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Enviro-RISKS:

Man-induced Environmental Risks: Monitoring, Management and Remediation of Man-made Changes in Siberia

Alexander Baklanov and Evgenyi Gordov, Editors

Volume 3:

Climate and Global Change and Risks

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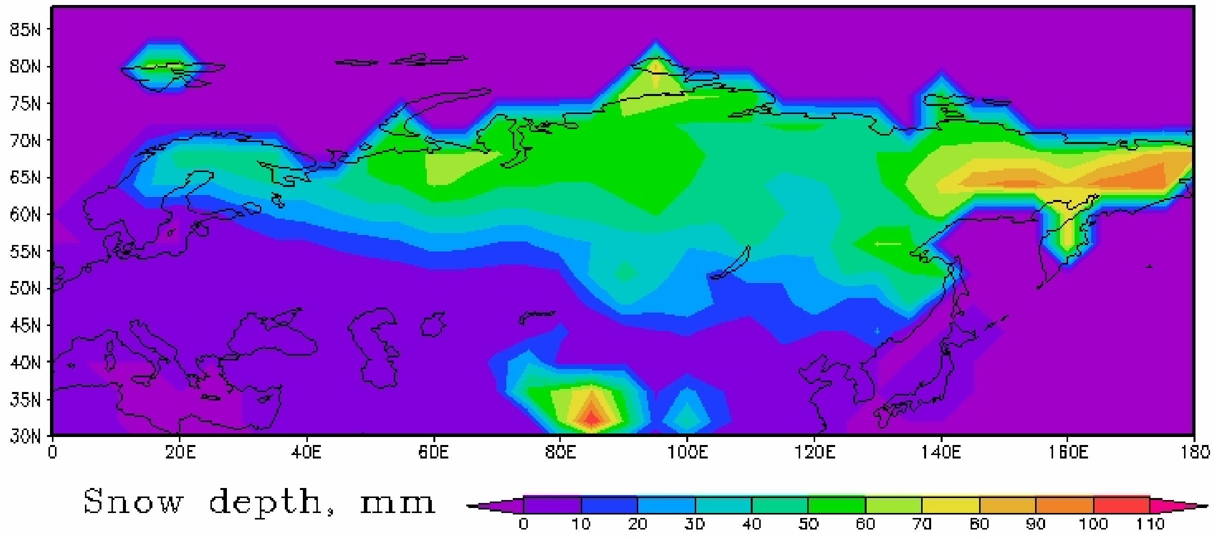

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Enviro-RISKS Report Content:

Executive Summary

Enviro-RISKS Project and its Major Outputs *(in a separate Volume1:* www.dmi.dk/dmi/sr08-05-1.pdf*)*

Thematic Focus 1: Atmospheric Pollution and Risk *(in a separate Volume 2:* www.dmi.dk/dmi/sr08-05-2.pdf*)*

Thematic Focus 2: Climate/Global Change and Risks *(in this Volume 3)*

Thematic Focus 3: Terrestrial Ecosystems and Hydrology and Risks *(in a separate Volume 4:* www.dmi.dk/dmi/sr08-05-4.pdf*)*

Thematic Focus 4: Information Systems, Integration and Synthesis *(in a separate Volume 5:* www.dmi.dk/dmi/sr08-05-5.pdf*)*

EXECUTIVE SUMMARY

Siberia environment has been subjected to serious man-made transformations during last 50 years. Current regional level environmental risks are: direct damages to environment caused by accidents in process of petroleum/gas production and transporting including their influence on water, soil, vegetation and animals; caused by deforestation (legal and illegal cutting and forest fires) variations in Siberian rivers runoffs and wetland regimes; direct and indirect influence of forest fires, flambeau lights and losses of gas and petroleum during their transportation on regional atmosphere composition; deposition of hazardous species leading to risks to soil, water and consequently to risks in the food chain.

In this Final Report, published in five separate Volumes, the major Enviro-RISKS project (http://project.risks.scert.ru/) outcomes are summarized. They include the state of the art of environmental RTD activity in Siberia, suggested methodology and recommendations on future environmental research in Siberia. These outcomes are based on results obtained by the four Thematic Expert Groups in process of preparation of Thematic Focuses Reports.

Three Thematic Focuses/Groups consider major risks inherent to Siberia environment. These groups (with their leaders) are the following:

1. **Atmospheric Pollution and Risks** (Alexander Baklanov (DMI) and Vladimir Penenko (ICMMG)),
2. **Climate/Global Change and Risks** (Martin Heimann (MPI for Biogeochemistry) and Vasily Lykosov (INM)), and
3. **Terrestrial Ecosystems and Hydrology and Risks** (Michael Kabanov (IMCES) and Anatoly Shvidenko (IIASA)).

The forth Focus has a generic nature and is devoted to:

4. **Information Systems for Environmental Sciences, Integration and Synthesis** (Evgeny Gordov (SCERT) and Edige Zakarin (KGC)).

The groups analyzed relevant RTD projects (lists of those are mentioned in the Introduction and attached to respective Focus Groups Reports) and summarized the state of the art, existing methodology and applications in the considered area. Additional contributions of all Project Partners also have been used in this Report.

On this basis also practical recommendation to international research community and regional environmental decision makers were formulated (see in Volume 1). These recommendations are translated into Russian and disseminated to targeted community via direct mailing and the Project web site.

Content of Volume 3:

Abstract

The state-of-the-art climate models are based on a combined atmosphere–ocean general circulation model. A central direction of their development is associated with an increasingly accurate description of all physical processes participating in climate formation. This direction appears to be reasonable because, in order to correctly describe the climate system's response (even its first moment) to small external forcing, it is necessary to adequately reproduce not only climate itself but also the dynamics on the attractor of the climate system (the probability of transition of the climate system from one state to another).

Experimental investigations of the real climatic system (monitoring) and theoretical investigations of the global climate system (mathematical modeling) came to a new turning point of combined investigations. To develop such investigations, it is necessary to construct the relevant hierarchy of interacting subsystems in the comprising the global climate system and to improve the description of the physical processes occurring in them. Industrial systems, the role of which, on the quantitative level, has not yet reliably been revealed, occupy special place among similar subsystems with different scales of spatiotemporal variations.

Analyzed projects results show that an access to significantly increased computing capacity will enable scientists to advance understanding and representation of the physical and biogeochemical processes responsible for climate variability and predictability. It is concluded in this report that the strategy of modeling climate and its global changes should be based on the following four main propositions: (i) construction of an original climate model, (ii) model implementation on computational system of parallel architecture, (iii) development of the mathematical theory of climate, and (iv) study of regional problems of climatic variability and its impact on environment, in particular, including risks for Siberia. This makes it possible to hope for the elaboration of an expert system used to obtain estimates and substantiated predictions of climate oscillations and changes on both a regional and global scales.

1. Introduction

The central problem of the modern theory of climate is the prediction of its changes caused by anthropogenic activities. In view of specific peculiarities of the climate system this problem cannot be solved with the use of the conventional methods repeatedly tested in natural sciences. It can be stated that, at present, the principal methodological basis for solving this problem is numerical simulation of the climate system with the aid of climate models based on global atmosphere–ocean general circulation models. It is clear that the formulation of the climate models requires a comparison with real data and special-purpose field experiments in addition to observations carried out on a continuous basis. Analysis of the results of these experiments must enable the construction of increasingly more accurate models of specific physical processes determining the dynamics of the climate system. However, this approach is insufficient for solving the principal problem, namely, the problem of determining the sensitivity of the actual climate system to small external forcing.

The state-of-the-art climate models are based on a combined atmosphere–ocean general circulation model. A central direction of their development is associated with an increasingly accurate description of all physical processes participating in climate formation. This direction appears to be reasonable because, in order to correctly describe the climate system's response (even its first moment) to small external forcing, it is necessary to adequately reproduce not only climate itself but also the dynamics on the attractor of the climate system (the probability of transition of the climate system from one state to another).

In modeling global climate, it is necessary to reconstruct the latitudinal spectrum of its characteristics: seasonal and monthly mean values, seasonal variability (monsoon cycle, parameters of storm-tracks, etc.), climatic variability (its dominating modes, such as El Niño or Arctic Oscillation), etc. At the same time, it is quite urgent now to use modern mathematical models in studying regional climate and ecological peculiarities, in particular, that of Siberia. It is related with the fact that, according to modern ideas, natural environment in mid- and high latitudes of the Northern hemisphere is most sensitive to the observed global climate changes. One should consider such tasks of modeling regional climate as detailed reconstruction of its characteristics, investigation of the peculiarities of hydrological cycle, estimation of the possibility of extreme phenomena to occur, and investigation of the consequences of the regional climate changes for the environment and socio-economic relations as its basic tasks.

Changes in nature and climate in Siberia are of special interest in view of the global change in the Earth system. This special interest has been initiated by some facts. First, the vast continental territory of Siberia (about 10 million km^2) is undoubtedly a ponderable natural territorial region of Eurasian continent, which is characterized by the various combinations of climate-forming factors. Second, forests, water, and wetland areas are situated on a significant part of Siberia, which play planetary important climate regulating role due to the processes of emission and accumulation of the main greenhouse gases (CO_2, CH_4, etc.). Third, the variety of climatic zones in Siberia and the presence of mesoscale regions with extremely high or absolutely absent industrial load create globally unprecedented conditions for scientific investigations of the changes in nature and climate, as well as for revealing the weights of natural and anthropogenic factors in the observed changes. The aforementioned and some other regional peculiarities of Siberia are undoubtedly important reason for integrated regional investigations in this region of the planet. But more important reasons for such investigations are the facts that evidence of the enhanced rates of the warming observed in the region and the consequences of such warming for natural environment. The Institute for monitoring of climatic and ecological systems, Siberian Branch of the Russian Academy of Sciences, is actively participating in such investigations.

In Fig. 1 the map of the linear trend of the annual mean near-ground temperature over the territory of Siberia calculated for the period since 1965 until 2000 is shown. This map is calculated using the data taken from the NCDC site (Ashville, USA, http://www.ncdc.noaa.gov) (the series of monthly mean temperature at the height of 2 m at 223 meteorological stations in Siberia). The detailed description of the technique and some results of calculations are presented in (Ippolitov et al., 2004).

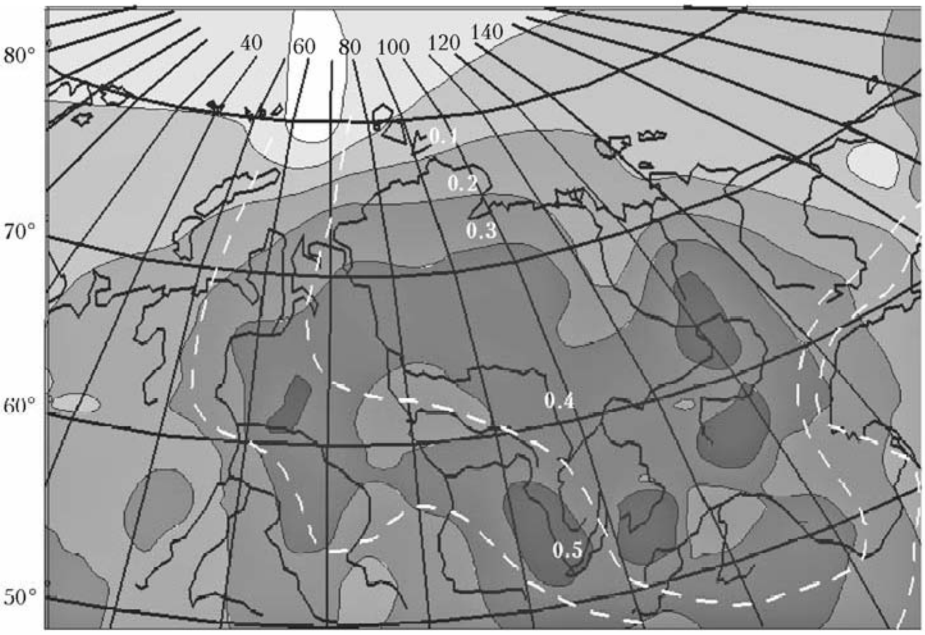

Fig. 1. *Map of linear trends of annual mean near-ground temperature during the period from 1965 to 2000. Dotted lines show contours of January monthly mean temperature during the period since 1881 until 1935 (the upper line for –28°C, the lower one for –20°C).*

Contours on this map show the regions with different value of the trend (different gray scales) in 0.1°C step of warming during 10 years. As is seen from this figure, the rates of warming on the entire territory of Siberia in the second half of XX-th century were quite high (more than 0.2°C per 10 years), and in some regions they reached the value of the linear trend of 0.5°C/10 years. These mesoscale regions, which can be called the centers of accelerated warming, are concentrated first of all in East Siberia. The contours of January mean temperatures for the period 1881–1935 in Fig. 1 (dotted lines) separate the regions of Siberia for colder (to the north from the contours) and warmer (to the south from the contours) and essentially deviate from latitudinal zonality in this period.

