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IMPROVED COMPUTING PERFORMANCE AND LOAD BALANCING OF ATMOSPHERIC GENERAL CIRCULATION MODEL*

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Tóm tắt. Trạng thái hiện nay của Trái đất là chưa từng có trong lịch sử, khi mà sự phát thải khí gây hiệu ứng nhà kính có thể làm tăng nhiệt độ không khí trung bình toàn cầu lên rất cao so với việc tăng nhiệt độ tự nhiên cũng không ít hơn vài thiên niên kỷ. Chính vì vậy, để nghiên cứu một cách cơ bản của vấn đề này cần có những mô hình toán học phù hợp. Các mô hình tính toán biến đổi khí hậu của Trung tâm Tính toán, Viện Hàn lâm Khoa học Nga cũng tỏ ra khá hiệu quả như mô hình hoàn lưu tổng quát của khí quyển, mô hình đại dương,... Tuy nhiên, trong những mô hình này vẫn còn một số chưa hoàn chỉnh. Bài viết này nhằm mục tiêu cải tiến thuật toán song song dùng cho mô hình hoàn lưu tổng quát của khí quyển (AGCM) để nâng cao hiệu năng tính toán. Đặc biệt là việc khai thác cân bằng tải khi số nút tính toán lớn, nguồn tài nguyên tính toán không đồng nhất. Sự cải tiến thể hiện qua việc khai thác đồng thời 2 nhóm bộ xử lý, tương ứng với hai khối physics và dynamics trên cùng dữ liệu. Kết quả cũng được thử nghiệm trên những số liệu thực nghiệm đo đạt được cho thấy sự hơn hẵn của thuật toán cải tiến.

Từ khóa. Thuật toán song song, cân bằng tải, biến đổi khí hậu, mô hình toán học.

Abstract. The current situation is unprecedented in the history of the Earth, as emissions of greenhouse gases could increase the mean global air temperature over several decades, while the natural temperature increasing by the same amount will take no less than several millennia. Therefore, To carry out basic research on this problem we must study the appropriate mathematical models. The climate model of the Computing Center, Russian Academy of Sciences also proved quite effective as general circulation models of the atmosphere, ocean model, etc. However, these models still contains some complete issues. The purpose of this paper is to modify the parallel algorithm used in general circulation models of the atmosphere (AGCM); thereby improve computing performance. Especially the exploitation of load balancing in case there are many compute nodes and the computing resources are heterogeneous. The improvement shown by the concurrent exploitation of two processor groups are corresponding to two blocks of physics and dynamics on the same data. The results are also tested on the experimental data, and hence show the effectiveness of the improved algorithm.

Keyworks. Parallel algorithm, load balancing, climate change, model.

1. INTRODUCTION

The climate is one of the major natural resources, which determine the impact to the

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economy, agriculture, energy, water, etc. The results of research in climate with increasing confidence suggest that human activity – an important climatic factor and the consequences of anthropogenic impact on the climate system over the coming decades could be catastrophic. Much uncertainty remains with respect to details of such changes, especially the regional scale. In addition, the extremely adverse socio-economic impacts of regional and even global character can be caused by natural climatic variations.

The scientific basis for developing a system of measures to limit the negative impact of economic activity on the environment, saving energy and resources, restructuring the economy and adapt to new natural and climatic conditions is needed. This basis can be developed only with joint study of global environmental changes and climate. It will give the ability of the transition to sustainable development [1].

General circulation models are the most complex climate models [2]. In the full version to study the greenhouse effect, they must include the atmosphere and ocean models. In addition, models are needed to describe the evolution of sea ice, as well as the various land surface processes, such as formation and changes in snow cover, soil moisture and evapotranspiration.

The structure of the observed climate change is more complex than the changes produced in the climate models. In some areas, changes in the individual seasons are opposite of simulation results, indicating the important role of different climatic factors or models imperfection. Numerical experiments with Atmospheric General Circulation Models (AGCM) give satisfactorily global results, but differ significantly at the regional level.

Outline The remainder of this article is organized as follows. Section 2 gives overview about observation and modeling of climate change. The structure and performance of AGCM parallel codes are described in Section 3. Our new and exciting results - modification of the original model parallel code to improve its computational efficiency and load balance of processors - are described in Section 4. The Section 5 gives some of experimental results. Finally, Section 6 gives the conclusions.

2. CLIMATE CHANGE: OBSERVATION AND MODELING

A number of difficulties and uncertainties arise in predicting the atmosphere temperature by AGCM depending on the concentration of CO_2. They are related to the fact that man-induced warming will take place against the backdrop of the natural effects of climate warming and cooling, comparable in intensity to the greenhouse effect. It is needed to be able accurately simulate the natural changes in climate for an accurate calculation of anthropogenic changes. In this case there are two main problems: an adequate description of the oceans and clouds.

