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Key problems of regional climate change modeling and assessment

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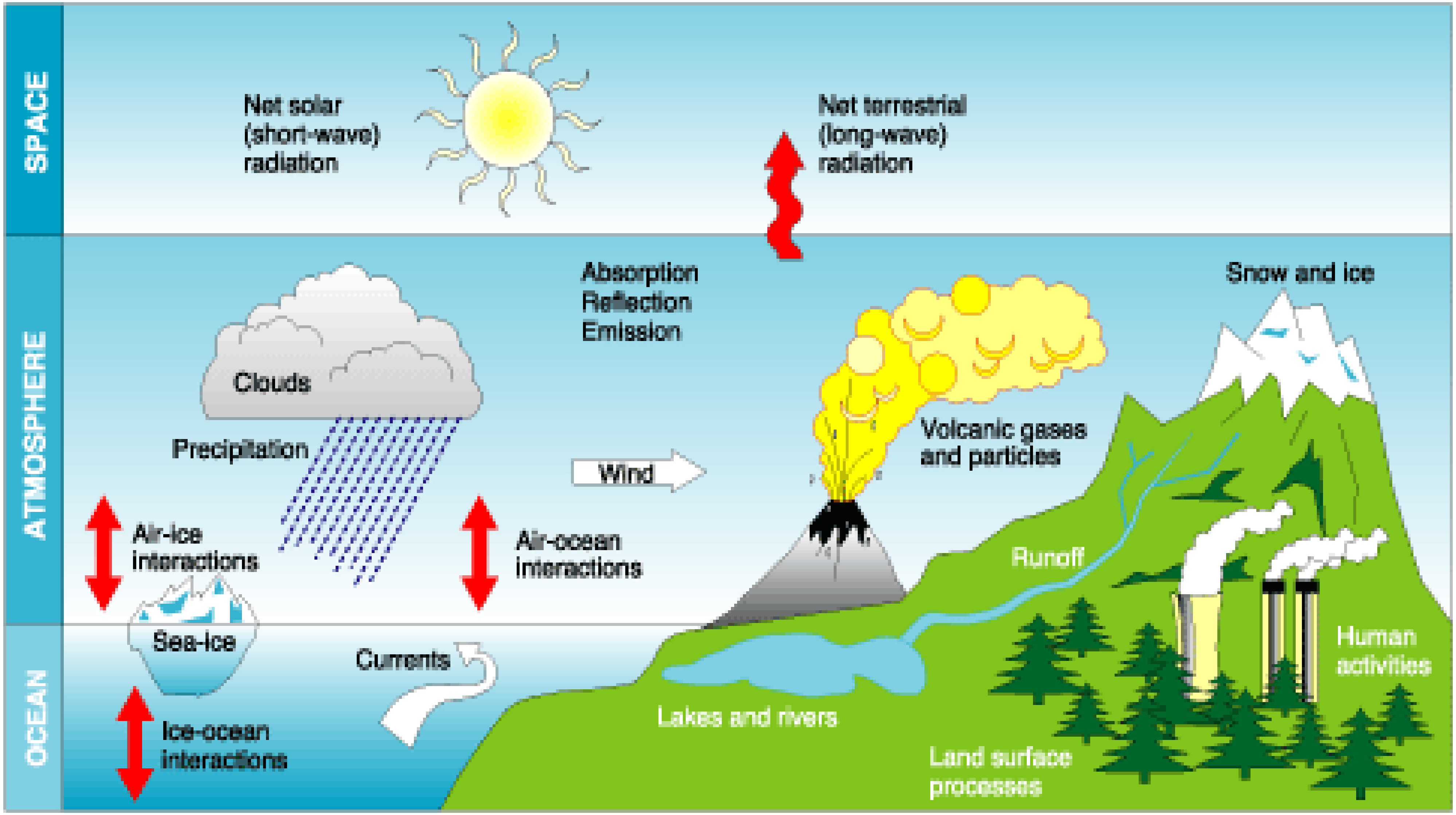
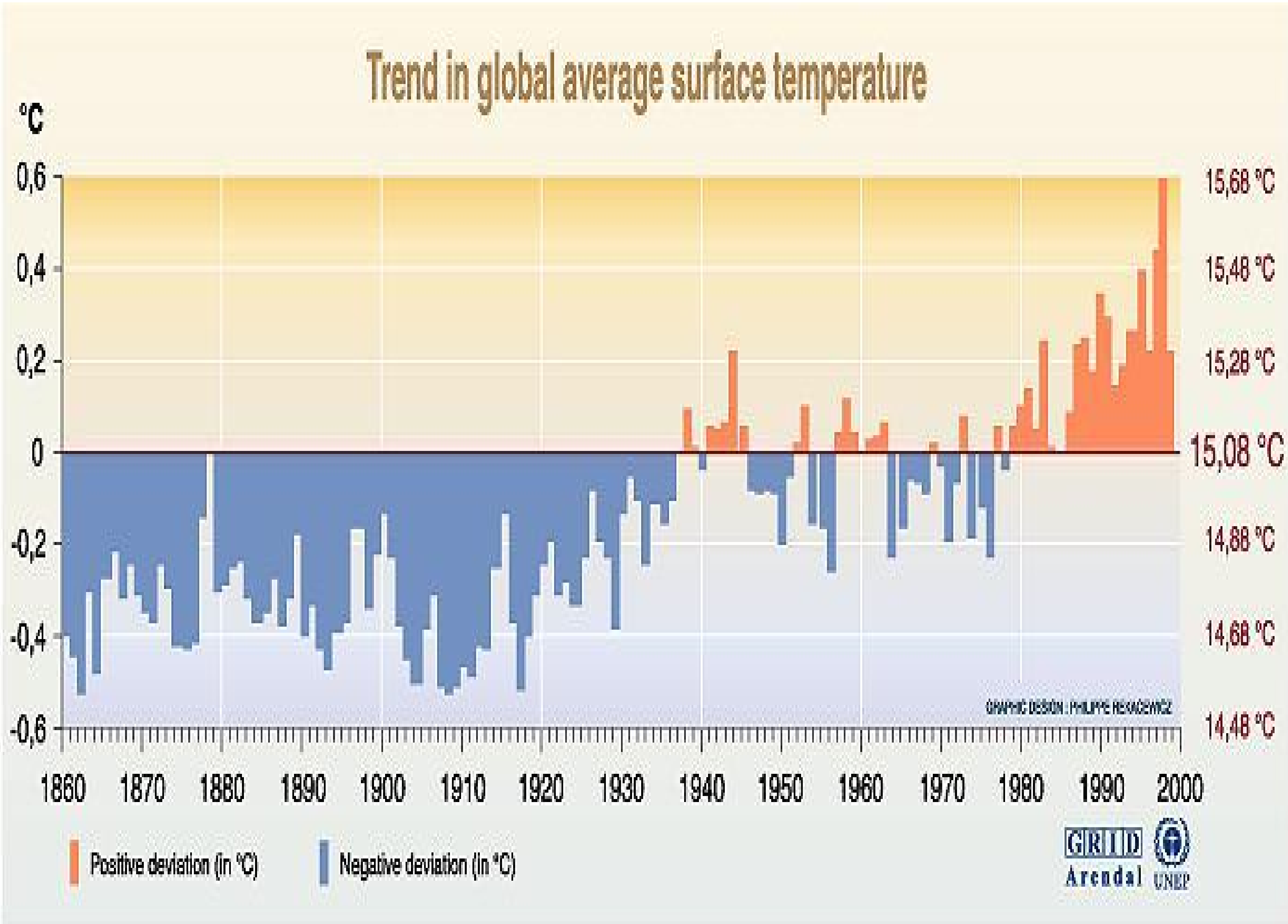
Climate System

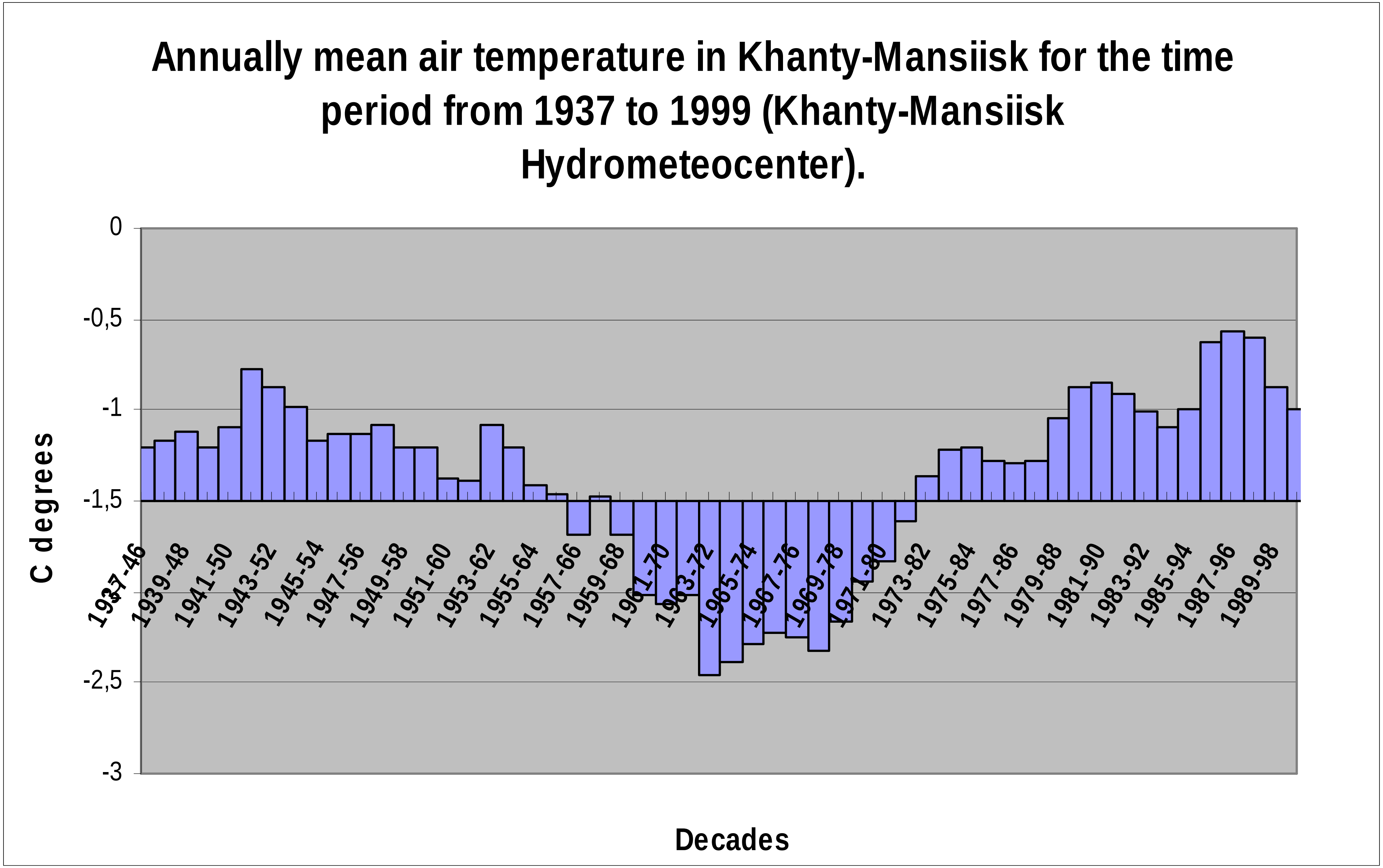
- 1. **ATMOSPHERE** – the gas envelope of the Earth (oxygen, nitrogen, carbon dioxide, water vapor, ozone, etc.), which controls the solar radiation transport from space towards the Earth surface.
- 2. **OCEAN** – the major water reservoir in the system, containing salted waters of the World ocean and its seas and absorbing the basic part of the incoming solar radiation (a powerful accumulator of energy).
- 3. **LAND** – surface of continents with **hydrological system** (inland waters, wetlands and rivers), soil (e.g. with groundwater) and cryolithozone (permafrost).
