the level of a wave source and above) plays an important role in the equatorial dynamics, with a mean zonal velocity shifted toward negative values. An important role in both general circulation models is also played by horizontal diffusion, which functions as a filter in the horizontal direction and can reduce the activity of short waves. These factors are the main differences in the simulation of equatorial dynamics between three-dimensional models and the low-parameter model.

We have briefly described the INM RAS general circulation models used here and preliminarily determined basic characteristics of the equatorial dynamics resolved in them. We now dwell in more detail on the oscillations of zonal velocity separately for each version in accordance with the conclusions about the implementation of the gravity-wave breaking mechanism in the $2° \times 2.5° \times 39$ model and of both mechanisms of wave–mean flow interaction in the $2° \times 2.5° \times 80$ model.

3. RESULTS OF THE EXPERIMENTS ON THE SIMULATION OF THE QBO IN THE INM RAS 2° × 2.5° × 39 GENERAL CIRCULATION MODEL

From results of the control experiment with the $2° \times 2.5° \times 39$ general circulation model and from analysis of results of the low-parameter models in Part I of [1], we have come to the conclusion that the mechanism of excitation of zonal velocity oscillations through the Hines gravity wave drag parametrization takes place in the equatorial dynamics simulated in this version of the model. At the given stage, the main question is whether it is possible to simulating realistic QBOs in a three-dimensional $2° \times 2.5° \times 39$ atmospheric model. Therefore, the primary goal of numerical experiments with various characteristics of the Hines parametrization is to simulate realistic QBOs generated only by a gravity wave breaking mechanism. This task arises from the fact that a similar result has been achieved in the low-parameter model with the mechanism of the formation of oscillations of zonal velocity in the equatorial stratosphere [1].

A primary strategy in designing experiments with the 39-level model consisted in varying the most significant characteristics of gravity-wave drag. It is necessary to confirm that dynamics of the equatorial stratosphere is indeed determined by the Hines parametrization, and the question remains whether the dependence of characteristics of simulated oscillations in a general circulation model on adjustment parameters remains the same as in the low-parameter model.