The ocean currents have a great influence on the magnitude of the greenhouse effect. The inclusion of this effect in the calculation leads to a weakening of the greenhouse effect. Simulation of clouds in climate models is faced with great difficulties, because the natural cooling effect of clouds is ten times greater than the total anthropogenic warming predicted in this century. Warming effect of clouds (the natural greenhouse effect) is also significantly larger than anthropogenic. This means that small changes in the types and amount of clouds can either reduce the greenhouse effect (in case of increase in special types cloud cover) or increase (in case of reduction), depending on whether negative or positive feedback. But small changes in cloud cover are very difficult to model correctly and, therefore, to predict which way it will change.

When we consider the greenhouse effect, it is very important to be able to predict not only the global trends, but also regional climate changes, say, in the European part of Russia or in Indochina. These regional changes may differ significantly from the global climate trends. For example, an analysis of temperature observations over the past 20 years shows that the climate is generally warmer, but it is colder in England and Western Europe.

The ongoing Fourth Assessment process of the IPCC includes a draft review of the most recent regional climate projections for the South East Asian Region and a few results of these are given here. These regional climate projections are based on the IPCC A1B emission scenario and assess the change in the climate of South East Asia in the period 2079-2098 compared with that of 1979-1998 to be as follows [3]:

The regional models have predicted between 1.5^0C and 3.7^0C temperature increase with little seasonal variation. Precipitation projections have varied considerable across different models. The average result of the models is a 6% increase in annual precipitation with a variation between -3% and 15%. It is predicted that there can be very large variations in precipitation change within the region as well as within different parts of Indochina.

Computers power increase is one of the most important requirements for more reliable climate predictions [3]. Increasing the number of climate observations in the atmosphere and ocean, the organization of continuous monitoring of the factors that cause climate change, such as the concentration of greenhouse gases, solar constant, the degree of transparency of the atmosphere associated with volcanic eruptions and other natural and anthropogenic effects are equally important need [4]. Ocean observations are particularly important because knowledge of them is much poorer than that of the atmosphere. More complete data on the variations of temperature, salinity, currents, depending on the depth of the ocean are needed.

Another important point - the full-scale observations of moisture convection processes in the atmosphere that determine the number and types of clouds. These small-scale processes in the atmosphere, along with the microphysics of clouds, remain poorly understood at present.

An adequate description of the interaction between the atmosphere and the surface is another challenge in modeling of climate and climate change. In particular, it is important to have the description of the filtering processes of soil moisture, evaporation from the surface in the presence of vegetation of any kind.

The ocean is a complex dynamic system, but with much poorer observations than the atmosphere. Sea surface temperature is determined by the balance between the intensity of surface heating and a variety of dynamic processes in which there is a redistribution of heat energy. The main ones are - it's small-scale turbulent mixing in the vertical and horizontal large-scale energy transport by sea currents. There are still no ocean general circulation models with sufficient spatial resolution to be able to describe the energy-containing eddy. Parameterization of subgrid processes using semi-empirical theory of turbulent diffusion exists even in more complex models that have strong influences to the results.

3. THE STRUCTURE AND PERFORMANCE OF AGCM PARALLEL CODE

The climate model of the Computing Center of RAS [5] includes an atmospheric unit, based on the AGCM with parameterization of a number of subgrid processes, and ocean model, which is an integral model of the active layer of the ocean with a given field and the geostrophic model of the evolution of sea ice [8]. Model version with a finer spatial resolution and ocean general circulation model is developed. The interaction between the blocks is carried out online. The atmospheric model describes the troposphere, below the expected level of isobaric tropopause.

The present model is constructed in the vertical using the σ - coordinate system [2]:

$$\sigma = \frac{p - p_T}{p_s - p_T} \tag{3.1}$$

where p – pressure, p_T – the constant pressure at the top of the model atmosphere, p_s – the variable surface pressure. The horizontal momentum equation in vector form is

$$\frac{\partial}{\partial t}(\pi V) + (\nabla.\pi V) + \frac{\partial}{\partial \sigma}(\pi V \dot{\sigma}) + fk \times \pi V + \pi \nabla \Phi + \sigma \pi \alpha \nabla \pi = \pi F \tag{3.2}$$

where

$$\nabla.A = \frac{1}{acos\varphi} + [\frac{\partial A}{\partial \lambda} + \frac{\partial}{\partial \varphi}(Acos\varphi)]$$

For vector with two components $A = (A_\lambda, A_\varphi)^T$, where λ – longitude and φ – latitude of the point. Here V - horizontal velocity vector, $\pi = p_s - p_T$, $\dot{\sigma} = d\sigma/dt$, f – Coriolis parameter, k – vertical unit vector, Φ – geopotential, α – specific volume, F – horizontal frictional force vector per unit mass.

