NUMERICAL SIMULATION OF CLIMATE PROBLEMS

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Keywords Climate theory, computational models, numerical modeling, carbone acid, greenhouse effect, global climate, regional climate

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Summary

Evaluation of the impact of climatic variability and climate changes on the development of societies around the world is one of the important challenges of science and international policy. This fact necessitates the implementation of a number of programs each aimed at tackling specific problems of the climate system. Three main areas of climate study are as follows:
(a) inter-seasonal/inter-annual variability,
(b) inter-decadal/inter-centennial variations and
(c) antropogenic impact on the climate changes.

Coupled atmosphere-land surface-ocean models are the most powerful tool for studying climate and its evolution. These climate models are a mathematical description of the processes governing a sophisticated climate system. The sets of nonlinear partial differential equations describing the climatic models can not be solved analytically and, therefore, require some special numerical methods by which the equations are approximated and solved on a numerical grid. These models are able to simulate global climate over time ranging from seasons to centuries and on large scales. In particular, the El-Nino event can be predicted by these models at least one year in advance, and much progress toward a modeling of the inter-decadal variability of North Atlantic Oscillations and Pacific-North America systems has been achieved. Also, a number of scenarios concerning the estimate of the future impact of anthropogenic greenhouse

gases on the climate have been developed. However, the climate models, especially those that simulate biosphere processes and describe hydrological cycles (including cloud effects), have some shortages leading to the drift of the coupled models and need correction. It is this challenging task that climate modeling should fulfill in the immediate future.

1. Introduction

Detection and prediction of the climate changes, which are taking place now and will go on happening in the future, as well as evaluation of the impact of these processes on the development of societies around the world represent one of the important challenge of the science. The importance of this problem is defined by its fundamental role for choosing the strategy to prevent the global and regional climatic and environmental disasters. The necessity of selecting this strategy lies in the fact that in spite of common expectations of a stable climate, in certain periods the climatic conditions change so dramatically that they can cause problems in human life and great social consequences. These are the changes of the monsoon circulation in the Asian regions, droughts and periods of prolonged flooding, considerable decrease in the sea level of the enclosed seas such as the Caspian Sea, the Aral Sea, etc. These events demonstrate “natural” climatic variability, which is inherent to the climatic system both at the short-range time scales (inter-annual) and at long-range time scales (decadal and centennial).

On the other hand, human activities become a significant factor affecting the Earth climate via production of the so-called “greenhouse” gases, which can raise the global surface temperature. The resulting effects may be rapid changes of the global climate regime, the World Ocean level, the landscape zones and regions of human inhabitation, etc. Thus, the entire Earth’s climate record is a combination of both natural variability and anthropogenic changes.

The importance and urgency of the problems related to climate changes have resulted in the development of the World Climate Program (WCP), which focuses on natural climatic variability and possible anthropogenic climate changes. In 1980 the World Meteorological Organization devised the World Climate Research Program (WCRP) co-sponsored by the Intergovernmental Oceanographic Commission (IOC) of UNESCO from 1993. The WCRP has the main goal of developing a scientific understanding of global climate system, as well as predicting global and regional climate changes at various time scales. The achievement of this goal implies carrying out a wide spectrum of investigations of the following components of the climatic system: atmosphere, ocean, sea-ice and land surface. Accordingly, the WCRP launched a number of projects or sub-programs, each addressing important and specific problems of the climate system. The first project initiated in 1985 was the Tropical Ocean and Global Atmosphere (TOGA) program devoted to the study of physical mechanism causing the strongest inter-annual climate variability, the El-Nino-Southern Oscillation phenomenon. Completed in 1994, TOGA was a good example of research on inter-annual climatic variability and its impact on global change problems. Studying the ocean climate was the objective of the World Ocean Circulation Experiment Project (WOCE). The present WCRP projects are as follows: the Global Energy and Water Cycle Experiment (GEWEX), the Arctic Climate System Study (ACSYS), the Study of

Stratospheric Processes and their Role in Climate (SPARC).