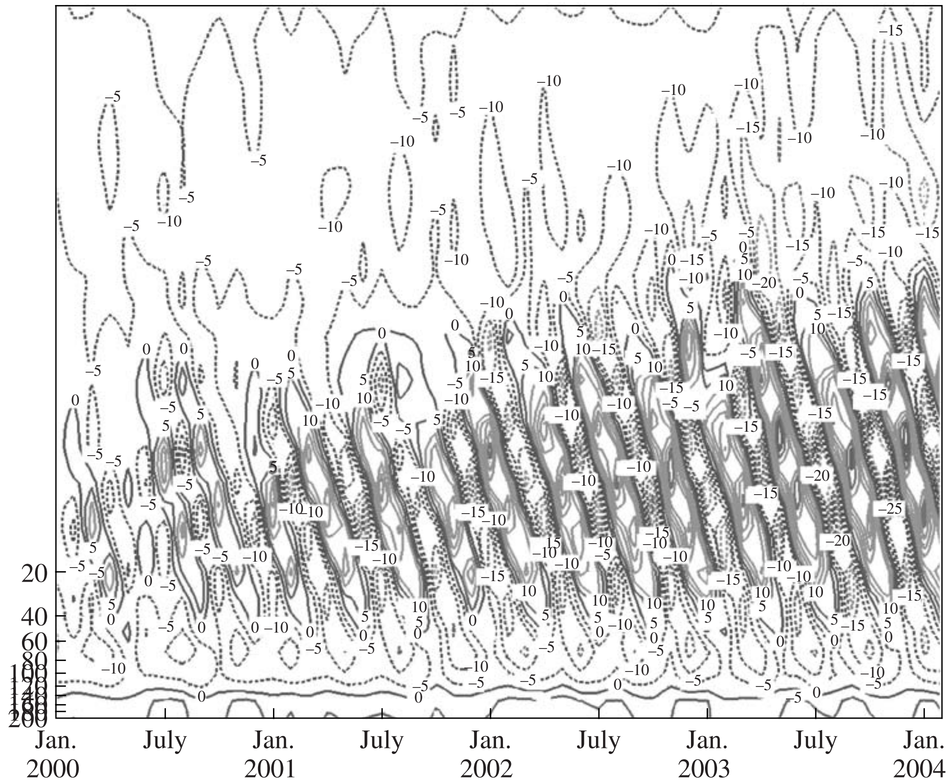

Fig. 6. Mean zonal equatorial wind (m/s) from the experiment with the INM RAS $2° \times 2.5° \times 39$ model for four years in the altitude zone from 200 to 0.003 mb with standard gravity-wave drag parameters and the increased initial rms deviation $\sigma_0^2 = 5$ m^2/s^2. The source level for both experiments is taken at 500 mb.

To answer the questions posed above, a large number of numerical experiments with the INM RAS $2° \times 2.5° \times 39$ general circulation model have been conducted with different values of significant characteristics of the Hines parametrization. As has been shown previously, this version of the model adequately reproduces the midlatitude climate; therefore, only characteristics of gravity-wave drag in a narrow equatorial zone (from 4° S to 4° N) were varied in all experiments. For the rest of the model atmosphere, the basic parameters of gravity-wave drag were identical in all experiments and were set equal to values in the control experiment (see Section 1). The other adjustment parameters of the model were also taken from the control experiment.

Basic results are exemplified by two selected experiments in which parameters of gravity waves were changed. Figure 6 shows the evolution of the zonal wind velocity in the $2° \times 2.5° \times 39$ model with the initial gravity-wave energy (wave energy is actually determined by the rms deviation for a given parametrization [1, 3]) being increased by almost three times relative to the control experiment (see Fig. 3a); the other parameters were taken to be the same as in the control experiment. In the equatorial dynamics in the stratospheric region, strong oscillations with a period of about 3.5 months and high amplitudes of zonal velocity in both directions are dominant, with no cyclicity of wind motions in the mesosphere (earlier, a semiannual harmonic was observed). The time evolution of zonal velocity with slightly smaller initial wave energies and lower horizontal wave numbers relative to the control experiment is shown in Fig. 7 (cf. Fig. 3a). These values of wave parameters are taken close to those with which the low-parameter model produced realistic QBOs of zonal velocity. With a decrease in the initial amplitude and wave number of equatorial gravity waves, downward-propagating oscillations in the $2° \times 2.5° \times 39$ model almost completely disappear in the stratospheric region (100 to 10 mb, where QBOs must exist); a very weak annual cycle with the shift toward easterly winds, which peaks at the stratopause, dominates in the higher layers; and semiannual oscillations are also absent.

For a detailed study of the dependence of the equatorial oscillations simulated in the three-dimensional 39-level model on gravity-wave drag parameters, a number of numerical experiments have been performed by analogy with the low-parameter model experiments [1]. Since the effect of gravity waves on the dynamics of the equatorial atmosphere is sensitive