The thermodynamic energy equation can be written in the form

$$\frac{\partial}{\partial t}(\pi c_p T) + \nabla.(\pi c_p T V) + \frac{\partial}{\partial \sigma}(\pi c_p T \dot{\sigma}) - \pi \alpha \sigma (\frac{\partial \pi}{\partial t} + V.\nabla \pi) = \pi \dot{H} \tag{3.3}$$

where c_p - specific heat for dry air, T – air temperature, $\dot{H}$ - air diabatic heating rate per unit mass. The mass continuity equation and the moisture continuity equation are given by

$$\frac{\partial \pi}{\partial t} + \nabla.(\pi V) + \frac{\partial}{\partial \sigma}(\pi \dot{\sigma}) = 0 \tag{3.4}$$

$$\frac{\partial}{\partial t}(\pi q) + \nabla.(\pi q V) + \frac{\partial}{\partial \sigma}(\pi q \dot{\sigma}) = \pi \dot{Q} \tag{3.5}$$

where q – water vapor mixing ratio, $\dot{Q}$ - rate of moisture addition per unit mass.

Equations (3.2) – (3.5) are the four prognostic equations for the dependent variables V, T, π and q. With the addition of the diagnostic equations of state

$$\alpha = RT/p \tag{3.6}$$

where R – specific gas constant for dry air and hydrostatic balance:

$$\frac{\partial \Phi}{\partial \sigma} + \pi \alpha = 0 \tag{3.7}$$

Table 1. Run time distribution (%) of the model blocks

$Number of processors$	$Dynamics block, \%$	$Dynamics block, \%$
1	63	33
8	67	30
16	70	27

and appropriate boundary conditions, the dynamical system in σ - coordinates is complete.

AGCM is the software package which simulates many physical processes [1]. There are two major program components: AGCM Dynamics block, which calculates the fluid flow described by the primitive equations (3.2) – (3.7) by finite differences, and AGCM Physics block which computes the effect of processes not resolved by the model's grid (such as solar and heat radiative fluxes, internal sub-grid scale adiabatic processes, moist and convection processes). The results obtained by AGCM Physics are supplied to AGCM Dynamics as forcing (members F, $\dot{H}$ and $\dot{Q}$) for the flow and thermodynamics calculations . The AGCM code uses a three dimensional staggered grid for velocity and thermodynamic variables (temperature, pressure, water vapor mixing ratio, etc.).

This three-dimensional grid is a C-grid of Arakawa [2] in the horizontal (latitude - longitude) direction with a relatively small number of vertical layers (usually much less than the number of horizontal grid points). The AGCM Dynamics itself consists of two main components: a spectral filtering part and the actual finite difference calculations. The filtering operation is needed at each time step in regions close to the poles to ensure the effective grid size there satisfies the stability requirement for explicit time difference schemes when a fixed time step is used throughout the entire spherical finite-difference grid [5].

Processors domain decomposition in the two-dimensional horizontal plane grid is used in a parallel implementation of the model. This choice is based on the fact that vertical physical processes strongly link grid points and that the number of grid points in the vertical direction is usually small. That makes parallelization less efficient in the vertical direction. Each subdomain of this grid is a rectangular area that contains all points of the grid in the vertical direction. Two types of interprocessor communications are mainly in this case [5]. Data exchanges are needed between logically adjacent processors (nodes) in the calculation of finite differences and remote data exchanges are needed, in particular, to carry out the operation of spectral filtering. The main blocks program running time elapse of the original parallel AGCM program realization, using $4^0 \times 5^0 \times 9$ levels resolution that contains $46 \times 72 \times 9$ points is shown in Table 1.

The cluster MVS-6000IM (256 CPU) (64-bit processors Intel ® Itanium-2 ® 1.6 GHz, with bi-directional exchange of data between two computers via MPI, bandwidth 450 - 500 Mbit/sec) was used for running. Computational modules are interconnected high-speed communications network Myrinet (bandwidth 2 Gbit/sec), the Gigabit Ethernet transport network and Fast Ethernet control network. Myrinet communication network is designed for high-speed exchange between computational modules in the calculations. The program was implemented also on the CCAS server with shared memory (2 CPU, 4 core, based on Intel Xeon DP 5160, the frequency of 3 GHz, 4 GB of RAM). The same measurements were carried out for 1, 2 and 4 processes.