Since 1995 the WCRP has been implementing the Climate Variation Program (CLIVAR). One of the scientific objectives of CLIVAR is to describe and understand the physical processes responsible for seasonal-to-centennial climate variability and predictability through the analysis of observations and modeling of the coupled climate models. Another objective is to improve the accuracy of seasonal to inter-annual climate prediction by means of coupled modeling of the upper ocean, atmosphere, land and ice system. In addition, the program is aimed at developing and implementing the observing/computing/data archiving/modeling systems needed to understand and predict anthropogenically induced variations of the climate.

2. Climate, Climatic Variability and Climate Changes

The atmospheric science includes two major parts: meteorology which is concerned with instantaneous atmospheric phenomena and their non-stationary behavior, and climatology which deals with a long-term statistical state of the atmosphere, which is called **Climate of the Atmosphere,** and its variations.

Today the distinction between meteorology and climatology is being diminished because climate is continually changing and it can no longer be completely characterized by means of statistics, and, therefore, it must be treated as a time-depended problem.

A climatic variation is defined as the difference between the maximal deviations of the monthly-, seasonally-, annually mean characteristics and their climatic values.

A climate change is defined as the difference in the long-term mean values of the climatic characteristics averaged in a few decades.

The so-called El-Nino-Southern Oscillation (ENSO) is at least one well-documented example of the inter-annual climatic variability. It indicates a strong interaction between the atmospheric and oceanic circulation, which causes an intermittent three-to-five-year quasi-periodicity observed in sea level pressure, surface wind, sea surface temperature (SST), cloudiness and precipitation over a wide area of the Pacific Ocean and adjacent coastal areas. The ENSO and its influence on the global climatic processes, including the changes in the monsoon system of the Asia-Australia region and the America-Africa region, as well as the anomalies of the climatic characteristics in the mid-latitudes are of great interest not only for the specialists, but for the total human community as well. The dynamics of the tele-connection between tropical and extra-tropical latitudes continues to be a central problem in climate research.

Another example of climatic variations, the so-called North Atlantic Oscillation (NAO), is associated with much of the recent increase in Northern Hemisphere temperature. The NAO is a large-scale alternation of the atmospheric mass with centers of action near the Iceland low-pressure region and the Azores high-pressure region. It is the dominant low frequency (from a few months to several decades) mode of atmospheric behavior in the North Atlantic sector, which is most pronounced in winter. A pattern involves both SST fluctuations and surface air temperature seesaws. NAO fluctuations are also found in the patterns of precipitation in the same area as well as in stormy weather over the ocean and adjacent land areas. Reconstruction of the recent past by using the historical data also shows a significant spread in the temperatures from century to century. For example, cold conditions prevailed between the middle of the sixteenth and nineteenth centuries with some inter-centennial variations.

Finally, most part of the specialists in climate study nave agreed that climate has changed over the past century, the balance of evidence suggests a distinctive human influence on the global climate and that climate is expected to continue to change in the future.

In this connection, the objective of the 1992 United Nations Framework Convention on Climate Change (FCCC) is “to achieve stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interface with the climate system. Such level should be achieved within time frame sufficient to allow ecosystem to adapt nature to climate change, to ensure that food production is not treatment and to enable economic development to proceed in a sustainable manner”.

General Circulation of the Atmosphere

Because of the Earth’s gravity, the atmosphere presses on the Earth’s surface. The force per unit of area due to the weight of the atmosphere can be expressed as a pressure. The vertical variability of pressure, density and temperature is much larger than the horizontal and temporal variability of these parameters. Therefore, it is useful to define the simplest model of the atmosphere that is called “standard atmosphere”. This model represents a horizontal and time-averaged structure of the atmosphere as a function of height only. The vertical profile of the temperature for “standard atmosphere” can be divided into four distinct layers (from below upwards): troposphere, stratosphere, mesosphere, and thermosphere. The upper boundaries of these layers are called the tropopause, stratopause, mesopause, and thermopause, respectively. The troposphere accounts for more than 80 percent of the mass and all of the water vapor, clouds and precipitation in the atmosphere. The transition from the troposphere to the stratosphere is marked by an abrupt change in the concentrations of some of the variable tracer. Water vapor decreases sharply, while ozone concentration increases by an order of magnitude within the first few kilometers above the tropopause. The strongly layered structure of the atmosphere is related to the vertical temperature gradient. The troposphere and stratosphere together account for about 99 percent of the atmospheric mass.