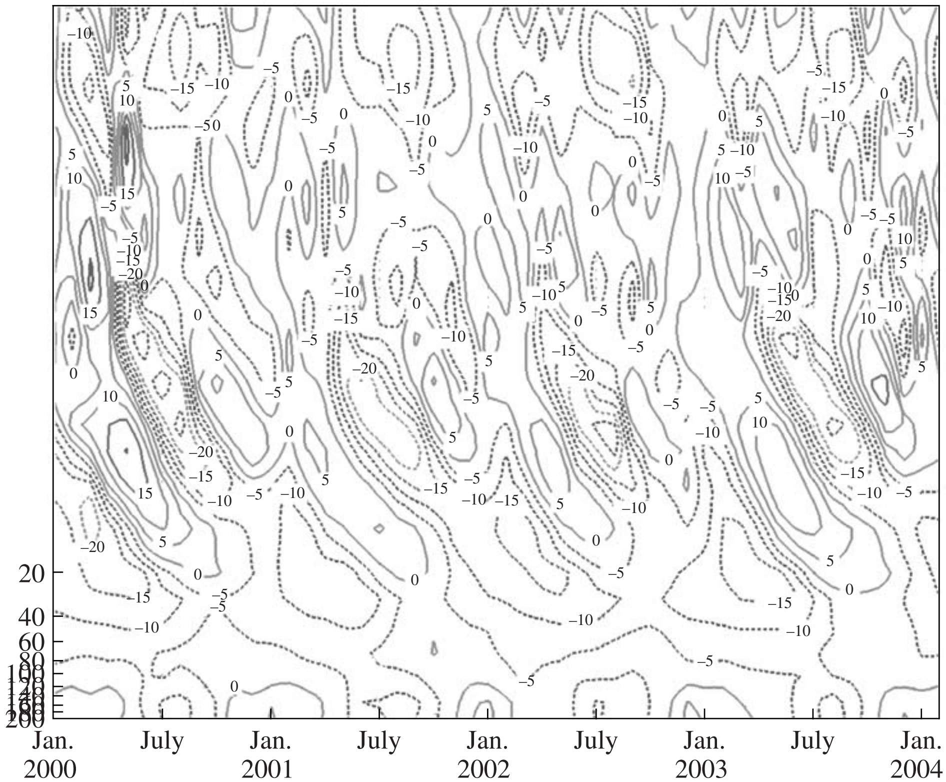

Fig. 7. Mean zonal equatorial wind (m/s) from the experiment with the INM RAS 2° × 2.5° × 39 model for four years in the altitude zone from 200 to 0.003 mb with gravity-wave drag parameters σ_0^2 = 1.5 m^2/s^2, $m_{\min} = 10^{-4}$ m^{-1}, and $h = 1.25 \times 10^{-5}$ m^{-1}. The source level for both experiments was taken at 500 mb. Vertical diffusion and other adjustment parameters were also given by standard values.

to external forcing, this series of experiments have been conducted with no annual solar cycle in the model. Different parameters and adjustments of the 2° × 2.5° × 39 model were chosen in accordance with the control experiment, apart from the gravity-wave drag characteristic being investigated.

From the results of variation in the initial energy of equatorial gravity waves, it is found that a steady periodic solution for the evolution of zonal velocity in the absence of the annual cycle is observed only in a narrow range of values at 3 m^2/s^2 ≤ σ_0^2 ≤ 7 m^2/s^2, which are certainly larger than the actual values. The oscillations have a period from 2 to 6 months, which also depends on the energy value. The dependence between the oscillation period and the wave amplitude in the global model is inverse, as is the dependence in the low-parameter model.

The studies performed here show that the period of the equatorial stratospheric zonal velocity oscillations induced by gravity-wave drag depends weakly on the minimum vertical wave number, which is in some disagreement with the results of a study of this mechanism in a simple model. However, the amplitude of oscillations drops substantially with increasing $m_{\min}$, i.e., when the wave spectrum is narrowed toward shorter waves. Analogous results have been obtained in the experiments with the low-parameter model.

Results of the experiments with a varying horizontal wave number h in the gravity-wave drag parametrization demonstrate the important role of this quantity in the generation of zonal wind oscillations, which is similar in significance to energy characteristics [1]. As the horizontal wave number is increased starting with about $h = 2 \times 10^{-5}$ m^{-1}, steady oscillations of the zonal equatorial wind are established. At small wave numbers, there is a deficiency in the energy of gravity waves, and at large h, the period is reduced, the amplitude increases and the zone of propagation of the oscillations broadens. It should be emphasized that the period varies inversely with this quantity, similarly to the results obtained earlier.

For a three-dimensional model, we also examine how the location of a wave source affects characteristics of the oscillation resulting from gravity waves. Numerical experiments were conducted with different levels of a wave source, while, in the other experiments, a source was placed at the 500-mb level as was indicated above. When the source is located below this level, gravity waves probably break as early as in the upper troposphere; therefore, without any generation of zonal velocity oscillations in the stratosphere, much of their energy is absorbed at low levels and does not alter the dynamics of zonal flow. When the wave source is raised, the main region of the action of gravity-wave drag shifts toward the stratospheric zone, where zonal velocity oscillations derive from the process of wave breaking. Their characteristics remain unchanged when the location of the source is varied in the zone from 500 to 150 mb, the region of their propagation remains constant (approximately from 80 to 10 mb), and the period and the amplitude increase slightly when the source level is raised. When the source is raised to the stratospheric level, oscillations in the layers above it change their character sharply and the main area of gravity-wave drag (where waves transfer much of the energy) shifts upward, but no steady cycle is established.