As it can be from Table 1, Dynamics block and Physics block take most of the run time, with the exclusion of input - output procedures. These procedures are performed only once, whereas the main part is repeated over time and dominated the run-time cost. Comparing these two blocks, we can see that the dynamic part takes most of the run time, especially when a large number of nodes is used. The ratio of the data exchanges time to computing time and the degree of processor load imbalance in the program affects the scalability of the parallel program. The results of the time estimates analysis show that the spectral procedures time is an appreciable part of the AGCM parallel program, especially when the number of nodes is large.

4. MODIFICATION OF THE ORIGINAL MODEL

The modification of original model impoves its computational efficiency and load balance of processors. As noted before, the two main components can be identified in the AGCM: a Dynamics block and Physics block (sources block). The results obtained in the Physics block are used in a Dynamics block as external sources for the flow calculation.

Prognostic equations (3.2) – (3.5) for the basic unknown functions (horizontal velocity components V, temperature T, water vapor mixing ratio q, variable $\pi = p_s - p_T$, that determines surface pressure p_s) can be written at the point (i, j) of the horizontal finite-difference grid in the form:

$$\left.\frac{\partial \psi}{\partial t}\right|_i = D(\psi) + S(\psi)$$

where ψ - any one of the basic functions.

Here as $S(\psi)$ are designated "sources" (as defined in the Physics block), which include the friction force F in the momentum equations (3.2), diabatic heating $\dot{H}$ in the energy equation (3.3) and the sources of moisture $\dot{Q}$ in the water vapor transport equation (3.5). These members are local, i.e. they do not contain horizontal space derivatives. All the rest ("dynamic") equations members are included in $D(\psi)$ and contain horizontal derivatives.

The physical processes splitting method is used to solve the prognostic equations in the original scalar version of the program. This is an explicit method for time integrating at which you make a six time steps with a step Δt_D, taking into account only the effect of dynamic members with different approximations of spatial derivatives, and then one step $\Delta t = 6t_D$, taking into account only sources (Physics block).

Thus, conceptually the original scheme of time integration is as follows:

Stage I: $\psi_D^1 = \psi^0 + \Delta t D(\psi^0)$

Stage II: $\psi^1 = \psi_S^1 + \Delta t S(\psi_D^1)$

where ψ^0 - the value of ψ at time t, ψ_D^1 - at the moment $t + \Delta t$ after calculating the dynamic members, $\psi^1 = \psi_S^1$ - the final value of ψ (after calculating the sources forcing) at the time $t + \Delta t$. The set of stages I and II provides an approximation of the equations.

The proposed parallelization method involves the simultaneous calculation of the physics and dynamics, respectively, on two groups of processors. Implementation of the method requires a change in the numerical time integration scheme. It consists in the simultaneous

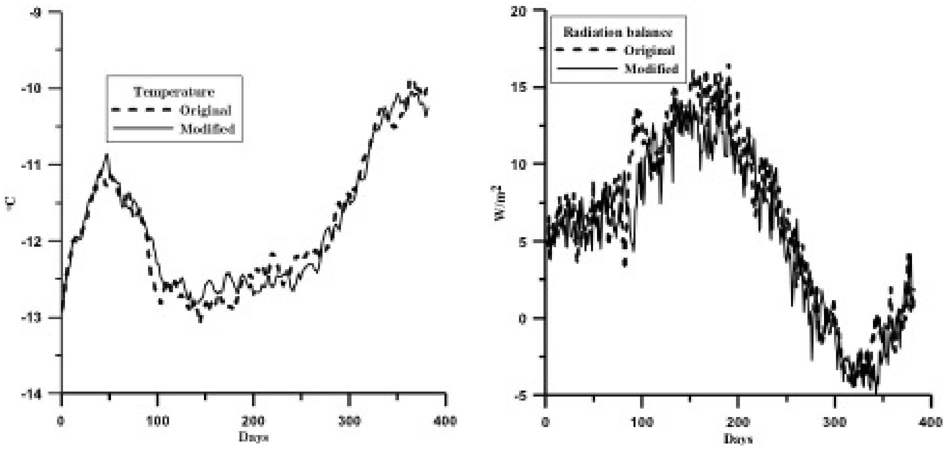

Figure 4.1. The global mean temperature (left) and the radiation balance (right) at the top of the atmosphere depending on the time for the original and modified schemes

calculation of the dynamics and physics in different groups of processors from the same input data. Thus, the modified scheme of calculation is as follows:

- Group I of processors: $\psi_D = \psi^0 + \Delta t D(\psi^0)$
- Group II of processors: $\psi_S = \psi^0 + \Delta t S(\psi^0)$

At the end of cycles, we obtain the values of basic variables ψ_D in the first group of processors at the next time step and ψ_S in the second group of processors at the next time step. After this, the processors exchange data on each of the groups of processors according to the formula

$$\psi^1 = \psi_D + \psi_S - \psi^0$$

It gives final values of the unknown functions at the time $t + \Delta t$. It is easy to see that this equations approximation is achieved, but it is clear that the results of the original and modified schemes will be different. It is used ψ_D^1 in the first method, and ψ^0 - in the second for sources calculations (Physics block). Difference has second order of Δt.