Ye and Ellison (2003) found that the transitional snowfall season length has statistically significantly increased in central Siberia during autumn and in southeastern Siberia during spring. Such an increase may indicate a higher frequency of anomalous weather conditions under a warmer climate during transitional seasons in high-latitude areas. The length of continuous snow cover has increased about 4 days per decade over small areas of western and central Siberia, but decreased about 2 days per decade over some areas of southern and southeastern Siberia. Permafrost and seasonally frozen ground in most regions (and, especially, in Siberia) show large changes in recent decades. Accordingly to Pavlov (2003), permafrost temperature increased approximately 1 ˚C at depths between 1.6 and 3.2 m from the 1960s to the 1990s in East Siberia, and about 0.3 ˚C to 0.7 ˚C at a depth of 10 m in northern West Siberia. Long-term monitoring of the permafrost active layer has shown that over the period 1956 to 1990, its depth exhibited a statistically significant increase of about 21 cm.

Experimental investigations of the real climatic system (monitoring) and theoretical investigations of the global climate system (mathematical modeling) came to a new turning point of combined investigations. To develop such investigations, it is necessary to construct the relevant hierarchy of interacting subsystems in the comprising the global climate system and to improve the description of the physical processes occurring in them. Industrial systems, the role of which, on the quantitative level, has not yet reliably been revealed, occupy special place among similar subsystems with different scales of spatiotemporal variations.

From this point of view, the **A**tmospheric **M**odel **I**ntercomparison **P**roject (AMIP), which was initiated by the World Climate Research Programme (WCRP) since 1990, is the first standard experimental protocol for testing the performance of global atmospheric general circulation models (AGCMs) under common specifications of observed ocean boundary conditions (Gates, 1992). It provided a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access. This framework enabled a diverse community of scientists to analyze AGCMs in a systematic fashion, a process which serves to facilitate model improvement. This project has revealed many key mechanisms responsible for climate formation (see http://www-pcmdi.llnl.gov/amip). At the same time, the AMIP can also be viewed as a program of study of the sensitivity of an "ideal" atmospheric model to the level of description of different physical processes. The AMIP project has been developed in the **C**oupled **M**odel **I**ntercomparison **P**roject (CMIP), which is the analog of AMIP for global coupled ocean-atmosphere general circulation models. During CMIP performance, the emphasis is made on the reproduction of the sea surface temperature and sea ice distribution (see http://www-pcmdi.llnl.gov/projects/cmip/index.php), because these characteristics were considered to be specified external parameters in the AMIP experiments. The Institute for Numerical Mathematics (INM), Russian Academy of Sciences, participates in both (AMIP and CMIP) programs.

2. Atmospheric Model Intercomparison Project (AMIP): a Way to Improve Climate Models

The initial phase of the AMIP (labeled as AMIP I, circa 1990 - 1996) involved the participation 30 modeling groups from different countries. Within the frame of this project many diagnostic subprojects, which analyzed various aspects of climate simulations of the decade 1979 – 1998, have been carried out, e.g. Diagnostic Subproject 12 on Land-surface Processes and Parameterizations, which is connected, in particular, with the diagnosis of processes, responsible for the surface hydrological cycle.

In Table 1, the land-surface hydrology representations of 30 AMIP I models are listed (Phillips, 1994). Here “prescribed soil moisture” means that a spatially and seasonally varying surface wetness is specified, while evaporation is predicted independently of runoff. The “simple bucket” land-surface schemes follow the approach of Manabe (1969): soil wetness, evaporation, and runoff are computed with a constant moisture field capacity. The “augmented bucket” schemes modify this approach (e.g. by including spatially variable field capacity, constrained evaporation, and/or a different runoff parameterization), but do not explicitly represent certain biophysical processes that are included in “vegetation canopy” schemes (e.g. precipitation interception and reevaporation by foliage, stomatal/canopy resistance to evapotranspiration, etc.).

Subproject 12 pointed out several substantial obstacles (Phillips et al., 2000): little reliable global validation data were in that time available; the standard set of land-surface variables provided by the AMIP modeling groups was quite limited (e.g. runoff was not included); and a rather narrow range of Land-Surface Scheme (LSS) complexity was represented, since many of AMIP I models used simple representations of land-surface processes (see Table 1).

Table 1*: A listing of the land-surface hydrology representations of 30 AMIP I models.*

Acronym	**AMIP Modeling Group**	**Hydrology Representation**
BMRC	Bureau of Meteorology Research Centre	Simple bucket
CCC	Canadian Climate Centre (now Canadian Centre for Climate Modeling and Analysis)	Augmented bucket
CCSR	Center for Climate System Research	Augmented bucket
CNRM	Centre National de Recherches Meteorologiques	Augmented bucket
COLA	Center for Ocean-Land-Atmosphere Studies	Vegetation canopy
CSIRO	Commonwealth Scientific & Industrial Research Organization	Augmented bucket
CSU	Colorado State University	Simple bucket
DEFR	Dynamical Extended Range Forecasting (at GFDL)	Simple bucket
DNM (INM)	Department (now Institute) of Numerical Mathematics	Simple bucket
ECMWF	European Centre for Medium-range Weather Forecasts	Vegetation canopy
GFDL	Geophysical Fluid Dynamics Laboratory	Simple bucket
GISS	Goddard Institute for Space Studies	Vegetation canopy
GLA	Goddard Laboratory for Atmospheres	Vegetation canopy
GSFC	Goddard Space Flight Center	Prescribed soil moisture
IAP	Institute of Atmospheric Physics	Simple bucket
JMA	Japan Meteorological Agency	Vegetation canopy
LMD	Laboratoire de Meteorologie Dynamique	Simple bucket
MGO	Main Geophysical Observatory	Augmented bucket
MPI	Max-Planck-Institut für Meteorologie	Vegetation canopy
MRI	Meteorological Research Institute	Augmented bucket
NCAR	National Center for Atmospheric Research	Prescribed soil moisture
NMC	National Meteorological Center (now National Centers for Environmental Prediction, NCEP)	Augmented bucket
NRL	Naval Research Laboratory	Prescribed soil moisture
SUNYA	State University of New York at Albany	Simple bucket
SUNGEN	State University of New York at Albany/NCAR Genesis	Vegetation canopy
UCLA	University of California at Los Angeles	Prescribed soil moisture
UGAMP	UK Universities' Global Atmospheric Modelling Programme	Augmented bucket
UIUC	University of Illinois at Urbana-Champaign	Augmented bucket
UKMO	United Kingdom Meteorological Office	Vegetation canopy
YONU	Yonsei University	Simple bucket

In these circumstances, Subproject 12 implemented a “zero-order” validation, i.e. it identified problematical features that could be readily discerned from inspection of the land-surface simulations. The main findings from this subproject were that: (i) no “best” land-surface simulation could be identified with every model showing some unsatisfactory results (Love and Henderson-Sellers, 1994); (ii) some models were unsuccessful to conserve surface energy and water balances at a continental scale and displayed pronounced trends in moisture stores (these discrepancies were caused by errors in coding/coupling of the LSSs and/or by inadequate initialization/ spin up procedures (Love et al. 1995)); and (iii) at a regional scale, the inter-model scatter in energy/moisture partitioning in the AMIP models was substantially greater than in comparable LSS off-line experiments. This result contradicted the prevalent expectation that two-way feedbacks in coupled atmosphere-land experiments would dampen inter-model differences in the simulation of continental climate (Irannejad et al., 1995).

In the AMIP II phase of the intercomparison, the experimental design was fundamentally the same, except that the simulation period has been extended to 17 years (from 1979 to 1996, later extended to 1979 – "near present"). In contrast with AMIP I, there were a number of advantages of analyzing AMIP II experiments in relation to the study of land-surface processes in global climate system: (i) a greater variety of complexity in land-surface schemes used (see Table 2); (ii) better control of the model initialization and spin-up processes with respect to moisture stores; and (iii) more extensive set of model output to diagnose land-surface processes (Zhang et al., 2002).

Table 2. *LSS features of the sixteen AMIP II models.*

Model, country	**Soil model complexit**	**Canopy representation**	N_t	N_m
CCSR, Japan	bucket	constant canopy resistance	3	1
CNRM, France	force-restore	interception+transpiration	2	2
DNM (INM), Russia	multi-layer diffusion	interception+transpiration	24	24
ECMWF, UK	multi-layer diffusion	interception+transpiration	4	4
JMA, Japan	multi-layer diffusion	interception+transpiration	4	3
NCAR, USA	multi-layer diffusion	interception+transpiration+CO_2	6	6
NCEP, USA	multi-layer diffusion	interception+transpiration	3	2
PNLL, USA	multi-layer diffusion	interception+transpiration	2	3
UGAMP, UK	multi-layer diffusion	interception+transpiration+CO_2	4	4
UKMO, UK	multi-layer diffusion	interception+transpiration+CO_2	4	4
CCCMA, Canad	multi-layer diffusion	interception+transpiration	3	3
GLA, USA	multi-layer diffusion	interception+transpiration	2	3
MRI, Japan	multi-layer diffusion	interception+transpiration	3	3
SANYA, USA	multi-layer diffusion	interception+transpiration+CO_2	6	6
UIUC, USA	bucket	no	1	1
YONU, Korea	bucket	no	1	1

In Table 2, N_t and N_m is a number of layers in the soil temperature and soil moisture calculations, respectively. The "force-restore" scheme means that in this model there is a thin top layer and a deep soil layer. In this scheme, two different time scales are used to represent the feedbacks between land and atmosphere: a rapid response to the atmospheric forcing in the top layer and a slow restore process in the deep layer (Zhang et al., 2002). The soil moisture is redistributing by its transfer from deep soil to the upper layer for surface evaporation. The "multi-layer diffusion" scheme includes soil hydraulic diffusion processes coupled with canopy and root-zone processes of water flow (see, for example, Volodin and Lykosov, 1998).

To provide information concerning changes in model performance from AMIP I to AMIP II, it is useful to construct a so-called "Taylor diagram" (Taylor, 2001). For every model, the statistics are displayed in such a diagram by a point in polar coordinates, which represents: (i) the correlation coefficient between the observed and simulated field (related to the azimuthal angle), (ii) the centered (mean removed) normalized root-mean-square (RMS) difference between the two fields, which is proportional to the distance to the x-axis point labeled as observed; and (iii) the ratio of the standard deviation (SD) of the simulated field to the observed (amplitude ratio), which is proportional to the radial distance. A model may be judged to have improved if: (i) the correlation increases, (ii) its diagram point shifts toward the observed point, indicating a reduction in RMS error, and (iii) the point, representing a model, moves toward the dotted arc, i.e. the simulated SD moves toward the observed.

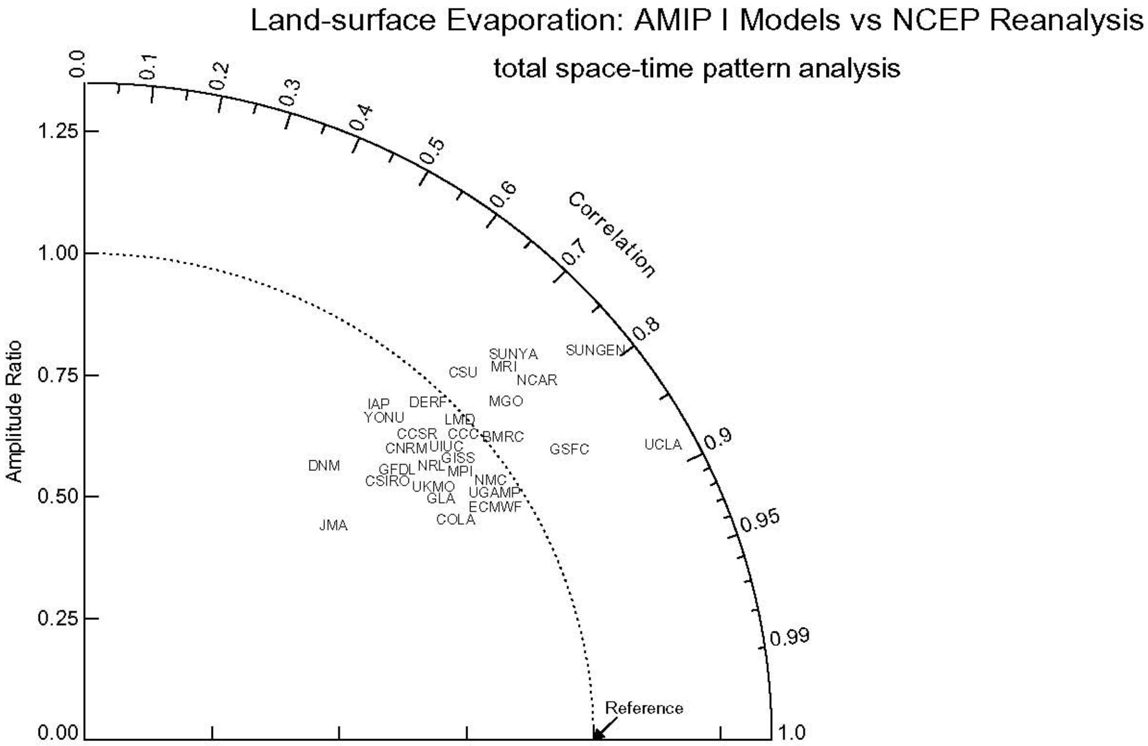

Fig.2. *Taylor diagram of the structure of the total variability of monthly mean land-surface evaporation in 1979 – 1988 simulations of the AMIP I models relative to that of NCEP Reanalysis-1 ("Reference") estimates over the same time period.*

An example of such a Taylor diagram is shown in Figure 2 for the land-surface evaporation from the AMIP I models (Phillips et al., 2000), where the validation reference is the NCEP Reanalysis-1 data ("Reference"). Though this data provide only a rough estimate of the actual variability of land-surface evaporation, it is seen from this diagram that the inter-model scatter is quite large: amplitude ratios range between 0.6 and 1.3 and correlations vary from 0.7 and 0.9.