Previously, in a description of the important processes that affect the equatorial dynamics in general circulation models, particular emphasis has been placed on horizontal and vertical diffusion, which, in addition to having physical meaning, serve as filters to conserve stability in a three-dimensional model. As for horizontal diffusion included in the 39-level model [8], a number of numerical experiments have shown that its value has no large effect on the oscillations driven by gravity-wave drag.

Recall that vertical diffusion in the equatorial upper troposphere and mesosphere is needed for both mechanisms whereby the QBOs are generated. For the low-parameter model, this process was artificially included as a term of the evolution equation, but realistic processes of vertical mixing in three-dimensional general circulation models have a subgrid scale and must be specified by appropriate parametrizations. In the stratosphere and mesosphere, the drag of gravity waves was found to be the main diffusion mechanism. The Hines parametrization provides the possibility of varying the independent statistical coefficient Φ_6 inserted into a parametrization when vertical diffusion is calculated. The technique of computing the coefficient is described comprehensively in [3], and, in this form, it is included in the INM RAS model with a value of $\Phi_6 = 0.25$. Numerical experiments have been performed with the general circulation model by analogy with the previous experiments; from their results, it is possible to trace the dependence of characteristics of the zonal wind oscillation driven by the gravity-wave drag on vertical mixing induced by the same process. When $\Phi_6 > 0.3$, the time variation of zonal wind exhibited no periodic motions. With a decrease in the vertical diffusion coefficient, a fairly abrupt qualitative transition is observed in which equatorial zonal wind oscillations are generated. When the diffusion coefficient is further decreased, the oscillation characteristics vary proportionally, the period increases slightly, and the amplitude grows rapidly. Note that the oscillation of zonal velocity due to gravity-wave breaking is observed with a zero diffusion coefficient as well; this suggests that, in the global model, there are internal diffusion processes that permit the implementation of the QBO excitation mechanism.

We can now formulate the main results of the experiments with the $2° \times 2.5° \times 39$ model: they confirm the key role of gravity-wave breaking in the dynamics of the equatorial stratospheric dynamics, and the characteristics of zonal velocity oscillations retain a qualitative dependence on diffusion that was obtained from the low-parameter model. However, with large parameter variations, the main goal, the simulation of realistic equatorial QBOs, cannot be achieved in this version of the model; i.e., the gravity-wave breaking mechanism does not produce a biennial cycle of the equatorial zonal wind.

4. RESULTS OF EXPERIMENTS ON THE SIMULATION OF THE QBO IN THE INM RAS $2° \times 2.5° \times 80$ GENERAL CIRCULATION MODEL

From the description of the high-resolution $2° \times 2.5° \times 80$ general circulation model that we developed and from spectral analysis for the control experiment, it can be argued at once that one of the key problems, implementing the excitation mechanism of zonal velocity oscillations through the interaction of planetary-scale waves with the mean flow, has been solved. In the control experiment on the simulation of climate in the new $2° \times 2.5° \times 80$ model, oscillations of zonal velocity in the equatorial stratosphere have been obtained with a biennial period but with unrealistic amplitudes deviating toward easterly winds (Fig. 3b). As was shown above, such results, when compared to those from the $2° \times 2.5° \times 39$ model, confirm the implementation of both mechanisms of QBO excitation in the new version. Since fundamentally different oscillations close in period to the realistic ones have been obtained, the problem of simulating realistic QBOs comes to the foreground, because, according to observational data, the amplitudes of zonal velocity vary from ~40 m/s in the east–west direction to ~30 m/s in the east direction, while oscillations in our case are much weaker (from 15 m/s to zero; that is, the zonal wind does not even change its direction).

To obtain higher amplitudes, side processes reducing the interaction of waves with the mean flow are to be taken into account. Summing up the results of the study of both mechanisms of QBO excitation in Part I [1] and the results presented in Section 3 of this work, it may be suggested that vertical diffusion has the largest effect precisely on amplitude characteristics of an oscillatory system in the equatorial stratosphere.