5. EXPERIMENTAL RESULTS

MPI library is used as a means of parallelization implementing. Currently, MPI is the most common means of parallelization; that allows for the portability of the program [8]. The original program was modified in accordance with the above considerations. Model calculations were carried out to verify the correctness of the method: the modified and original versions of software. They started from identical initial conditions.

Some comparison results are shown in the figures below. Mean air temperature and radiation balance at the top of the atmosphere depending on the time are shown for the original and modified methods in Figure 4.1. These day and globe mean values demonstrate a good agreement between the results, taking into account the strong variability of the atmosphere over a short interval of one day.

The graphs of the zonal components of velocity and air temperature depending on the latitude, averaged over longitude for July and January are shown in Firgure 5.2. The analysis shows very good temperature agreement for both seasons; winds have differences in winter in areas of strong gradients.

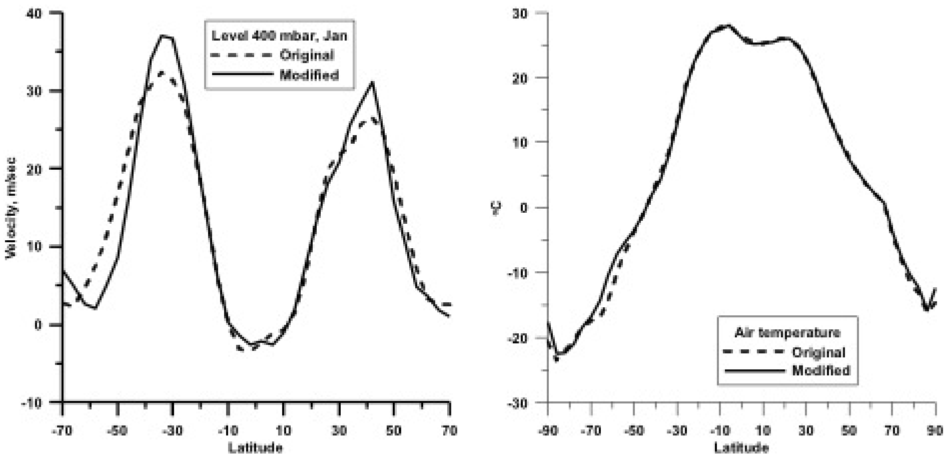

Figure 5.2. Zonal means of zonal velocity component (left) surface and air temperature (right) for January

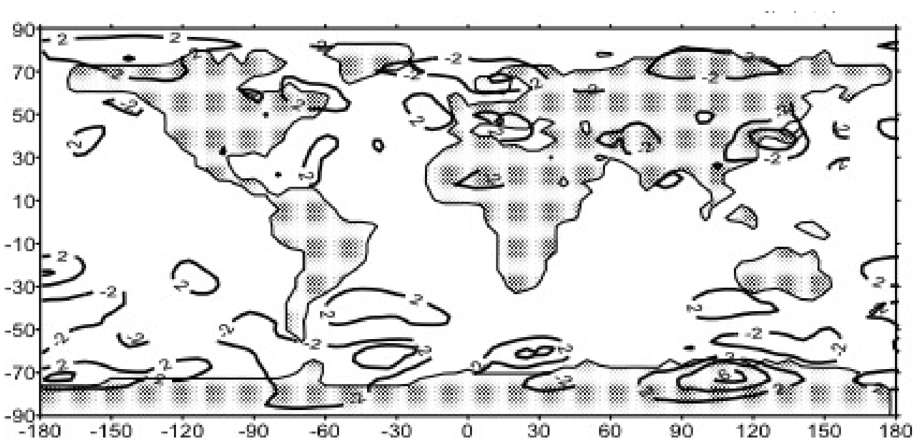

Figure 5.3. Isolines of air temperature differences at 400 mbar, calculated from the original and modified schemes, July

We note a general feature of the main climatic characteristics distributions, calculated for the original and modified schemes - the greatest differences of the results are observed in middle and high latitudes in winter. This is due, apparently, with precipitation in the form of snow, and intense time-dependent convective processes in the atmosphere. Differences in surface temperature in more than 90% of the cells are less than 2^0C. The difference is 10^0C in only two cells for winter in the Northern Hemisphere over the continent. A similar pattern is observed in the Southern Hemisphere for the winter: there are noticeable differences in the three cells in the Antarctic.