Given the wider range of land surface schemes employed in AMIP II, diagnostic Subproject 12 was aimed to analyze the surface energy and water budgets as a function of LSS complexity (Irannejad et al., 2000). As validation datasets, model-derived estimates such NOAA's National Centers for Environmental Prediction (NCEP), the Department of Energy (DOE), the National Center for Atmospheric Research (NCAR), Variable Infiltration Capacity (VIC), and the Global Precipitation Climatology Project (GPCP, http://www.dwd.de/en/FundE/Klima/KLIS/int/GPCC) data were used. NCEP/DOE is not fundamentally different from NCEP/NCAR, but it has been prepared on the basis of an improved forecast model and data assimilation system (Kanamitsu et al., 2000). The VIC dataset has been generated using the VIC land surface scheme driven by forcing from meteorological stations observations of precipitation and extremes (maximum and minimum) in surface air temperature and humidity (Nijssen et al., 2000).

In validating AMIP II simulations of continental climate on the large (continental to global scale), Phillips et al. (2004) examined both coupled atmospheric forcing (e.g., precipitation) and surface response (e.g., evaporation/latent heat flux). They constructed the Taylor diagram to compare the precipitation variability structure of 23 AMIP II against observational data for northern summer, when land – atmosphere coupling is strongest, and found that continental precipitation is generally not well simulated (see Fig. 3). The analogous diagram for JJA continental latent heat flux, which is roughly proportional to evaporation (Fig. 4), shows the generally reduced variability amplitudes of the AMIP II simulations with those of AMIP I results for land-surface evaporation (Fig. 1) and precipitation in Fig. 2.

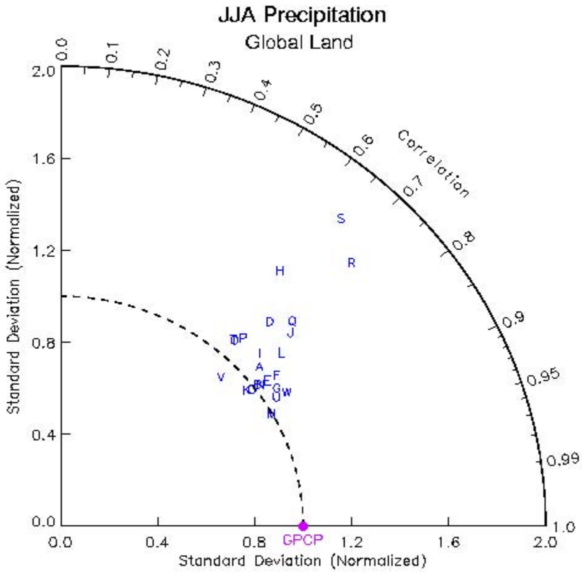

Fig. 3. *Taylor diagram of integrated spatiotemporal structure of continental precipitation variability as obtained from 23 AMIP II simulations labeled as A, B, C,…,W(Phillips et al., 2004).*

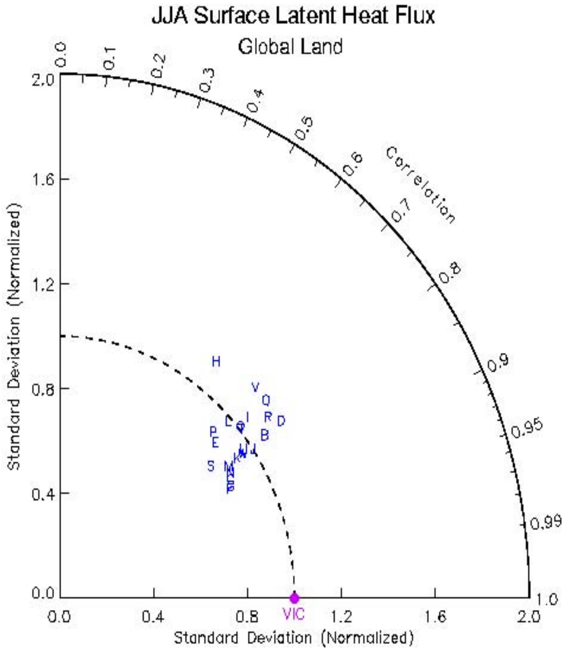

Fig.4. *As in Fig. 3, except for the integrated JJA spatiotemporal structure of continental latent heat flux variability as obtained from 23 AMIP II simulations (Phillips et al., 2004).*

The land surface water balance components simulated by 20 atmospheric global circulation models (AGCMs) were also analyzed globally and over seven Global Energy and Water Cycle Experiment Coordinated Enhanced Observing Period (GEWEX – CEOP) basins: BALTEX, CATCH, GAME-Siberia, GCIP, LBA, MAGS, and MDB (Irannejad et al., 2004, Irannejad and Henderson-Sellers, 2007). It was found that the available reanalysis datasets are not appropriate for evaluation of simulated land surface water components. In particular, NCEP reanalyze does not close the surface water balance. On the other hand, the VIC dataset is generated by observed precipitation and tuned for large river flows, and thus it might be expected that VIC provides a reliable surface water budgets, at least when averaged over large basins and a long period of time.

Most of the AMIP II models close surface water balance within the acceptable range globally and in most of the GEWEX – CEOP basins. The worst simulation of the surface water budget is performed in the Murray–Darling, the most arid basin, where all the reanalysis and seven of the models produced a negative surface water budget, with evaporation exceeding precipitation and soil moisture decreasing over the whole AMIP II period in this basin. The spatiotemporal correlation coefficients between observed and simulated runoff are smaller than those for precipitation. In almost all basins (except for the two most arid basins), the spatiotemporal variations of simulated evaporation are more coherent and agree better with observations, compared to those of simulated precipitation. It is possible to assume that differences among the AGCMs' surface water budget predictions are not solely due to model-generated precipitation differences. It is shown that different land surface schemes partition precipitation between evaporation and runoff differently and that this is also responsible for different predictions of basin-scale water budgets. This means that the selection of a land surface scheme for an atmospheric model has significant impacts on the predicted continental and basin-scale surface hydrology.

An important output of the AMIP program has been the solution of the following problems: (i) description of the present-day climate (1979–1995), (ii) study of the nature of monsoon circulation, (iii) investigation of the response of atmospheric circulation to an El Niño event, (iv) study of the role of soil processes in the formation of atmospheric dynamics, and (v) investigation of the interaction of radiation with cloudiness related to superabsorption in clouds. Among other interesting problems, one can note the modeling of (i) the stratosphere and mesosphere, (ii) the negative trend of temperature near the mesopause during the past three decades, and (iii) the role (in this process) of increasing carbon dioxide concentration and decreasing ozone concentration in the stratosphere.

The recent intercomparison of atmospheric general circulation models made within the framework of AMIP II has shown that the best of these models are presently capable of reproducing the main features of the observed atmospheric circulation with good accuracy. Errors in reproducing many climatic quantities with such models are only slightly greater in value than the uncertainties with which these quantities are determined from observations. At the same time, there are also systematic errors in climate reproduction, which are inherent in virtually all of these models. The most complete analysis of climate reproduction with the models participating in AMIP II can be found at http://www-pcmdi.llnl.gov/amip.

3. Coupled Model Intercomparison Project (CMIP) Achievements

Diagnostic studies of the surface air temperature indicate the following: (i) for the past 30 years, marked changes have occurred in the surface air temperature averaged over decades - it has increased; (ii) maximum winter temperature changes are observed in Siberia and northwestern Canada; (iii) summer temperature changes are substantially smaller; and (iv) the sea surface temperature of the North Atlantic has not increased but even decreased. The question arises as to what the cause of these changes is. Do these changes result from proper oscillations of the climate system's parameters or do they result from anthropogenic impacts associated, for example, with increasing concentrations of carbon dioxide and sulfate constituents in the atmosphere?

To answer this question, the AMIP project has been developed in the Coupled Model Intercomparison Project (CMIP), which is the analog of AMIP for global coupled ocean-atmosphere general circulation models. During CMIP performance, the emphasis is made on the reproduction of the sea surface temperature and sea ice distribution (see http://www-pcmdi.llnl.gov/projects/cmip/index.php) because these characteristics were considered to be specified external parameters in the AMIP experiments. At present, CMIP is being performed to compare the climate-change predictions obtained with different climate models under the scenarios proposed by IPCC (2001) for possible future variations in the atmospheric concentrations of greenhouse gases, aerosols, and other pollutants. This program is a step forward as compared to a similar comparison that was carried out in 2001 and whose results were reflected in the third IPCC report (IPCC, 2001). The results obtained in the course of this program are reflected in the fourth IPCC report (IPCC, 2007).

Table 3. *A listing of CMIP3 climate models*

CMIP3 I.D.	Country	Originating Group(s)
BCC-CM1	China	CM1Beijing Climate Center
BCCR-BCM2.0	Norway	Bjerknes Centre for Climate Research
CCSM3	USA	National Center for Atmospheric Research
CGCM3.1 (T47)	Canada	Canadian Centre for Climate Modelling & Analysis
CGCM3.1 (T63)	Canada	Canadian Centre for Climate Modelling & Analysis
CNRM-CM3	France	Météo-France / Centre National de Recherches Météorologiques
CSIRO-Mk3.0	Australia	CSIRO Atmospheric Research
CSIRO-Mk3.5	Australia	CSIRO Atmospheric Research
ECHAM5/MPI-OM	Germany	Max Planck Institute for Meteorology
ECHO-G	Germany / Korea	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group
FGOALS-g1.0	China	LASG / Institute of Atmospheric Physics
GFDL-CM2.0	USA	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory
GFDL-CM2.1	USA	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory
GISS-AOM	USA	NASA / Goddard Institute for Space Studies
GISS-EH	USA	NASA / Goddard Institute for Space Studies
GISS-ER	USA	NASA / Goddard Institute for Space Studies
INGV-SXG	Italy	Instituto Nazionale di Geofisica e Vulcanologia
INM-CM3.0	Russia	Institute for Numerical Mathematics
IPSL-CM4	France	Institut Pierre Simon Laplace
MIROC3.2 (hires)	Japan	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)
MIROC3.2 (medres)	Japan	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)
MRI-CGCM2.3.2	Japan	Meteorological Research Institute
PCM	USA	National Center for Atmospheric Research
UKMO-HadCM3	UK	Hadley Centre for Climate Prediction and Research / Met Office
UKMO-HadGEM1	UK	Hadley Centre for Climate Prediction and Research / Met Office

Global coupled ocean - atmosphere general circulation models that include also interactive sea ice simulate the physical climate system, given only a small number of external boundary conditions such as the solar "constant" and atmospheric concentrations of radiatively active gases and aerosols. Coupled GCMs have been used to separate natural variability from anthropogenic effects in the climate record of the 20th century, and to estimate future anthropogenic climate changes including global warming (AchutaRao et al., 2004). In 1995 the JSC/CLIVAR Working Group on Coupled Models, part of the World Climate Research Program, established the Coupled Model Intercomparison Project (CMIP; Meehl et al., 2000).