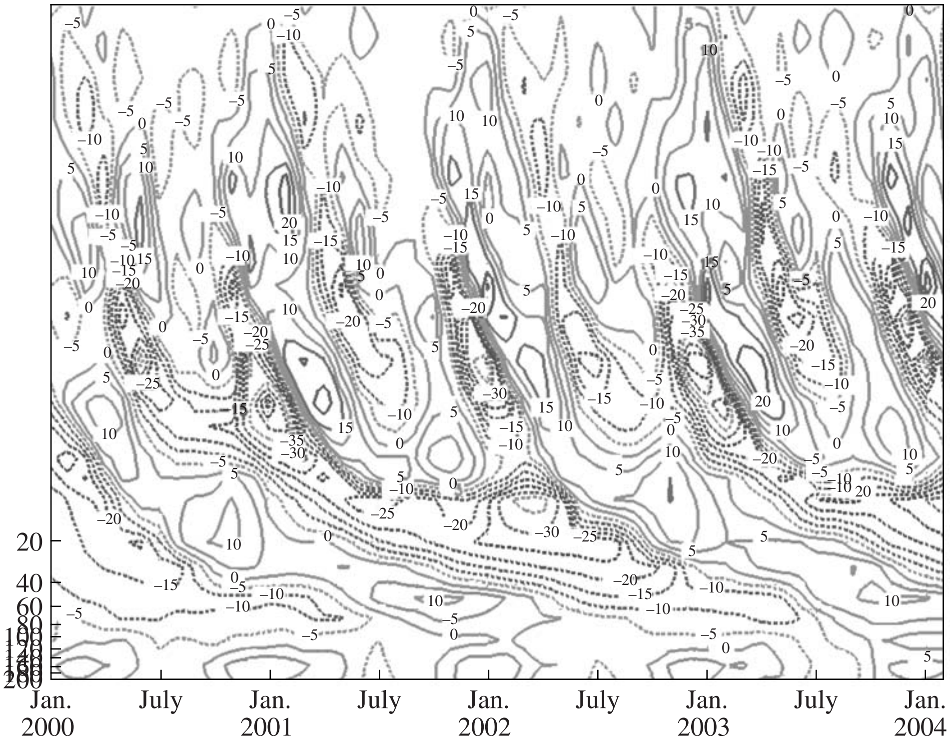

Fig. 8. Mean zonal equatorial wind (m/s) from the experiment with the INM RAS $2° \times 2.5° \times 80$ model for four years in the altitude zone from 200 to 0.003 mb with standard gravity-wave drag parameters and one-fifth of the coefficient of vertical diffusion.

By analogy with the 39-level model study, we conducted a series of numerical experiments with the new $2° \times 2.5° \times 80$ model in which the diffusion coefficient Φ_6 was varied. All experiments with the new version of the model were completely analogous to those described above; only gravity-wave drag characteristics were varied in a narrow equatorial region (from 4° S to 4° N), while the basic parameters for the rest of the model atmosphere were taken to be the same as in the control experiment. The most significant result is presented in Fig. 8, where the evolution of zonal velocity in the 80-level model is shown for $\Phi_6 = 0.05$ in the equatorial atmosphere. The most realistic QBOs are simulated in the stratospheric region with a period of slightly over two years and maximum amplitudes of about 35 m/s for the easterly wind and 15 m/s for the westerly wind. The asymmetry of the two phases of the biennial cycle is simulated with a prevalence of easterly winds, which is very close to the observed pattern. Zones of the amplitude maxima are slightly underestimated relative to observations, but the comparatively lower location of the westerly wind maximum is reproduced as well. The rate of descent of the wind reversal zone also corresponds to the observational data. Importantly, the model retains a realistic semiannual harmonic in the upper stratosphere and mesosphere.

At the same time, many questions about understanding the relative role of large-scale wave dynamics and gravity-wave drag when they are combined in a general circulation model remain. A series of numerical experiments has been performed to study the sensitivity of the oscillations of the equatorial zonal velocity in the $2° \times 2.5° \times 80$ model to the variation of gravity-wave drag parameters by analogy with that described in the previous section, because only these parameters, important for driving the QBO excitation mechanism, can actually be varied in a particular range of values.