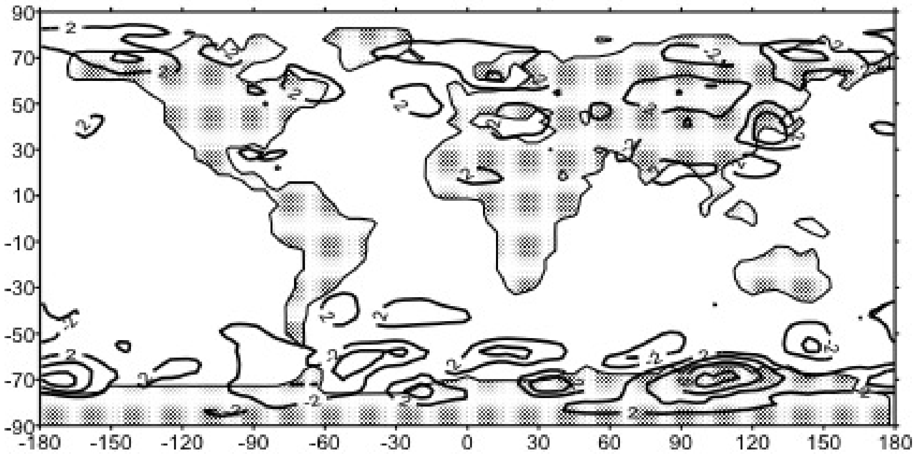

Figure 5.4. Isolines of air temperature differences at 800 mbar, calculated from the original and modified schemes, July

Differences in the surface pressure do not exceed 15 mbar in a few cells and is mostly less than 5 mbar. The distribution of the air temperature difference for July at 400 mbar and 800 mbar levels is shown in Fig. 5.3 and 5.4, respectively. Differences at the 400 mbar level does not exceed 2^0C throughout, except for one point where achieve 6^0C. Picture is similar at 800 mbar level. It can be argued that the differences in results are more significant in the surface areas.

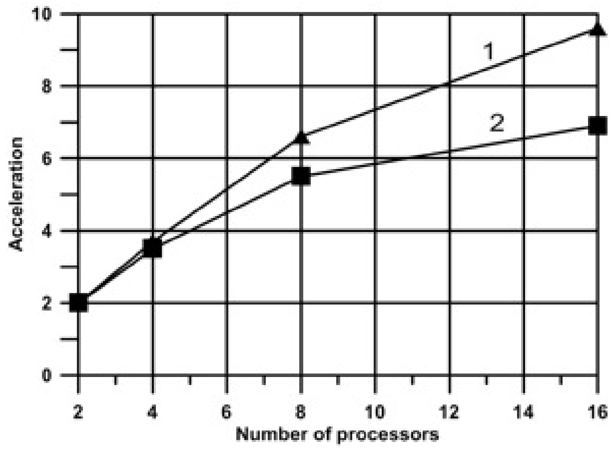

Figure 5.5. The acceleration dependence on the number of processors. 1 - modified method, 2 - original method

Table 2. Processors distributions for A, B, C and D numerical experiments

Run identification	A	B	C	D
Total number of processors	16	22	38	34
Dynamics block processors	10	10	10	10
Physics block processors	6	12	18	24

Thus, the analysis shows that the results for the modified scheme give satisfactory results and it is possible to use it. Scalar program calculation time takes 33% for the Physics block and 63% - for the Dynamics block (Table 1). This means that the parallelized program can be achieved faster one and a half times if use different processors for two blocks. The proposed procedure is used in conjunction with procedures of the computational domain decomposition [5, 7]. This allows optimizing the processor loading and parallelization efficiency (Fig. 5.5).

Another possible effective application of the method – to use the more detailed Physics block, without increasing the total computation time. We consider 4 numerical experiments, named A, B, C and D to demonstrate results: A – it is used $4^o \times 5^o$ horizontal grid, 9 vertical levels, original Physics block. B - it is used $4^o \times 2.5^o$ horizontal grid for Physics block variables, 9 vertical levels. C - it is used $4^o \times 2.5^o$ horizontal grid for Physics block variables, 18 vertical levels for radiation and hydrology models in Physics block. D – as C, plus 2 times more number of spectral levels in radiation model. The fixed $4^o \times 5^o$ horizontal grid is used in all experiments for Dynamics block.

Processors distributions between Dynamics block and Physics block are shown in the Table 2.

Modified method advantages are clear for experiments with relatively large amount of processors, when many interprocessors data exchange exist in Dynamics block, but Physics block does not have this problem. This effect explains the slowing down of original method calculations (Fig. 5.6) [8]. Number of processors, distributed for Dynamics block in the modified method is the same for all experiments, and number of processors, distributed for Physics block increase with the more detailed description of physical processes in the model subsequently in A, B, C, D experiments.