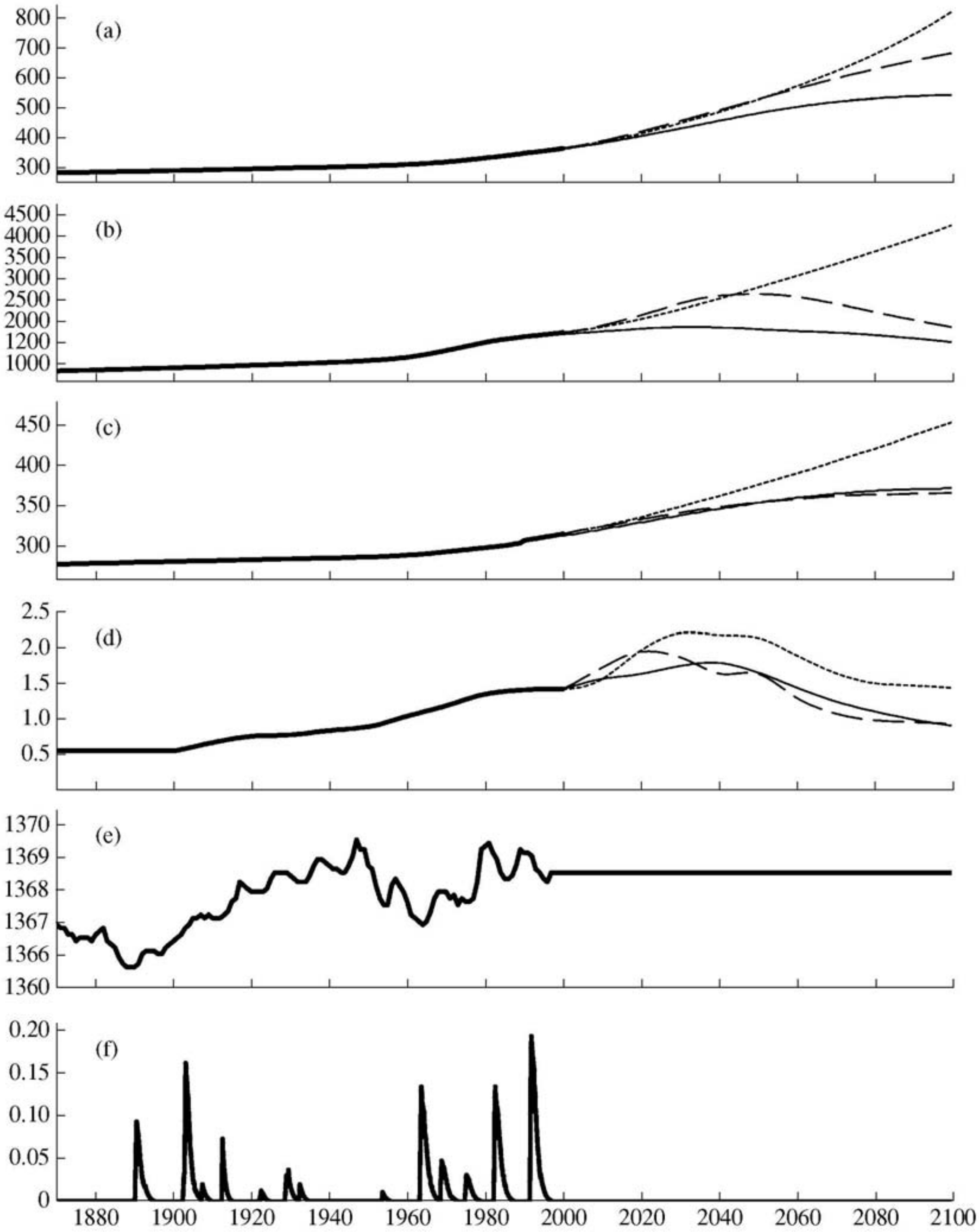

Fig.5. *Variations in the contents of (a) carbon dioxide (ppm), (b) methane (ppb), (c) nitrous oxide (ppb), and (d) integral sulfate aerosol (mg/m^2); in (e) the solar constant (W/m^2); and in (f) the integral optical thickness of volcanic aerosol (dimensionless) in (heavy solid line) the experiment for the 20th century and in the experiments with IPCC scenarios (thin solid line) B1, (dashed line) A1B, and (dotted line) A2.*

The first phase of CMIP, labeled as CMIP1, collected output from coupled GCM control runs in which CO_2, solar brightness and other external climatic forcing was kept constant. A subsequent phase, CMIP2, collected output from both model control runs and matching runs in which CO_2 increases at the rate of 1% per year for a period of 80 years. No other anthropogenic climate forcing factors, such as anthropogenic aerosols (which have a net cooling effect), are included. In the CMIP3 phase, output from coupled ocean-atmosphere model simulations of 20th - 22nd century climate was collected in support of research relied on by the 4th Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). As of February 2007, over 32 Tb of data were generated in the archive (see http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). Table 3 contains a listing of the CMIP3 climate models. Results of numerical experiments with the INM climate model on reproduction of climate changes in the 20th century and estimation of possible climate changes in the 21st and 22nd centuries in accordance with three scenarios of changes in the contents of greenhouse and other gases (IPCC, 2001) have been presented by Volodin and Diansky (2006). The temporal behaviors of external forcing and of the contents of carbon dioxide, methane, nitrous oxide, and sulfate aerosol in the 21st century according to different scenarios are shown in Fig. 5. In Russia, such experiments have been performed for the first time and their results were used in AR4 (IPCC, 2007).

The IPCC scenarios for future concentration of greenhouse gases were used to estimate possible both global and regional (in particular, for Siberia) consequences. Accordingly to the INM climate model results, the global warming to the end of 21st century will be, depending on scenario, of value from 2.0^{o}C to 3.5^{o}C. The most pronounced warming is expected in Arctic and in middle latitudes, especially, in Russia. For example, under scenario A1B the global warming is expected to be about 3.3^{o}C, while the winter warming in Russia is estimated from 4-6^{o}C in southern part to 8-10^{o}C in northern regions. In summer, the warming in Russia is estimated from 5-6^{o}C in south to 3-4^{o}C in north. Thus, one can expect essential consequences of this warming to the Siberia environment. In Fig. 6 possible catastrophic shortage of the permafrost area in Siberia to the end of 21st century are shown. The results of numerical experiments with the INM climate model show that the possible changes in the snow water equivalent depth (Fig. 8) may be comparable with the present-day quantities (Fig. 7).

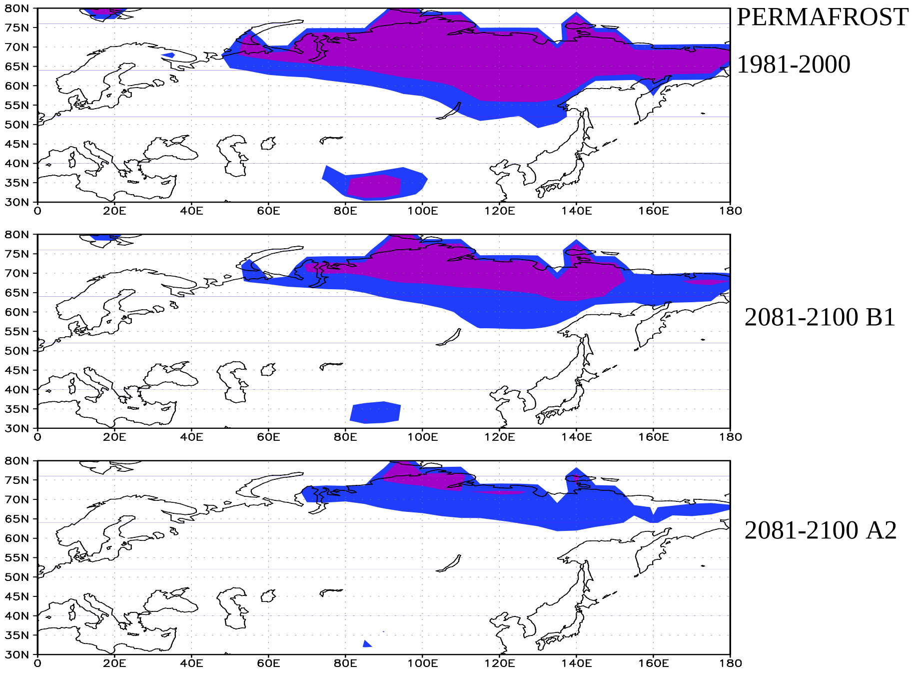

Fig. 6. *Spatial distribution of continuous (violet) and sporadic (blue) permafrost as follows from INM climate model experiments: in 1981-2000 (top), 2081 - 2100 under scenario B1 (middle) and in 2081 - 2100 under scenario A2 (bottom).*

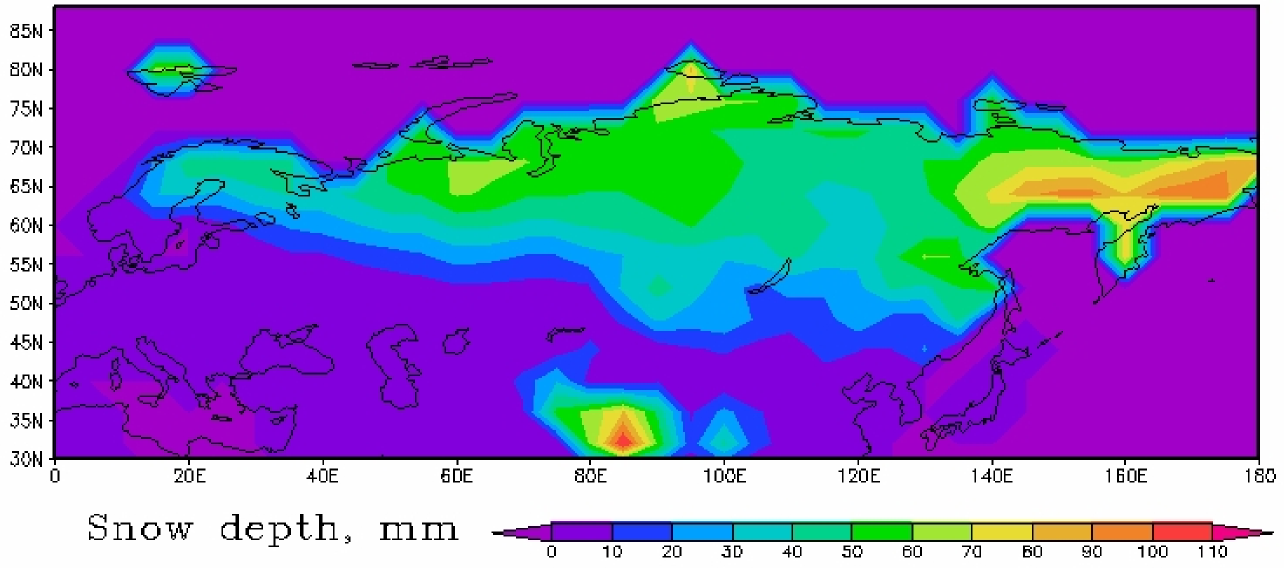

Fig. 7. *Spatial distribution of the snow water equivalent depth for the present-day climate as follows from the INM "Climate of the 20th Century" experiment (max snow depth = 111 mm; CGCM INM RAS).*

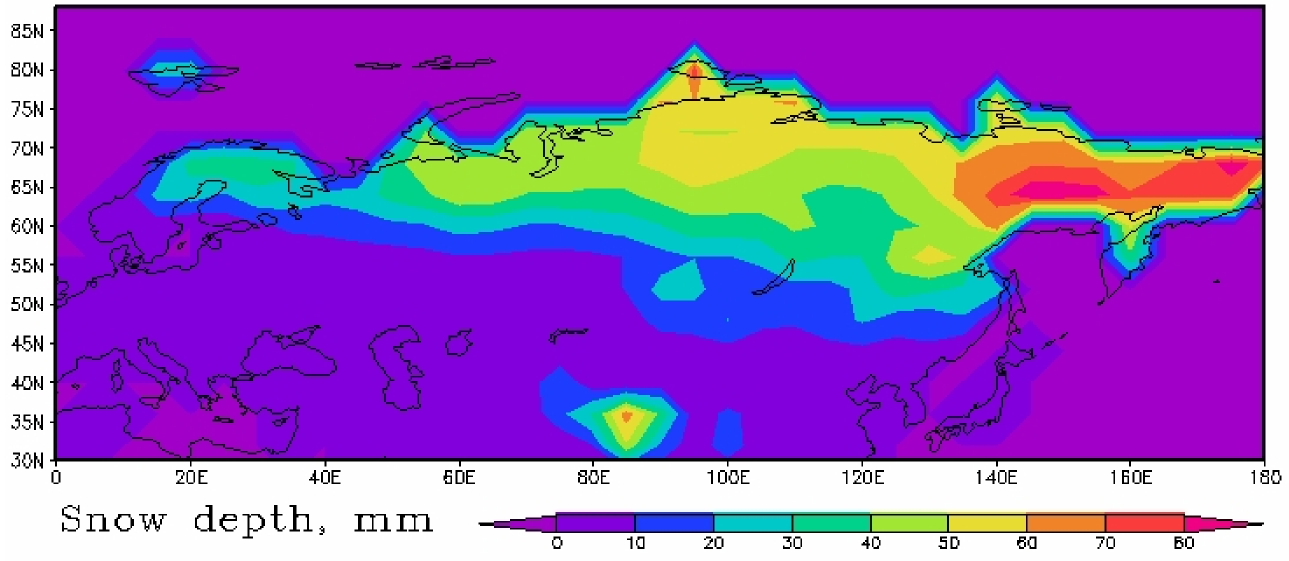

Fig. 8*. Spatial distribution of the snow water equivalent depth difference between the IPCC scenario A1B experiment and present-day climate experiment with the INM model (max snow depth = 89 mm; CGCM INM RAS).*

4. Modelling of Cryospheric and Biogeochemical Processes

As it is abovementioned, cryospheric processes play very important role in the surface energy and water balance under the cold climate conditions. Numerous observational studies and model simulations have shown that the snow cover affects atmospheric circulation, air temperature, and the hydrologic cycle. The adequate prediction of the melting rate of the snow and time of its complete ablation is of particular importance for the climate modelling since these processes determine the moment, after which the ground temperature starts to rise above the freezing point value. Snow-albedo feedback (SAF) enhances Northern Hemisphere extra tropical climate sensitivity in climate change simulations. Qu and Hall (2007) found that the strength of SAF in the current generation of transient climate change simulations of AR4 is determined primarily by the surface-albedo decrease associated with loss of snow cover rather than the reduction in snow albedo due to snow metamorphosis in a warming climate. The large inter-model spread in SAF strength they attributed mostly to the snow cover component.

To represent land surface processes in atmospheric models different schemes have been developed, including soil–vegetation–atmosphere transfer schemes (SVATs) that incorporate snow models of the different complexity (see, for example, Slater et al., 2001). At the moment many time series of different meteorological and hydrological characteristics have been accumulated from different field experiments and regular observations. It makes possible thorough evaluation and intercomparison of snow models to understand what snow processes must be represented in the coupled SVAT and atmospheric models.