In the experiments with various values of the coefficient of vertical diffusion, significant changes were observed in the amplitudes of the simulated oscillations of zonal wind, and their period remained approximately a multiple of half-year. Apart from the biennial oscillations, oscillations with either a period of about 2.5 years or 1.5-year oscillations were produced, while for those with a zero vertical diffusion, the model reproduced oscillations of the equatorial zonal velocity with a 3-year period. Unlike the 39-level model, these experiments were conducted with the annual solar cycle. Similar results were obtained in the experiments with the $2° \times 2.5° \times 80$ model, where the key characteristics of gravity-wave drag were varied: the initial rms deviation σ_0 and the horizontal wave number *h*. When the energy characteristics of gravity waves were increased within real limits, the period of zonal velocity oscillations became 1.5 years first and then 1 year, and amplitudes increased substantially in the upper stratosphere. This logically follows from the enhancement of the role of small-scale waves in the excitation of oscillations. Recall that the $2° \times 2.5° \times 39$ version produced similar results, but with a very small annual cycle whose period could not be increased. Small fluctuations in the period that are a multiple of half-year correspond to variations in the QBO period obtained from observational analysis [12], although these results in the $2° \times 2.5° \times 80$ model are derived for unrealistic values of the parameters. This may point to the presence of resonance with the equatorial annual oscillation and the multiyear variation of the wave characteristics in the equatorial atmosphere.

Of some interest is the result obtained in the experiments with the $2° \times 2.5° \times 80$ model with the shift in the position of a gravity-wave drag source. When the source is located above 100 mb, the gravity-wave drag launches its mechanism in the stratopause region, exciting oscillations with a semiannual harmonic (the $2° \times 2.5° \times 39$ model behaves similarly). However, there are no cycles (either annual or biannual) below 20 mb; that is, independent annual oscillations of the equatorial zonal velocity are very weak and there is no wave activity transferring them from the troposphere, while the mechanism of the interaction of long waves with the mean flow does not work because the zone of critical levels in the lower layers is absent.

To examine properties of the mechanisms of QBO excitation in the absence of side processes in the equatorial dynamics, experiments were conducted on the sensitivity of the oscillations in the 80-level model to parametrization characteristics without the annual solar cycle (for a perpetual January). When the model was adjusted as in the control experiment, the picture was somewhat different (cf. Fig. 3b): biennial and annual oscillations of the equatorial wind in the stratosphere were both nonexistent, and zonal velocity remained almost unchanged with a strong shift toward easterly winds. Weak small-period oscillations dominated in the mesosphere. High-amplitude oscillations of the equatorial zonal velocity in the lower stratosphere were obtained by substantially increasing the energy of gravity waves in the $2° \times 2.5° \times 80$ model with no annual cycle. In this case the sensitivity of the oscillation characteristics to variations in the parameters of gravity-wave drag remained the same as in the low-parameter models in the experiments with the $2° \times 2.5° \times 39$ general circulation model (strong sensitivity with an inverse dependence of the oscillation period on wave characteristics). However, the values of the oscillation period and amplitudes have changed significantly relative to the analogous results of the 39-level model. The period was varied within one or two years (it is important that the quasi-biennial cycle was obtained in the absence of the annual solar cycle), and amplitudes reached unrealistic values of ~80 m/s.

Thus, the new INM RAS $2° \times 2.5° \times 80$ general circulation model made it possible to implement the main mechanisms of the excitation of the QBOs of zonal velocity in the equatorial stratosphere and to obtain a rather realistic pattern for the equatorial dynamics of the atmosphere. Results of numerical experiments with this version of the model presented here help to assess the relative role of each of the mechanisms in this model and to describe their properties.

DISCUSSION OF RESULTS AND CONCLUSIONS

Following the problems of simulating the QBO formulated in the Introduction, we have obtained quite encouraging results. Proceeding from the formulated conditions for implementation of the main mechanisms of QBO excitation, we have constructed a new $2° \times 2.5° \times 80$ version of the INM RAS general circulation model of high vertical resolution on the basis of the 39-level model, which was also used in our study. A satisfactory simulation of the present-day climate by both models is shown, and the possibility of implementing the mechanism of the excitation of oscillations of the equatorial zonal wind through gravity-wave breaking in the 39-level and two mechanisms of QBO oscillation in the $2° \times 2.5° \times 80$ model is demonstrated.