Atmospheric motions have a wide spectrum of horizontal scales, ranging from the Earth’s size to the size of a molecule. It is convenient to divide the spectrum in such a way: planetary scale motions (the feature of the global circulation with horizontal scales comparable to the scales of the continents and oceans), synoptic scales motions (waves and eddies with horizontal scales large enough to be resolved by the observing hydro-meteorological network, but smaller than planetary scale motions), mesoscale motions (waves, eddies and jets with horizontal scales ranging from a few ten kilometers up to a few hundred kilometers) and small scale motions (the remaining part of the spectrum).

A common feature of the planetary motions, synoptic motions, and mesoscale motions is the fact that they are quasi-horizontal, it means that the vertical motions are more than an order of magnitude smaller than horizontal flows.

To denote the global atmospheric air motions, the scientific community uses the term “General Circulation of the Atmosphere”. General circulation can be viewed in the context of an energy cycle in which atmospheric air motions draw on the store of potential energy of the spatial distribution of atmospheric mass in order to maintain themselves against dissipation. At lower latitudes most of the kinetic energy is contained in quasi-steady, thermally driven circulations, which are directly related to the geographical distribution of sources and sinks of heat. These thermally driven circulations include the seasonally varying monsoons that are an atmospheric response to land-ocean heating contrasts and a large scale meridional overturning over the mid-Atlantic and Pacific Oceans, which gives rise to the inter-tropical convergence zone, the east-west band of heavy cloudiness and precipitation. At middle and high latitudes a lot of kinetic energy is linked with transient disturbances called baroclinic waves, which develop within the zones of strong horizontal temperature gradients. Most weather disturbances at mid latitudes are attributed to the baroclinic waves system possessing frontal zones. Planetary and synoptic atmospheric waves are subject to dissipation, which causes them to lose their kinetic energy. Therefore, the supply of kinetic energy is required to maintain the general circulation against dissipation.

Ocean Dynamics and Climatic State

The World Ocean is an important part of the coupled climatic system including also the atmosphere, cryosphere, and land surface and plays a key role in the global climate formation.

The physical properties of sea-water relevant to fluid dynamics are the functions of pressure, temperature, and salinity. From a point of view of ocean dynamics the most important aspect is the non-linear quantitative manner in which the density varies with changes in temperature, salinity, and pressure. Density decreases as temperature increases and increases as salinity and pressure increase. Sea-water is much denser than air. This difference accounts for the fact that the total mass of the ocean is much larger (270 times) then that of the atmosphere. What is more important, this leads to a considerable difference in the heat capacity (about 4 times), which enhances the role of the ocean in climate dynamics, especially for long periods.

The ocean, in average, has stable stratification, i.e., the mean density increases with the depth. In the regions where by some reasons (cooling or salting) stratification is unstable, i.e., the density of the upper layers is larger then that of the lower ones, there occurs a vertical movement called “convection”, which tries to bring the system to stable stratification. These processes are mostly significant in high latitude zones with weak stratification and substantially control the climatic state of the World Ocean by “deep water” formation. The vertical gradients in the major parts of the World Ocean are significant enough. A vertical structure of the ocean can be formally divided into a few layers: a “mixed layer” with very weak vertical gradients induced by the wind and convective mixing with a depth of 10–200 m for different regions. Under the mixed layer there exists a strong gradient layer with the depth depending on the season. The "main thermocline" characterized by the significant density gradients lies deeper down to a depth of 1–1.5 km. Below this layer an "intermediate" layer is located, with a "deep" water layer (or "abyssal") down under. The average depth of the ocean is about 4 km, while its horizontal span amounts to 10000 km. Although the ocean can be represented as a very thin "slice" on the sphere and the movements as in the atmosphere are mainly quasi-horizontal, nevertheless, like in the atmosphere, the vertical component of the circulation can not be neglected.