In particular, Volodina et al. (2000) have considered three consecutively complicated versions of description of the heat and moisture transfer processes in snow cover for the one-dimensional model of the atmosphere-soil interaction (Volodin and Lykosov, 1998). It is assumed that the snow melting occurs, if the surface temperature is above the freezing point. In the version 1, the snowmelt water and rain are allowed immediately reach the soil surface (this approach is widely used in recent climate models). A more complete approach is that according to which the snowmelt water at the snow surface would not be at once at the soil surface, but would percolate through the snow cover, refreeze and give the latent heat to snow (version 2). The third version of the model approximates real physical processes most detailed. Here, the snow cover is considered as a multilayer medium, each layer of which is characterized by its own temperature, water content, depth, density and porosity, depending on the snow density.

The comparison of the results of simulation between each other and with observed data from the Russian research station Valdai was performed. The observed data spans the 18-years period from 1966 to 1983. It is found that processes of the percolation of melted water and rain through the snow cover and its freezing, as well as refreezing of the water that is trapped within the snow, affects essentially the water-equivalent snow depth and as the result, the runoff. In Fig. 9, the mean annual cycle of the water-equivalent snow depth calculated with different versions of the model and from observed data is presented. One can note that the model catches basic qualitative features of the observed snow cover dynamics. At the same time, one can also see that the water-equivalent snow depth, simulated by the basic model version 1, is systematically underestimated during all the winter and spring months. The observed maximum value of snow depth can be noted on 19 March and is equal to 13.3 cm, whereas this version of the model produces the maximum value of 9.9 cm on 3 March. On the average, snow completely disappears on 10 May, but in the basic version of the model it disappears to 5 May.

From Fig. 9, one can see that the best results are obtained by means of the version 3 that contained the most detailed description of physical processes in the snow cover. The maximum of the mean snow depth is simulated to occur on 16 March and equals to 11.8 cm. The difference between observed and simulated snow depth values during the winter months is approximately 2 times less then in both previous versions. The maximum difference is obtained on 28 March and equals to 1.8 cm. Moreover, the date of complete snow withdraw is shifted to 8 May. Thus, one can conclude that the inter-model spread in SAF strength might be decreased (at least, partially) by the use of more sophisticated parameterization of processes in the snow cover.

Machul'skaya and Lykosov (2002) have used routine observations made at the Franklin Bluffs research station (Alaska) and four meteorological stations located in northern and central Siberia to perform a series of experiments with a one-dimensional model of heat and moisture transfer in the snow – permafrost system. The model is shown to be capable of reproducing qualitative and quantitative features of the thermal conditions in permafrost. The ground temperature and the depth of seasonal thaw are shown to be highly sensitive to processes that affect snow densification. It is also shown that the thickness of the active layer is highly sensitive to variations in the moss – lichen – peat cover depth, which is relatively small in nature.

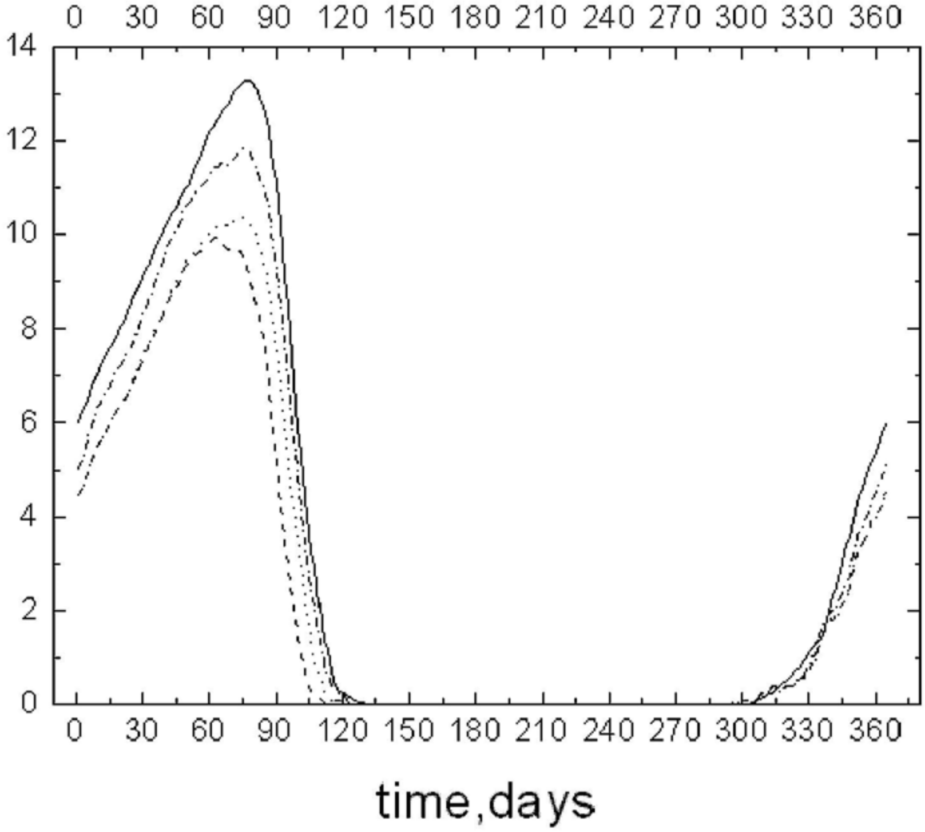

Fig. 9. *Mean annual cycle of observed (solid line) and simulated water-equivalent snow depth (cm). Dashed, dotted and dot-dashed lines show results of simulation with 1st, 2nd and 3rd version of the above mentioned model, respectively.*

Implications of global climatic change to Siberia and Siberian contributions to global climate change are two sides of one medal. Globally effective anthropogenic influences are of relevance on local scales, while local response to these implications on the global scale. Linked with this anticipated changes are potential risks or unknowns, which are related for example with changes in land cover/land use (fires, forest logging, transition steppe ⇆ agriculture), changing permafrost conditions (deepening of active layer, destruction of frozen soil C stores) or changes in snow cover, sea ice extension, etc. which might provoke alterations in atmospheric circulation schemes. One aim of scientists is therefore the qualification and the quantification of the occurring processes and their effects on ecosystems and the atmospheric composition and circulation patterns. This goal needs at least a description the previous conditions, the acquisition of the actual status and predictions regarding the future development.

The Siberian boreal forest is a significant component of the global carbon cycle, since it stores about 10% of the global terrestrial carbon in vegetation and soils, whereby about 65% of the Siberian forests contain permafrost with a carbon storage assumed to be in the order of roughly 400 PgC. Environmental risks, i.e. affections by anthropogenic influences via global climate change, as well as direct impacts on the local/regional scale will provoke changes and adaptations of the present ecosystems. Recent research on the impacts of climate change in high latitudes has mostly assessed the “equilibrium” response of ecosystems. An example is the question what the “potential” location of the Arctic tree-line or the southern limit of permafrost would be under conditions of global warming. However, of much greater importance, not least from a political perspective, are transient responses of the climate system. Examples of such questions are: How quickly will the Arctic tree-line migrate? How quickly will permafrost thaw? How quickly will enhanced soil organic matter decay result in increased greenhouse gas emissions? Different time lags in these processes will cause significant deviations from the equilibrium response.

To answer some of these questions, in frame of the RFBR (**R**ussian **F**oundation for **B**asic **R**esearch) project "Development of atmospheric and oceanic general circulation model with carbon cycle" (INM, Grant # 06-05-64331) a carbon cycle block is included into the INM climate model. This block includes description of the plant, soil, ocean and atmospheric carbon evolution. The model was run from 1860 to 2100 with prescribed scenario of CO_2 emission due to the fuel burning and land use. It was found that the simulated spatial distribution of carbon in plants, soil and ocean agrees with present estimations. The model is capable to reproduce observed increase of CO_2 in 20-th century as well as the absorbing of additional carbon by terrestrial and marine ecosystems in 80-th and 90-th years of 20-th century. The feedback between climate change and carbon cycle in the model is found to be positive with the feedback coefficient close to the value obtained by averaging over all present-day climate models with the carbon cycle. The global warming in 2081-2100 with respect to 1981-2000 is found to be equal 2.3 degrees.

The Danish Meteorological Institute also has a long tradition in permafrost modeling. The zonation of present-day permafrost can be estimated from deep-soil temperatures obtained from global coupled atmosphere-ocean general circulation models (Stendel and Christensen, 2002) by accounting for heat conduction in the frozen soil. But it is impossible to explicitly resolve soil properties, vegetation cover and ice contents in reasonable details. The coarse resolution of contemporary general circulation models (GCMs) that prevents a realistic description of soil characteristics, vegetation, and topography within a model grid box is the major limitation for use in permafrost modeling. On the local scale, descriptions of the heterogeneous soil structure in the Arctic exist only for limited areas. Furthermore, if it is necessary to model the future fate of permafrost, one should use dedicated scenarios, which, due to computer limitations, so far only exist for global models.

In principle, semi-empirical approaches, e.g. based on the Stefan (1891) formula, can give a more realistic depiction of permafrost temperatures and active layer thicknesses while at the same time avoiding problems inevitably associated with the explicit treatment of soil freezing and thawing in climate models. In order to narrow the gap between typical GCMs on one hand and local permafrost models on the other, one can use as an intermediate step a high resolution regional climate model (RCM) to downscale surface climate characteristics to a scale comparable to that of a detailed permafrost model (Stendel et al., 2007). The global model, which was used, is the coupled ECHAM4-OPYC in a horizontal resolution of T42, the RCM is HIRHAM4, run at 50 km resolution and the permafrost model (GIPL) is from the University of Alaska, Fairbanks with a resolution of 0.5 degrees. This means that it is possible to force the permafrost model directly with RCM output.

Such an introduction of dynamical downscaling in permafrost modeling results in a more realistic depiction of present-day mean annual ground temperature and active layer depth, in particular in mountainous regions. By using global climate change scenarios as driving fields, one can obtain permafrost dynamics in high temporal resolution on the order of years. For the 21st century under the IPCC SRES scenarios A2 and B2, an increase of mean annual ground temperature by up to 6 K (Fig. 10) and of active layer depth by up to 2 m within the East Siberian transect are found. According to these simulations, a significant part of the transect will suffer from permafrost degradation by the end of the century.

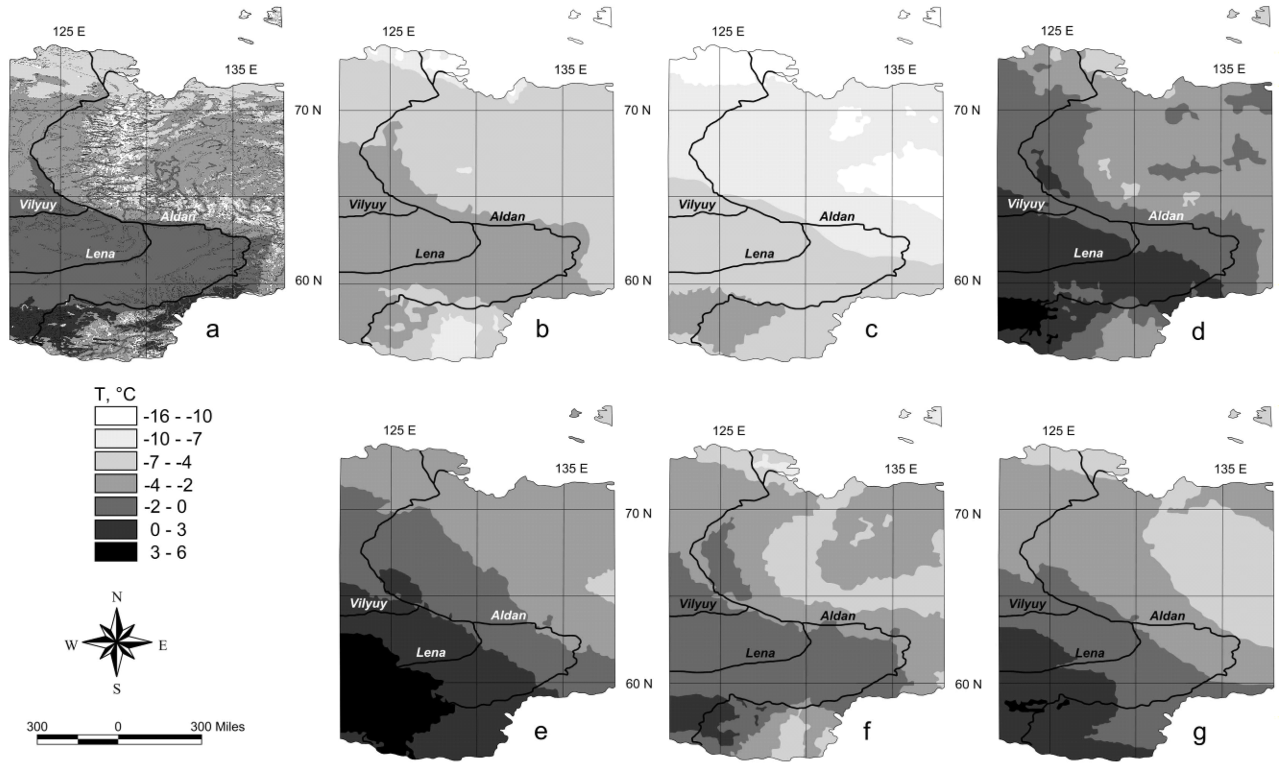

Fig. 10. *Temporal change of mean annual ground temperature [°C] (a) derived from the Map of Landscapes and Permafrost Conditions in Yakutia (scale 1:2,500,000) (Melnikov, 1988) , GIPL model forced with (b) HIRHAM control run, (c) ECHAM control run, (d) HIRHAM, scenario A2, average 2071-2100, (e) ECHAM, scenario A2, average 2071-2100, (f) as (d) and (g) as (e), for scenario B2.*