Preliminary spectral analysis of wave activity in the equatorial stratosphere has been performed. From the data of this analysis, it may be concluded that the mechanism of the interaction of equatorial planetary waves with the mean flow at critical levels is possible in the $2° \times 2.5° \times 80$ version of the model; this mechanism is not simulated in the low-resolution $2° \times 2.5° \times 39$ model, the wave energy being substantially less.

The excitation mechanism of zonal wind oscillations has been studied in detail for the $2° \times 2.5° \times 39$ model. The results have shown that oscillations in the 39-level model in the equatorial stratosphere are entirely induced by the Hines nonorographic gravity-wave drag parametrization. This confirms that the excitation mechanism of zonal velocity oscillations by small-scale wave breaking works in this version. Characteristics of the oscillations generated by this mechanism in a three-dimensional model have been studied and compared to the results of the low-parameter model. The inverse dependence between the period of simulated oscillations and the rms deviation derived in Part I [1] also remained in the general circulation model. Importantly, the general circulation model with a high wave energy accurately simulates the result of simulating oscillations in a simple model; however, when the wave activity is low, the influence of side processes is observed. It is concluded that zonal velocity oscillations driven by gravity-wave breaking are very sensitive to adjustments of the wave-forcing parametrization itself, as well as to other processes that exist in the modeled equatorial dynamics of the atmosphere. When the wave activity is reduced, the mechanism of oscillation generation by gravity-wave drag does not supply sufficient momentum to zonal flow and becomes comparable in scale to other equatorial processes. In the given case, the synchronization of the annual cycle and of the effect of gravity waves on the zonal flow may occur when wave energy is redistributed.

An important result of the $2° \times 2.5° \times 39$ model study is the understanding of the significant role played by vertical diffusion in the implementation of the QBO generation mechanisms in the general circulation models.

In the new $2° \times 2.5° \times 80$ version of the general circulation model, it has become possible to reproduce the QBOs of the equatorial zonal velocity that are very close to observations. This is a key finding of the study. The result obtained here is close to that derived in the model described in Section 3 of Part I [1], in which the combined action of both mechanisms is simulated and oscillations generated by waves of different scale are considered. The results of both parts of the study for the models with the two mechanisms of QBO excitation demonstrate that gravity-wave breaking plays a secondary role in the formation of the typical period of the oscillation of the equatorial zonal wind with reasonable parameter values and comes to the foreground only when the energies of small-scale wave activity are large in relation to planetary-scale waves. In this case, the interaction of long waves with the mean flow generates oscillations in the zone located closer to a wave source, i.e., in the lower layers of the stratosphere. This result agrees with those obtained in present-day atmospheric general circulation models that simulate the QBOs [13, 14]. The QBOs in the model of [14] are close to observations, but the amplitude of oscillations at ~100 mb is insufficient and the asymmetry of the easterly and westerly phases of zonal wind is weak. We have not conducted a comprehensive quantitative analysis of wave interaction with the mean flow; however, numerical experiments with the $2° \times 2.5° \times 80$ model produce realistic asymmetric high-amplitude QBOs of the easterly and westerly flow in the lower stratosphere. Furthermore, on the basis of studying the sensitivity of characteristics of the QBO to model parameters, the parameters have been determined through which the equatorial profile of zonal wind can be varied in the model.

Our studies of the basic properties of the mechanisms driving the oscillations in the 80-level model highlight the special role that synchronization plays in the generation of the QBOs, which actually involves three processes: weak annual and even weaker semiannual oscillations of the equatorial zonal velocity in the atmosphere, the generation of oscillations by gravity-wave breaking, and the generation of oscillations by the interaction of planetary waves with the mean flow. This problem calls for a special study, and we have only attempted to emphasize the important role of the annual cycle, without which the equatorial dynamics of the atmosphere cannot be considered.