Described calculations were performed using AGCM and the ocean model [9], in which the basic currents are calculated. Model predicted change in global mean surface air temperature with a doubling of CO_2 for January is 4^0C. And the warming is stronger over the continents and the largest in Asia in the winter, where it reaches values 6^0C (Figures 5.7, 5.8). This is associated with the snow line shift to the north during this period. Increasing amounts to $0.5^0 - 1^0$C in Europe and the North Atlantic. The lowest observed warming is in the Southern Hemisphere, especially over the oceans in the summer. It is worth noting that in the process of entering the stationary regime in the region of Antarctica, there was even a slight cooling.

The analysis shows a "spotty" structure of the precipitation changes field (Fig. 5.9). Their growth is associated with an increase in evaporation from the ocean surface and the subsequent fallout. However, there are areas where rainfall decreases. This occurs in the equatorial region of South America, in the central regions of Africa, South-East Asia and a small draining western Siberia and western North America. These processes occur in the summer. In winter in the Northern Hemisphere precipitation changes are less than 0.5 mm/day.

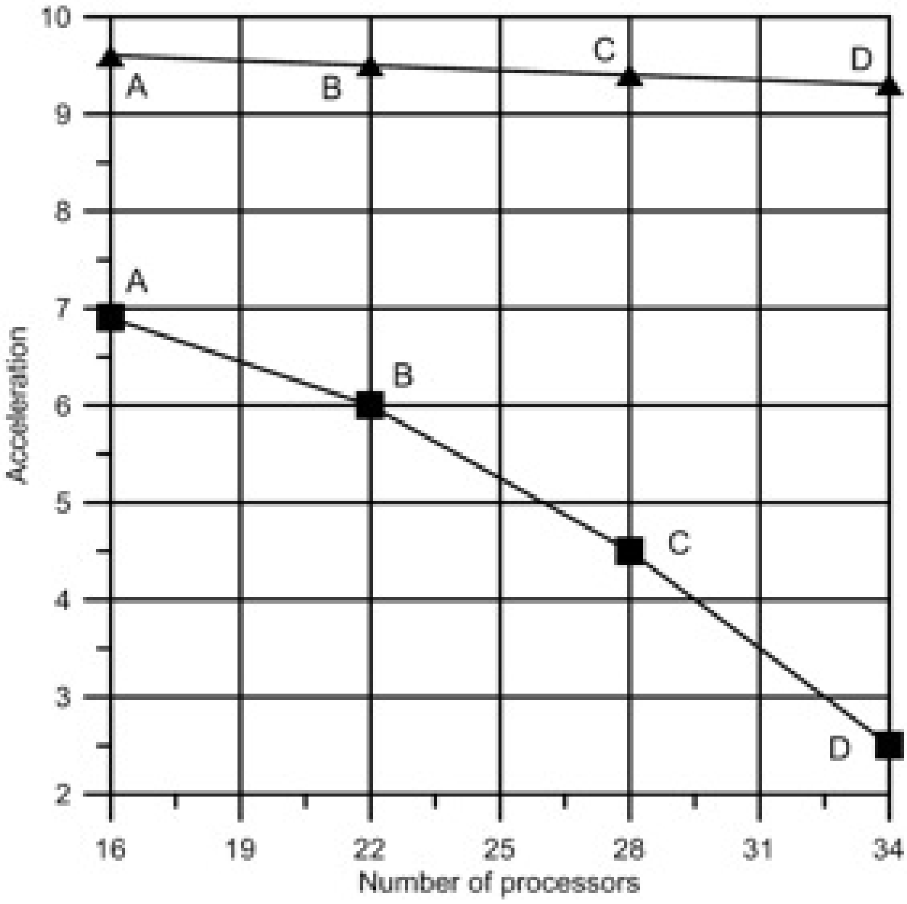

Figure 5.6. The run acceleration for A, B, C and D numerical experiments. Corresponding results are marked on the figure. Upper line – modified method, down line – original method

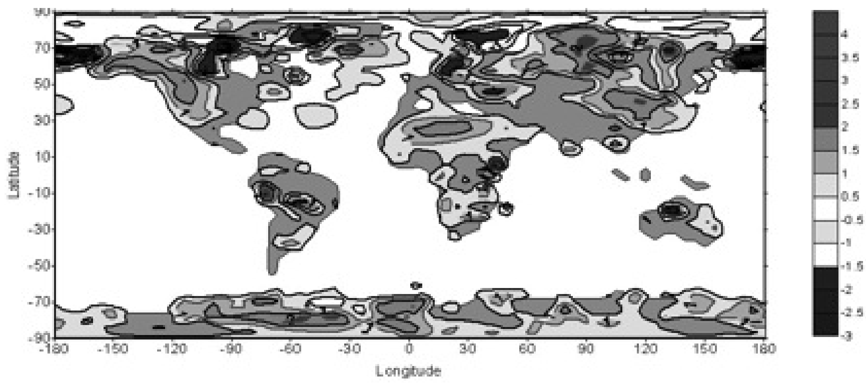

Figure 5.7. The air temperature changes, a doubling of carbon dioxide concentrations (Winter)