Large amounts of soil carbon deposited in permafrost may be released due to deeper seasonal thawing under the climatic conditions projected for the future (Anisimov, 2007). An increase in the volume of the available organic material together with the higher ground temperatures may lead to enhanced emission of greenhouse gasses, in particular, of methane, which has a much stronger greenhouse effect than an equal amount of CO_2. Production of methane is favored in the wetlands, which occupy up to 0.7 million km^2 in Russian permafrost regions and have accumulated about 50 Gt of carbon (Gt C). In the abovementioned paper, a permafrost model and several climatic scenarios are used to construct projections of the soil temperature and the depth of seasonal thawing. To evaluate the effect of such changes on the volume of the seasonally thawing organic material, the permafrost projections were overlaid on the digitized geographically referenced contours of 59 846 wetlands in the Russian Arctic. Results for the mid-21st century climate indicated up to 50% increase in the volume of organic substrate in the northernmost locations along the Arctic coast and in East Siberia, where wetlands are sparse, and a relatively small increase by 10%–15% in West Siberia, where wetlands occupy 50%–80% of the land (see Fig. 11). A soil carbon model was developed to estimate the changes in the methane fluxes due to higher soil temperature and increased substrate availability. It was found that by mid-21st century the annual net flux of methane from Russian permafrost regions may increase by 6–8 Mt, depending on climatic scenario. If other sinks and sources of methane remain unchanged, this may increase the overall content of methane in the atmosphere by approximately 100 Mt, or 0.04 ppm, and lead to 0.012 °C global temperature rise.

It should be noted that current development of mathematical models of climate is characterized by a permanent increase of its spatial resolution and by the rejection the hydrostatic approximation (at least in regional models). These tendencies cause new problems in the parameterization of subgrid-scale processes. Among those problems one of crucial importance is the interaction of the atmosphere with hydrologically heterogeneous land – the territory, occupied by a dense network of water bodies (lakes, rivers, wetlands, etc.), covering a significant fraction of the total area. A good example of hydrological heterogeneity is the territory of Western Siberia (where water bodies occupy up to 50% of the area), Karalee, and North America. Due to the difference in the vertical heat exchange mechanisms between water bodies and soil, the distribution of surface temperature in such a territory in warm season is very heterogeneous: during daytime water bodies (for example, lakes) act as cold patches, and at night as ‘heat islands’, initiating in both cases breeze like circulations. Under conditions of strong synoptic flow, the breeze circulation is almost negligible, but even in this case lakes still considerably affect the structure of the boundary layer (Stepanenko et al., 2006). Thus, it is possible to suggest that the further improvement of land-surface schemes might be done by taking into account effects of the land surface heterogeneity.

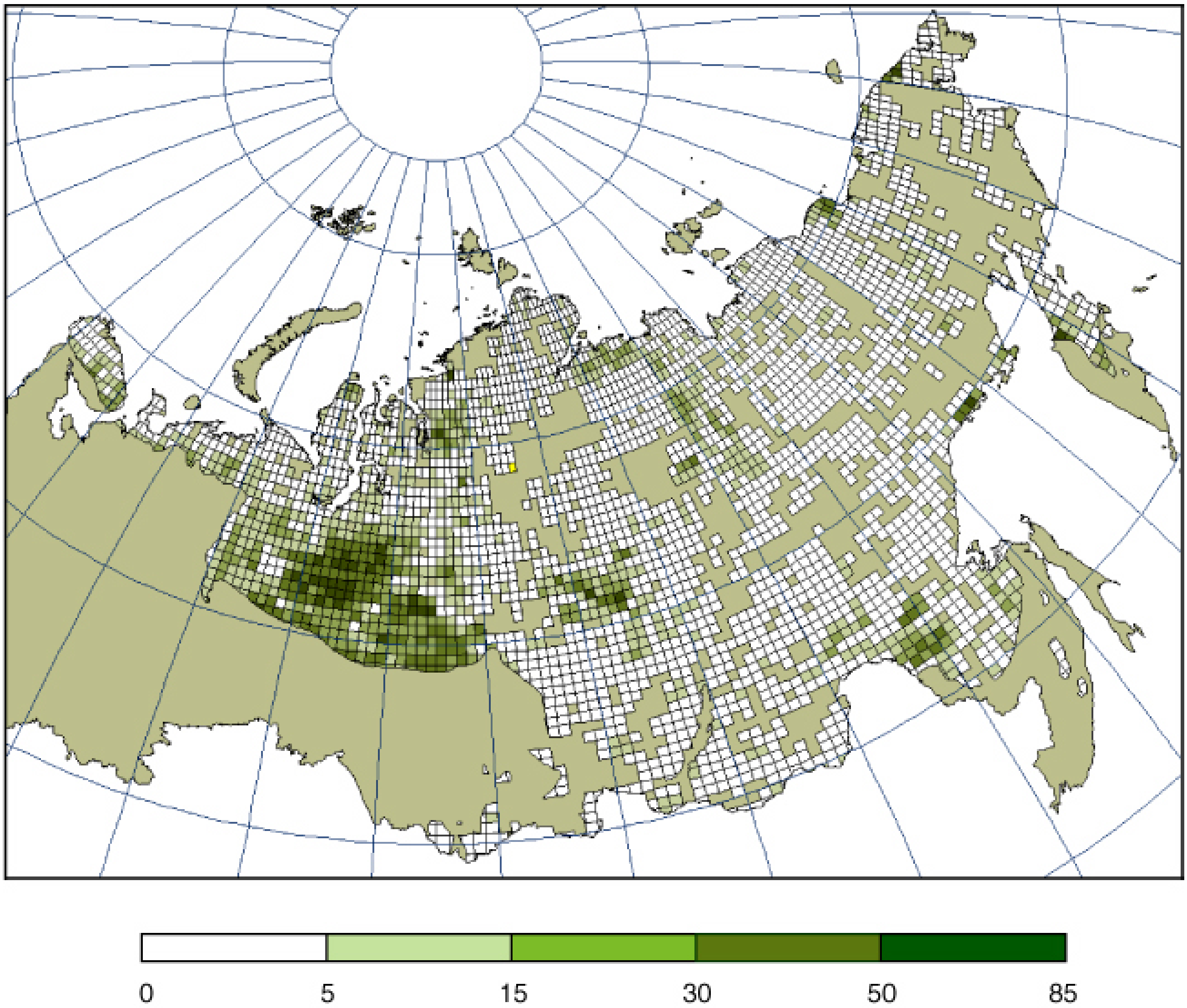

Fig. 11. Fraction of land area occupied by wetlands in Russian permafrost region (Anisimov, 2007).

5. Regionalization of Climate Models

Joint use of experimental data and the results obtained by mathematical modeling seems to be the most expedient both for estimation of the current state of the climate system and for forecasting its further evolution using the verified climate models. At the same time, there is an essential circumstance related to the spatial scales of the system under study. The problem arises, in mathematically modeling the global climate system, on the parameterization of the processes of subgrid scales that assumes the necessity of studying its regional (most likely, the mesoscale) peculiarities. On the other hand, the results of empirical modeling based on instrumental data obtained on a limited territory are often overburdened with its microscale peculiarities and do not reveal the macroscale regularities. The approach seems to be a compromise, which uses the results obtained using global climate models of sufficient spatial resolution (along with the data of the network of meteorological, aerological, and remote observations) as characteristics of the external climate-forming factors, while the empirical and local (mesoscale) mathematical models are used for climate-ecological estimation of the regional consequences of the global processes, especially in the boundary layer of the atmosphere as human natural habitat.

Analysis of results of reproduction by the INM climate model of regional features of the atmosphere and land interaction has shown that there are systematic errors in characteristics of heat- and moisture exchange in the Western Siberia region in warm season. It is important to stress out that widely used NCAR/NCEP reanalysis data and ECMWF reanalysis data are significantly differ in this region. The possible reason of this inconsistency could be non-adequate accounting of hydrological processes. In many forecast models and land data assimilation systems inland waters are considered as land surface elements. In reality, lakes in middle and high latitudes are vertically stratified on density.

Moreover, the current development of climate models is characterized by a permanent increase of spatial resolution. This tendency causes new problems in the parameterization of subgrid-scale processes. Among those problems one of crucial importance is the interaction of the atmosphere with hydrologically heterogeneous land – the territory, occupied by a dense network of inland waters, covering a significant fraction of the total area (for example, the territory of Western Siberia). Two-way approach might be employed to solve this problem: an aggregation of subgrid-scale turbulent fluxes and the use of a physically sound and computationally efficient lake model capable of predicting the lake vertical temperature structure, as well as the evolution of the ice and snow cover. It is especially important to reveal the climatic characteristics (as well as the accuracy of their determination) necessary to simulate hydrologic processes (with consideration for the response of the latter to variations in the corresponding climatic characteristics). With the aim to study processes of interaction of the atmosphere and underlying surface, covered by a dense net of hydrological objects the one-dimensional model of lake was included into nonhydrostatic mesoscale atmospheric model (Stepanenko V.M. et al., 2006). Numerical experiments have demonstrated that modified in such a manner mesoscale model is adequately reproduced the complicated structure of breeze-like flows over the hydrologically inhomogeneous land surface, as well as classical mountain-valley circulation.

Recently started RFBR project "Mathematical modeling of mesoscale interaction between the atmosphere and hydrologically heterogeneous land" (INM, Grant # 07-05-00200) is devoted to the study of physical processes and mechanisms, which are responsible for the mesoscale interaction between the atmosphere and hydrologically inhomogeneous land surface under cold climate conditions (in particular, in the Western Siberia). A special attention is paid to modeling admixtures transport, e.g. in the case of snow storm. Here, very intrigue (both from theoretical and applied points of view) problem is an interaction between turbulence and snow particles, which leads sometime to an intermittency of the atmospheric dynamics and snow transport. Poetically, this idea was firstly expressed by the famous Russian writer Alexander Pushkin ("Winter Evening", 1825, see http://www.pushkins-poems.com/push02.htm):

The storm wind covers the sky
Whirling the fleecy snow drifts,
Now it howls like a wolf,
Now it is crying, like a lost child,
Now rustling the decayed thatch
On our tumbledown roof,

Now, like a delayed traveler,
Knocking on our window pane.

An advance snow-ice module will be developed and implemented in the mesoscale model on the basis of a thermodynamic ice model and a multi-layer snow model, which includes refined parameterizations of various complex processes, such as accumulation, aging and melting of snow, saltation, diffusion and evaporation of snow particles. Numerical experiments will be carried out to study the formation and evolution of a snow storm.

The RFBR granted Project “Development of new and improvement of known technologies to solve inverse problems of climatology by statistical methods” (INM, Grant # 07-05-00328) is aimed on the reconstruction of regional peculiarities of meteorological parameters on the basis of statistical downscaling of climate model output and/or observational data. Although hydrodynamic climate models represent the main features of the global atmospheric circulation reasonably well, their performance in reproducing regional climatic details (for example, such as precipitation and surface wind speed) is rather poor. With respect to the simulation of regional climates global models suffer from several limitations, including lack of accurate surface condition data, inability of model parameterizations to model fine scales, and computational time required for high resolution numerical experiments. Hence, most climate models are still run at relatively coarse spatial resolutions. As a result, there is a need to develop tools for downscaling model predictions of climate change to regional and local scales. The statistical approach, which involves relating large scale parameters (upper level wind, geopotential, temperature, etc.) to routine observations of the surface parameter of interest (temperature, precipitation, wind speed, etc.), will be used to reconstruct regional details of meteorological fields.

Basic processes, which form the annual cycle of climate, are connected with seasonal changes in the thermal regime of the atmosphere over continents, in the large-scale atmosphere – ocean interaction and in the latitudinal heat and mass exchange. The consideration of four seasons, two of which one can call as extreme seasons (winter and summer) and two others as transition seasons (spring and autumn), is connected with changes in the annual cycle of the solar radiation, which achieves extreme values in winter and summer and is sharply changing in transitional seasons. As it is stated in (IPCC, 2007), many regional climate changes can be described in terms of preferred patterns of climate variability. For example, the North Atlantic Oscillation (NAO) is a measure of the strength of the Icelandic Low and the Azores High, and of the westerly winds between them. When the atmospheric pressure over the central Atlantic is higher than normal, strong westerly winds transport heat and precipitation toward Northern Eurasia more intensively. The RFBR Project “Reproduction of climate anomalies on intra-seasonal scale by coupled model of general circulation of the atmosphere and ocean” (INM, Grant # 07-05-00893) is devoted to the study of seasonal climate anomalies on the basis of numerical experiments with the coupled semi-Lagrangian atmospheric model and finite-difference oceanic model.