On the basis of the results presented here and their discussion, several challenging problems for future research can be pointed out at once. First, one important practical task is the further development of the atmospheric general circulation model, with emphasis on the influence of quasi-biennial oscillations on the dynamics of the atmosphere in general. Second, in order to understand all of the processes that take part in the formation of the QBOs, it is necessary to study the relative role of wave activity on different scales in the equatorial dynamics and phenomena of periodic-process synchronization and to consider possible resonances in the circulation of the equatorial stratosphere.

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REFERENCES

1. D. V. Kulyamin, E. M. Volodin, and V. P. Dymnikov, "Simulation of the Quasi-Biennial Oscillations of the Zonal Wind in the Equatorial Stratosphere: Part I. Low-Parameter Models," Izv. Akad. Nauk, Fiz. Atmos. Okeana **44**, 5–20 (2008) [Izv., Atmos. Ocean. Phys. **44**, 3–17 (2008)].
2. R. A. Plumb, "The Interaction of Two Internal Waves with the Mean Flow: Implications for the Theory of the Quasi-Biennial Oscillation," J. Atmos. Sci. **34**, 1847–1858 (1977).
3. C. O. Hines, "Doppler Spread Parameterization of Gravity Wave Momentum Deposition in the Middle Atmosphere: Part 1. Basic Formulation," J. Atmos. Terr. Phys. **59**, 371–386 (1997).
4. C. O. Hines, "Doppler-Spread Parameterization of Gravity Wave Momentum Deposition in the Middle Atmosphere: Part 2. Broad and Quasi-Monochromatic Spectra, and Implementation," J. Atmos. Terr. Phys. **59**, 387–400 (1997).
5. L. J. Campbell and T. G. Shepherd, "Constraints on Wave Drag Parameterization Schemes for Simulating the Quasi-Biennial Oscillation. Part I: Gravity Wave Forcing," J. Atmos. Sci. **62**, 4178–4195 (2005).
6. L. J. Campbell and T. G. Shepherd, "Constraints on Wave Drag Parameterization Schemes for Simulating the Quasi-Biennial Oscillation. Part II: Combined

Effects of Gravity Waves and Equatorial Planetary Waves," J. Atmos. Sci. **62**, 4196–4205 (2005).

7. V. A. Alekseev, E. M. Volodin, V. Ya. Galin, et al., *Modeling Present-Day Climate with the INM RAS Atmospheric Model* (IVM RAN, Moscow, 1998) [in Russian].
8. E. M. Volodin and G. Schmitz, "A Troposphere–Stratosphere–Mesosphere General Circulation Model with Parameterization of Gravity Waves: Climatology and Sensitivity Studies," Tellus A **53**, 300–316 (2001).
9. T. N. Palmer, G. J. Shutts, and R. Swinbank, "Alleviation of a Systematic Westerly Bias in General Circulation and Numerical Weather Prediction Models through an Orographic Gravity Wave Drag Parameterization," Q. J. R. Meteorol. Soc. **112** (474), 1001–1031 (1986).
10. E. L. Fleming, S. Chandra, J. J. Barnett, and M. Corney, "Zonal Mean Temperature, Pressure, Zonal Wind and Geopotential Height As Functions of Latitude," Adv. Space Res. **10**, 1211–1259 (1990).
11. R. Kistler, et al., "The NCEP/NCAR 50-Year Reanalysis: Monthly Means CD-ROM and Documentation," Bull. Am. Meteorol. Soc. **82**, 247–266 (2001).
12. A. N. Gruzdev and V. A. Bezverkhnii, "Long-Term Variations in the Quasi-Biennial Oscillation of the Equatorial Stratospheric Wind," Izv. Akad. Nauk, Fiz. Atmos. Okeana **35**, 773–785 (1999) [Izv., Atmos. Ocean. Phys. **35**, 700–711 (1999)].
13. A. A. Scaife, et al., "Realistic Quasi-Biennial Oscillations in a Simulation of the Global Climate," Geophys. Rev. Lett. **27**, 3481–3484 (2000).
14. M. A. Giorgetta, et al., "Climatology and Forcing of the Quasi-Biennial Oscillation in the MAECHAM5 Model," J. Clim. **19**, 3882–3901 (2006).