The movements in the ocean are mainly derived by the atmospheric wind, surface heating, and fresh water fluxes at the surface. They are usually referred to as "wind-stress" and "thermohaline" forcing and cause the corresponding circulation. Atmospheric wind is responsible for the main features and currents of the horizontal circulation. Some features of the distribution of atmospheric motions form equatorial currents and countercurrents, sub-tropical gyres with Golfstream and Kuroshio western boundary currents, sub-polar gyres and, finally, the Arctic and the Southern oceans polar circulation. These horizontal circulation structures are accompanied by the vertical motions (up- and down-welling). The sub-tropical gyres transport warm and saline water from low to higher latitudes, thus redistributing the heat and fresh water between the equator and the pole. The global thermohaline circulation is driven by the North Atlantic Deep Water (NADW) formation. It is controlled by the convection in the marginal Greenland and Labrador seas and export to the North Atlantic of the sea ice formed on the Arctic shelves. The NADW spreads to the south and together with the Antarctic Deep Water (ADW) is redistributed by the Antarctic Circumpolar Current to the Indian and Pacific oceans at deep layers. The warm, saline water is brought back to the Atlantic by the surface current. This is so-called "Conveyor Belt".

3. Atmosphere and Ocean Circulation Models

The most powerful tools for studying climate and climate evolution are coupled atmosphere-surface land-ocean models. These climate models are mathematical descriptions of the processes governing a sophisticated climate system, as becomes evident now. Of course, the climate models have various shortages, especially those that simulate biosphere processes and describe the hydrological cycle, including cloud effects. Nevertheless, they are able to simulate global climate on a large scale and over time ranging from seasons to centuries.

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Biographical Sketches

Vladimir N. Krupchatnikoff was born in Mogilev. He graduated from the Novosibirsk State University with the degree in numerical mathematics in 1969. In 1980 he obtained the degree of candidate in Geophysics. In 1995 he got the Doctor of Sciences degree in Geophysics and Atmospheric Sciences with the thesis "Modeling of the large-scale troposphere dynamics in the Northern Hemisphere". In the last years V. Krupchatnikoff worked in the last years on various aspects of the modeling of atmosphere dynamics and climate. His researches are focused on three-Dimensional General Circulation Models (GCM) of the atmosphere, weather prediction models, finite-difference, semi-Lagrangian and spectral schemes, land surface processes scheme for using in GCM. Parallel to this work, he reads a course of lectures on atmosphere dynamics and climate theory at the Novosibirsk State University. He wrote more than 70 scientific papers including review articles and 2 monographs. Since 1988 V. Krupchatnikoff is a senior researcher in the Computing Center of the Russian Academy of Sciences in Novosibirsk (now the Institute of Computational Mathematics and Mathematical Geophysics of the Russian Academy of Sciences). In 1997and 2001 he was awarded with State Grants.

Victor I. Kuzin was born in Novosibirsk in 1946. He graduated from the Novosibirsk State University with the degree in numerical mathematics and mechanics in 1969. In 1975 he obtained the degree of candidate in Geophysics. In 1988 he got the Doctor of Sciences degree in Geophysics and Atmospheric Sciences with the thesis "Finite element method in ocean circulation modeling". In the last years V.I. Kuzin worked on various aspects of the modeling of ocean dynamics and climate. His researches are focused on Three-Dimensional Ocean Circulation Models. Also he reads a course of lectures on Geophysical Hydrodynamics and Computational Mathematics at the Novosibirsk State University. He published more than 80 scientific papers including 2 monographs. Since 1988 V.I Kuzin is the Head of the Department of Atmosphere, Ocean Studies and Environment in the Computing Center of the Russian Academy of Sciences in Novosibirsk (now the Institute of Computational Mathematics and Mathematical Geophysics of the Russian Academy of Sciences). From 1993 he was awarded with State Grants.