Parameterization of sub-grid scale turbulent processes is one of important topics of climate modeling. The RAS Program “Computational and information aspects of solving the huge problems” Project “Large-eddy simulation of geophysical boundary layers on computational systems of parallel architecture” (INM) is aimed on study of turbulent processes in the atmospheric and oceanic boundary layers, using mathematical models based on modern computational technologies and implemented on supercomputers of parallel architecture with distributed memory. According to A.S. Monin, turbulence is defined as “… an eddy flow with a very large number of disturbed degrees of freedom and a chaotic distribution of dispersion relationships and phase shifts”. The behavior of a turbulent flow cannot be predicted exactly. However, one can try to construct a model that adequately reproduces the statistical characteristics of turbulent motion of interest. Due to Kolmogorov’s low, for sufficiently high Reynolds numbers, the distribution of three-dimensional isotropic turbulence includes an inertial range where no energy is produced or dissipated but there is its transport from large to small scales. A reasonable alternative to the direct numerical modeling is the approach based on eddy-resolving simulations. The statistical characteristics of large-scale eddies can be described by a numerical large-eddy simulation model that adequately reproduces the generation of turbulent motions in the low-frequency range and the redistribution of energy over the whole inertial range (or at least in its portion). It means that the spatial resolution of such a model should be fine enough (see Fig. 12). Due to huge amount of computational work (memory resources and CPU time) required for modeling real geophysical phenomena (e.g., turbulent flow and transport of admixtures between and over city buildings), computers based on the parallel architecture should be used.

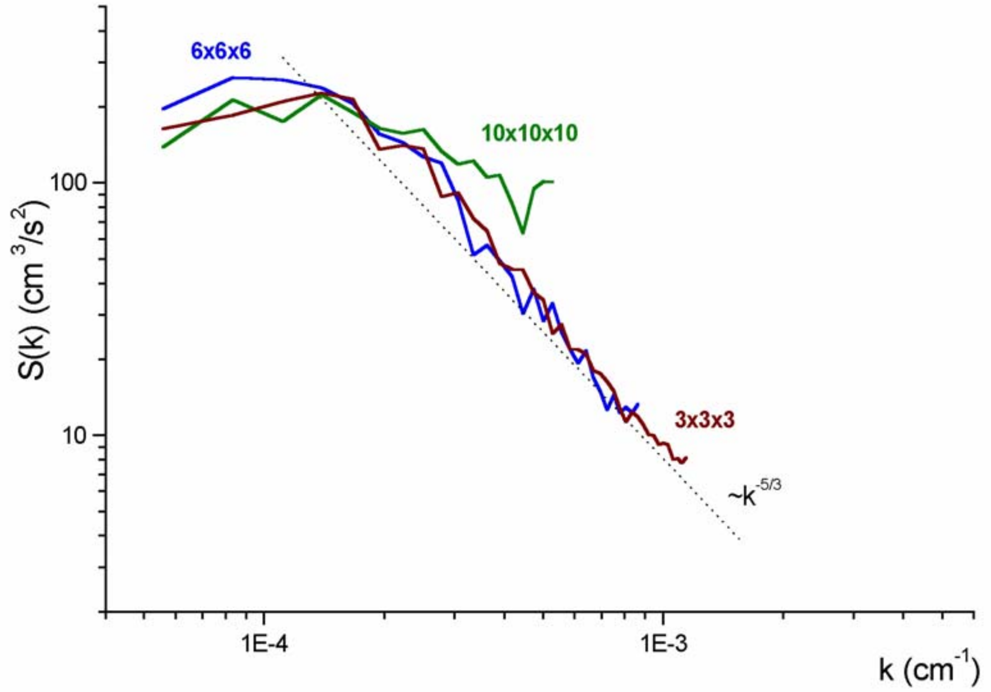

***Fig. 12.** Spectrum of the kinetic energy calculated from the results of numerical experiments with different spatial resolution (10^3, 6^3 and 3^3 cubic meters, respectively) of the upper ocean layer model. The dotted line corresponds to Kolmogorov's low.*

The Russian – British conference and a seminar on hydrologic consequences of climate changes were held in Novosibirsk, Russia, in 2007 (June 13–15). The main objective of the conference was to become acquainted with studies (conducted in both countries) on the effect of climate changes on hydrologic processes in rivers, lakes, and reservoirs (Vasil'ev et al., 2008). The methods used in these studies and the results of estimating possible changes in the hydrologic regime of water bodies and river runoff were considered. The problems under consideration were mainly related to the following lines of investigations: (1) identification of variations in water balance and river runoff under conditions of changing climate according to multiyear hydrological and meteorological observations; (2) analysis of variations in hydrological and meteorological characteristics on the basis of modeling global processes (with the use of atmospheric circulation models); (3) estimation of the response of important hydrologic systems to possible climate changes; (4) analysis of the influence of climate changes on the recurrence and characteristics of extreme hydrologic phenomena; (5) consideration for uncertainty in determining (modeling) hypothetical climate changes in estimating their hydrologic consequences; and (6) consideration for possible climate changes and their hydrologic consequences in the planning and development of water-related activities.

Much attention was given to the indicated problems as applied to water bodies and hydrologic processes under the natural conditions of Siberia and the northern region. In particular, it is noted that a characteristic feature of the formation of river runoff in northern Siberia under permafrost conditions is the influence of the hydrologic conditions of the preceding year. Under these conditions, when the air temperature becomes negative, a certain portion of the water reaching watersheds is conserved in the overwetted soil and only next year does it take an active part in the water cycle and in the formation of runoff.

The RFBR Project “Estimation of feedbacks between vegetation, surface hydrology of Northern Eurasia and Arctic climate on the base of coupled model ocean - atmosphere – vegetation – soil under global climate changes” (Institute of Computational Mathematics and Mathematical Geophysics, Siberian Branch of the Russian Academy of Sciences - ICMMG, Grant # 08-05-00457) is aimed on the study of natural variability of the Earth system. In particular, it is planned to investigate the impact of the North-Atlantic Oscillation in the atmosphere and of the North Atlantic oceanic circulation on climate, surface hydrology and dynamics of vegetation in Northern Eurasia under conditions of increase in greenhouse gases content. Coupled INM climate model and ICMMG land surface model will be used to achieve this aim.

The FP6 project called “CARBO-North” has the aim to quantify the carbon budget in the Northern Russia across the temporal and spatial scales. In the framework of the project, field studies will be conducted in the north-east European Russia (Fig. 13). It is a region, which is characterized by the gradual lowland transitions in vegetation and permafrost conditions. The DMI will contribute with dedicated climate model simulations and provide the requested variables and time slices needed as input for detailed ecosystem studies. It will be necessary to analyze the sensitivity of climate models to a whole suite of land cover, soil and permafrost schemes and to use proxy data to evaluate rates of ecosystem change und past climatic variability. These activities will go along with detailed monitoring and mapping of vegetation, soil and permafrost, which will give input for process-oriented studies, such as tree-line patch dynamics, tundra/forest/river carbon fluxes and ground subsidence, and to GIS-based up-scaling to the regional or pan-Arctic level.

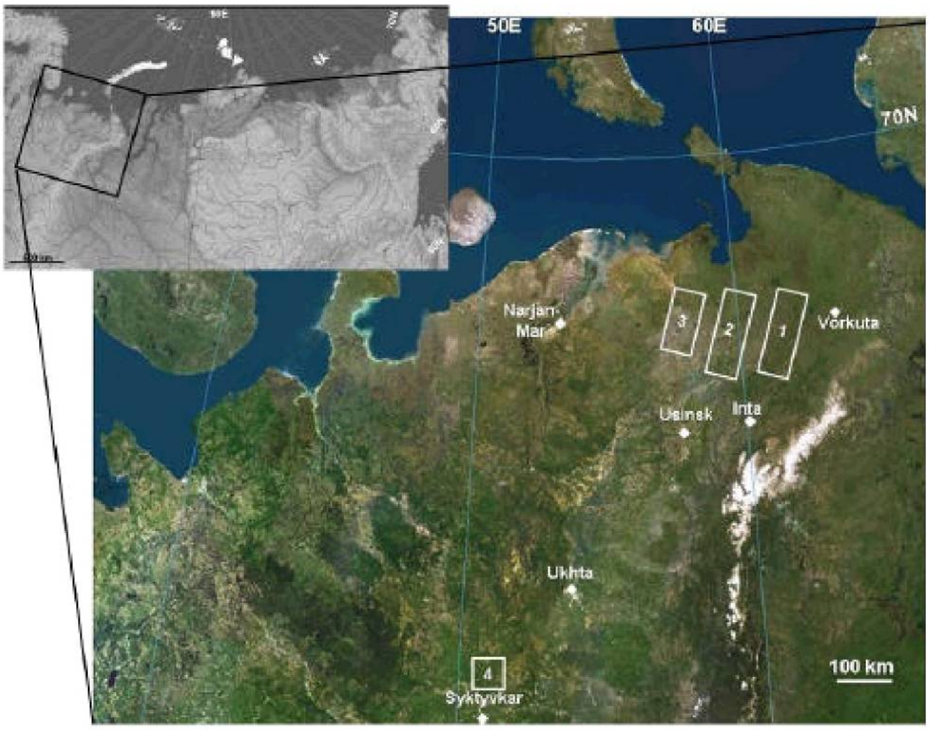

Fig. 13. *Satellite composite of north-east European Russia, with a general location map and major towns in the region. The approximate locations of selected study areas in treeline-tundra and in taiga are indicated. (1: Bolshoya Rogovaya, 2: Adzva, 3: Upper Kolva, 4: Achym).*

From the data obtained from the **T**errestrial **C**arbon **O**bservation **S**ystem Siberia (TCOS-Siberia) project the expected high inter-annual variability of terrestrial carbon fluxes became clearly obvious, that is driven by the large variability of climate and fire occurrence. A very interesting finding was that Siberia seems to be a smaller sink than generally assumed: the amount of the carbon sequestration of Siberia is only less than 20% of the fossil fuel emissions from the Russian Federation. Thus, the question if Siberia acts on a long-term scale as source or sink for carbon is still unsolved. In consequence, the continuation of measurements is mandatory, with broadening the focus on additional effects due to climate change for example on permafrost and ecosystem migration, and on effects of local and regional anthropogenic impacts. Globally effective anthropogenic influences are affecting directly the local scale, while local contamination and exhaustive cultivation are responsible vice versa for global impacts. Max-Planck-Institute for Biogeochemistry (MPI-BGC) has a great experience in ecological and atmospheric scientific research and conducts several projects focusing on Siberian key ecosystems and atmospheric research with respect to climate change (Sabine et al., 2003, Canadell et al., 2004). From these studies status information of environmental conditions and their response to global and local impacts can be provided, information will become available also from on-going activities. As an example, Fig. 14 presents CO_2 data from the lowest flight level at Zotino profile site (~60°N / ~90°E).

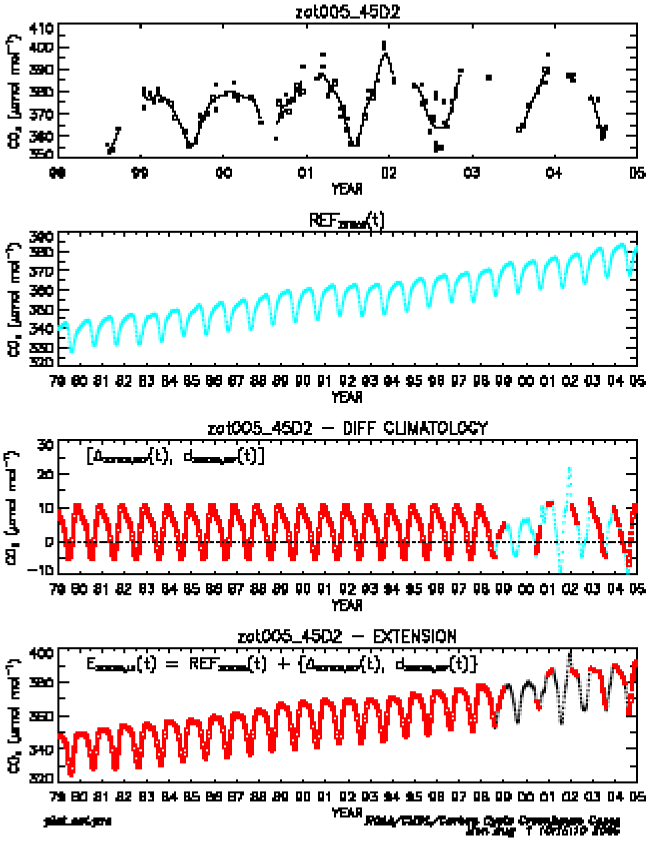

Fig. 14. *CO_2 data from the lowest flight level at Zotino profile site (implemented in NOAA/CMDL GLOBALVIEW-CO_2 database). [Panels from top to bottom : top - Time series of CO_2 mixing ratios; middle - Reference marine boundary layer time series; bottom - Difference between measurement and reference (blue circles; interpolated red circles and extrapolated red squares differences) and extended record including smoothed measurement data and interpolated and extrapolated values derived from data extension procedure].*