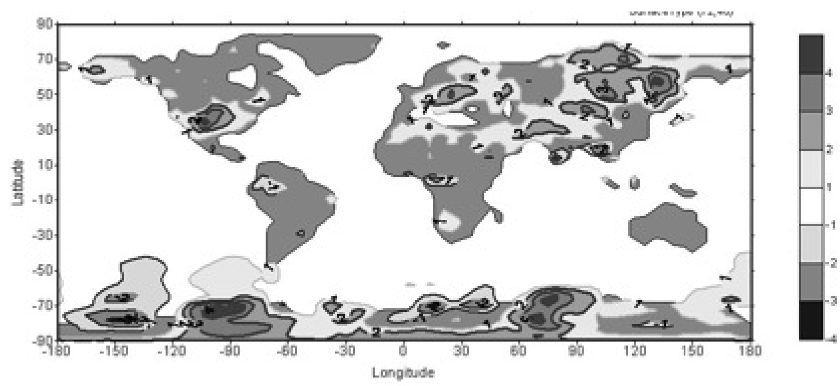

Figure 5.8. The air temperature changes, a doubling of carbon dioxide concentrations (Summer)

The calculations show a cloud cover decrease to a few percent at low latitudes. It is possible that this leads to some additional heating of the underlying surface. Changes in zonal wind are quite small, especially for the lower level (800 mb) - less than 0.5 m/sec. Wind changes at the 400 mbar level are up to 1 m/sec at mid-latitudes of the Northern Hemisphere. This is connected some increase in the equator - pole temperature difference in the upper atmosphere.

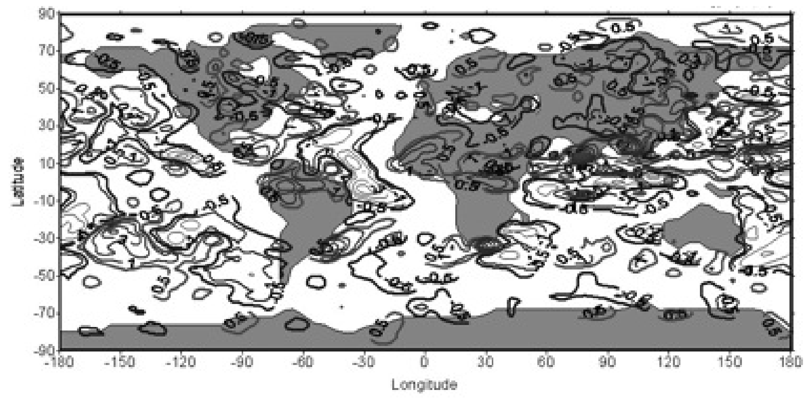

Figure 5.9. Precipitation change, a doubling of carbon dioxide concentrations (Summer)

6. CONCLUSIONS

The current situation is unprecedented in the history of the Earth - as emissions of greenhouse gases can increase the mean global air temperature over several decades, while the natural reasons temperature increase by the same amount will take no less than several millennia. Unprecedented, so is not the absolute magnitude of future changes, but their rate of growth.

The strategy should be developed to respond to changes in environment and climate, which provides two key areas: adapting to new economic sectors climatic conditions and the development of measures to limit anthropogenic pressures, leading to noticeable changes in climate and natural environment. It is essential that control measures must be international and produced in accordance with relevant international instruments, scientific and technical programs.

Thus, we can draw the following general conclusions. The use of multiprocessor computers in climate studies, particularly in the calculation of the atmospheric circulation, is one of the most promising ways to achieve results. This will create more adequate computational models that can be used in research related to the physics of the earth and ocean, and in the ongoing environmental assessments.

It is briefly described the climate model of the Computing Center of RAS, that includes an atmospheric unit, based on the AGCM with parameterization of a number of subgrid processes, global ocean model and a model of the evolution of sea ice. Modified method of AGCM parallelization with calculating the contribution of physics and dynamics, respectively, on two groups of processors with the same input data has been proposed. It leads to a more efficient and flexible scheme of calculation. Special features of this method have been discussed. Carbon dioxide growth numerical experiments were performed using AGCM parallel program and the ocean model, in which the basic currents are calculated.

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