6. Mathematical Theory of Climate

Though the mathematical (numerical) modelling is the basic method to investigate the climate system dynamics, a question arises: What and to what accuracy must the climate model reproduce in order that its sensitivity to various small disturbances would be close to sensitivity of the actual climate system? To answer this question, it is necessary to find the operator of the model's response to small external forcing in an explicit form. In INM, studies related to the construction of the mathematical theory of climate are intensively carrying out (e.g., Dymnikov and Gritsoun, 2005). The methods of the mathematical theory of climate are methods of the theory of dynamical systems. To apply these methods to studies of the actual climate system, it should be assigned a certain mathematical object that represents an idealization of the system of interest and can be referred to as its "ideal" model. It is suggested that such an ideal model exists and the observed dynamics of the climate system is a realization of the trajectory generated by this model. It is also assumed that this model belongs to the class of dynamical dissipative systems and can be described by the following system of equations

$$\frac{\partial \psi}{\partial t} + K(\psi) \cdot \psi = -D\psi + f\,, \qquad \psi\big|_{t=0} = \psi_0\,,$$

where ψ is a vector-function of the climatic system parameters, depending on the spatial coordinates and time, $K(\psi)$ is the "dynamical" operator of the problem, D is the dissipation operator, and f is an external forcing. The entire dynamics of this system can conventionally be divided into two stages: motion toward the attractor and motion on the attractor and in its vicinity. To answer the above stated question, it is necessary to find the operator of the model's response to small external forcing in an explicit form. This operator can be constructed in principle if the model's attractor (as a set of states) and the measure on it depend continuously on the external forcing

Within the frames of the mathematical theory of climate, it is possible to construct the linear operator, which connects the vector of disturbed parameters of the problem under consideration with the vector of response on these disturbances under natural condition that its norm is small enough. A method for calculating the operator of dynamical response for climate models and the actual climate system to this external forcing is based on the application of the "dissipation – fluctuation" relationships for systems with the large number of positive Lyapunov's exponents. If the dynamical system is regular (the energy conservation law is quadratic and the phase volume in the phase space is incompressible), one can use statistical parameters of the system to calculate the operator U of response to small time-invariant external forcing δf (Dymnikov and Gritsoun, 2005):

$$\langle \delta\psi(t) \rangle = U\delta f\,,$$

where the angle parentheses denote averaging over uniform ensemble of the system,

$$U = \int_0^\infty C(\tau) C^{-1}(0)\, d\tau\,,$$

and $C(\tau)$ is the covariance matrix of ψ with a shift τ

$$C(\tau) \equiv \langle \psi(t) \cdot \psi^T(t+\tau) \rangle.$$

In the ergodic case (when the statistical parameters are calculated by averaging in time along a single trajectory), the response operator can be constructed from a single and sufficiently long system trajectory.

The approximate response operator makes it possible to reproduce with a high accuracy both the magnitude and the spatial structure of the linear part of dynamical response of the climate model. This result gives also the methodological basing for studying the sensitivity of a certain characteristics of the actual climate system to disturbances of external parameters with the help of calculations, using observational data. As an illustration, Fig. 15 presents the results of one of numerical experiments on reproducing the linear part of the model's response (in the stream function field) to a vertically extended equatorial thermal source with a heating maximum located at 60° E. The left-hand column shows the responses obtained from the approximate response. The fields depicted in Fig. 8 indicate that the results of calculations with the response operator and of direct modeling (the right-hand column) are very close to each other.

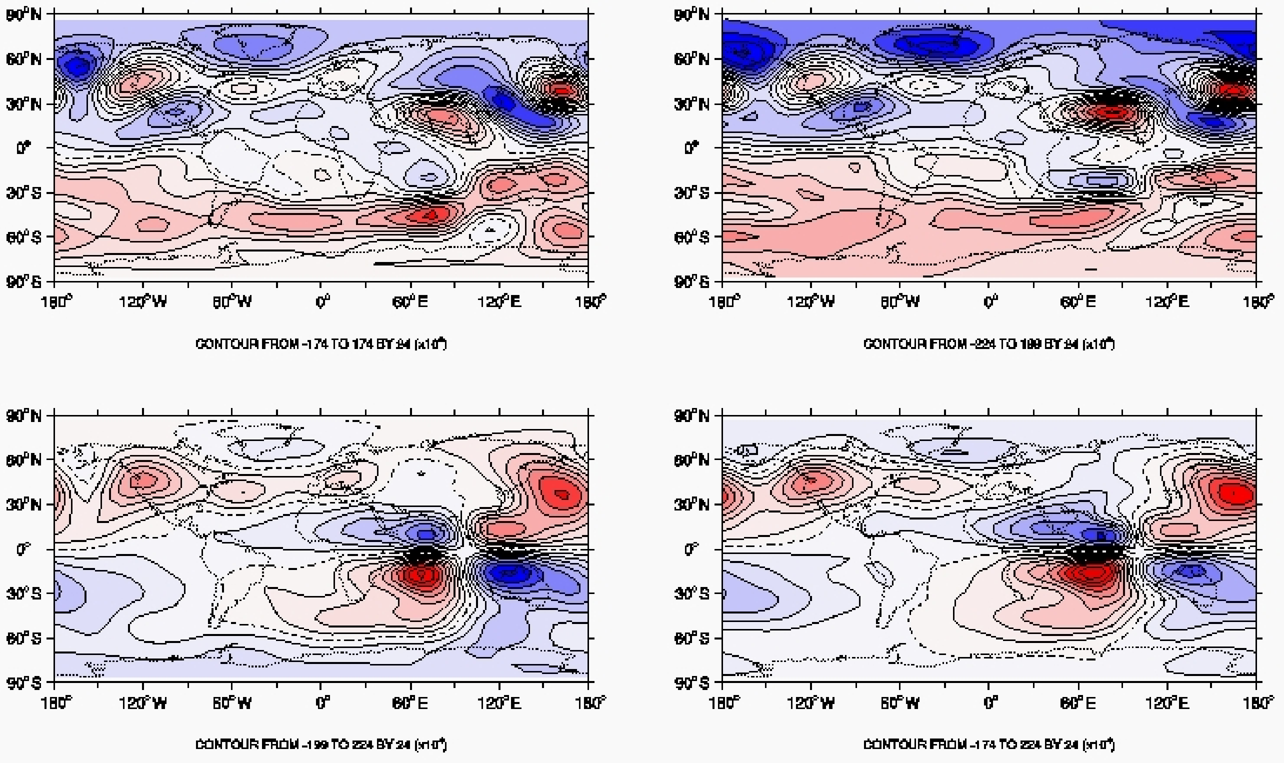

Fig. 15. *Linear part of the model's response (right) to a vertically extended anomaly of temperature at the equator and response obtained via fluctuation–dissipation relations (left). The responses are shown in the field of stream function at a height of 336 hPa (top) and 811 hPa (bottom) for heating with maxima at the point 60° E.*

To support these investigations, the RFBR project "Periodic and stationary solutions in the models of atmospheric dynamics" (INM, Grant # 08-05-00738), devoted to the study of periodic and stationary solutions in models of the atmosphere, was suggested. The problem under consideration is closely related to the question: How periodic trajectories are connected with dynamical and stationary regimes of the atmosphere circulation, their predictability and "time of life". A special attention is paid to possible stabilization of a model solution to the given periodic orbit. Numerical experiments will be carried out to study such characteristics of system as mean state, standard deviation, empirical orthogonal functions and corresponding fractions of variability, dimension of attractor, projections of the probability density function on most energy- valuable directions.

7. Concluding Remarks

Climate models based on the global coupled atmosphere-ocean-land-cryosphere system modelling exhibit a wide range of dynamical, physical, biological and chemical interactions. The traditional boundaries between weather and climate are conditional. At present, the challenge facing the weather and climate scientists is to improve the prediction of interactions between weather/climate and Earth system. The World Modelling Summit for Climate Prediction was held at the European Centre for Medium-Range Weather Forecasts on 6 – 9 May 2008 with the aim to develop a strategy to revolutionize prediction of the climate in the 21st century, in particular, at the regional level (http://wcrp.ipsl.jussieu.fr/Workshops/ModellingSummit/). It was recognized that considerably improved predictions of the changes in the statistics of regional climate (especially, of extreme events) are required to assess the impacts of climate change and to develop adaptive strategies to ameliorate their effects on environment and society. Despite progress in climate modelling (e.g., within the frame of AMIP and CMIP), the present time ability to provide robust estimates of the risk to society, in particular, from possible catastrophic changes in regional climate, is still constrained by limitations in computer power and scientific understanding. Neither the necessary scientific expertise nor the computational capability is available now in any single nation.

Thus, the Summit suggested initiating a Climate Prediction Project coordinated by the World Climate Research Programme, in collaboration with the World Weather Research Programme and the International Geosphere – Biosphere Programme. This climate initiative will be a world climate research facility for climate prediction that will enable the national centers to accelerate progress in improving operational climate prediction in wide diapason of time scales, especially, at decadal to multi-decadal lead times. The world's fastest computers run at hundreds of teraflops, but today's climate models rarely run on machines that can manage more than a few tens of teraflops. This corresponds to spatial resolution of climate models of about a hundred kilometers. There is a general agreement in scientific community that more realistic models will require resolutions in the tens kilometers and even higher (a kilometer or less). Thus, the central component of the above mentioned facility should be dedicated high-end computing facilities (managing hundreds of petaflops) that will permit scientists to employ kilometer-scale modelling of the global climate system.

Access to significantly increased computing capacity will enable scientists to advance understanding and representation of the physical and biogeochemical processes responsible for climate variability and predictability. The Climate Prediction Project will enable the climate research community to make better estimates of model uncertainties and assess how they limit the skill of climate predictions. Climate models should be tested in sub-seasonal and multi-seasonal prediction mode, including use of data assimilation and ensemble systems. Such synergy between the weather and climate prediction efforts will motivate the development of seamless prediction systems. This project will help sustain the excitement of the young generation to better prepare humanity to adapt to and mitigate the consequences of climate change.

In summary, it is possible to emphasize that the strategy of modeling climate and its global changes should be based on the following four main propositions: (i) construction of an original climate model, (ii) model implementation on computational system of parallel architecture, (iii) development of the mathematical theory of climate, and (iv) study of regional problems of climatic variability and its impact on environment, in particular, in Siberia. The main directions, in which the development of the mathematical theory of climate and the improvement of modeling of climate and climate change will be possible in the coming years, can be formulated as follows (Dymnikov et al., 2006):

(1) Mathematical theory of climate: (a) elaboration of stability theory for the attractors of climate models, (b) study of the structure of the attractors of climate models, (c) development of sensitivity theory for climate models (theorems on the linear approximation for different moments, numerical study of the linear theory of response to small perturbations, optimal perturbations, and algorithms for constructing the response operator), and (d) control theory for dissipative systems (climate control).

(2) Climate models: (a) development of parameterizations for physical processes (stochastic parameterizations), (b) improvement of coupled atmosphere – ocean models, (c) development of regional climate models and methods to assess the consequences of climate changes for the natural medium, and (d) elaboration of models of the middle and upper atmosphere for solving the problems related to “space weather.”

(3) Numerical methods and parallel computations: (a) development of the theory of approximation of hydrothermodynamic equations on attractors (approximation of an attractor as a set and approximation of the measure on it), (b) approximation of the dynamics of the climate system on attractors, (c) elaboration of schemes with a specified symmetry group, (d) construction and use of spatiotemporal adaptive grids, and (e) design of computing technologies oriented toward massively parallel computing systems.

The aforementioned makes it possible to hope for the elaboration of an expert system used to obtain estimates and substantiated predictions of climate oscillations and changes on both a regional and global scales.

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Appendix: List of Projects Analyzed

1. International **A**tmospheric **M**odel **I**ntercomparison **P**roject (AMIP-I and AMIP-II)
2. International **C**oupled **M**odel **I**ntercomparison **P**roject (CMIP3)
3. International Climate Prediction Project
4. International FP6 Project “CARBO-North”
5. International **T**errestrial **C**arbon **O**bservation **S**ystem Siberia (TCOS-Siberia) Project
6. National RFBR (**R**ussian **F**oundation for **B**asic **R**esearch) Project “Development of atmospheric and oceanic general circulation model with carbon cycle” (Grant # 06-05-64331)
7. RFBR Project “Mathematical modeling of mesoscale interaction between the atmosphere and hydrologically heterogeneous land” (Grant # 07-05-00200)
8. RFBR Project “Development of new and improvement of known technologies to solve inverse problems of climatology by statistical methods” (Grant # 07-05-00328)
9. RFBR Project “Reproduction of climate anomalies on intra-seasonal scale by coupled model of general circulation of the atmosphere and ocean” (Grant # 07-05-00893)
10. RFBR Project “Estimation of feedbacks between vegetation, surface hydrology of Northern Eurasia and Arctic climate on the base of coupled model ocean - atmosphere – vegetation – soil under global climate changes” (Grant # 08-05-00457)
11. RFBR project “Periodic and stationary solutions in the models of atmospheric dynamics” (Grant # 08-05-00738)
12. National Project “Large-eddy simulation of geophysical boundary layers on computational systems of parallel architecture”, Russian Academy of Sciences Program “Computational and information aspects of solving the huge problems”.