- 4. **CRYOSPHERE** – continental and see ice, snow cover and mountain glaciers.
- 5. **BIOTA** – vegetation on the land and ocean, alive organisms in the air, water and soil, **mankind**.

The Climate System(T. Slingo, 2002)



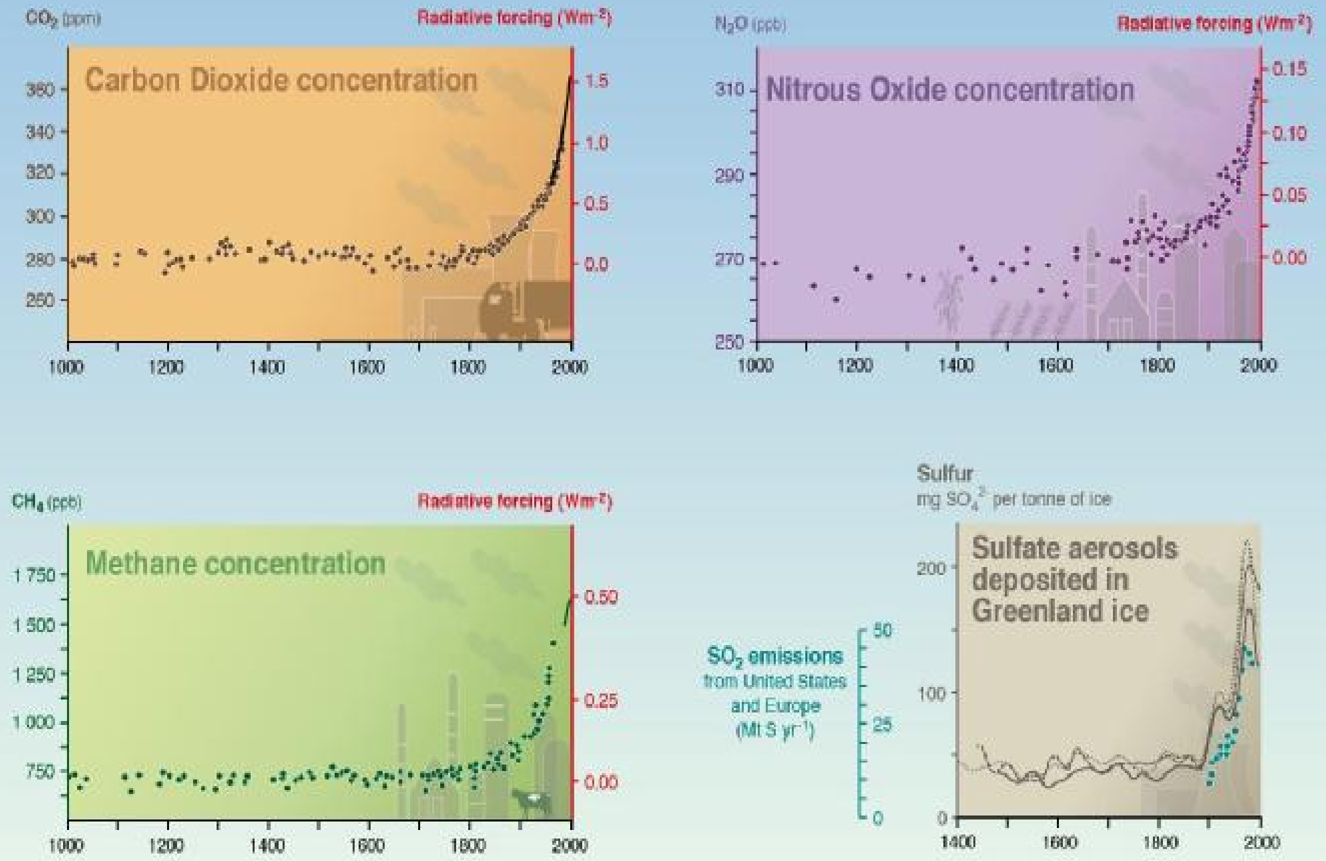


Source: School of environmental sciences, climatic research unit, university of East Anglia, Norwich, United Kingdom, 1999.



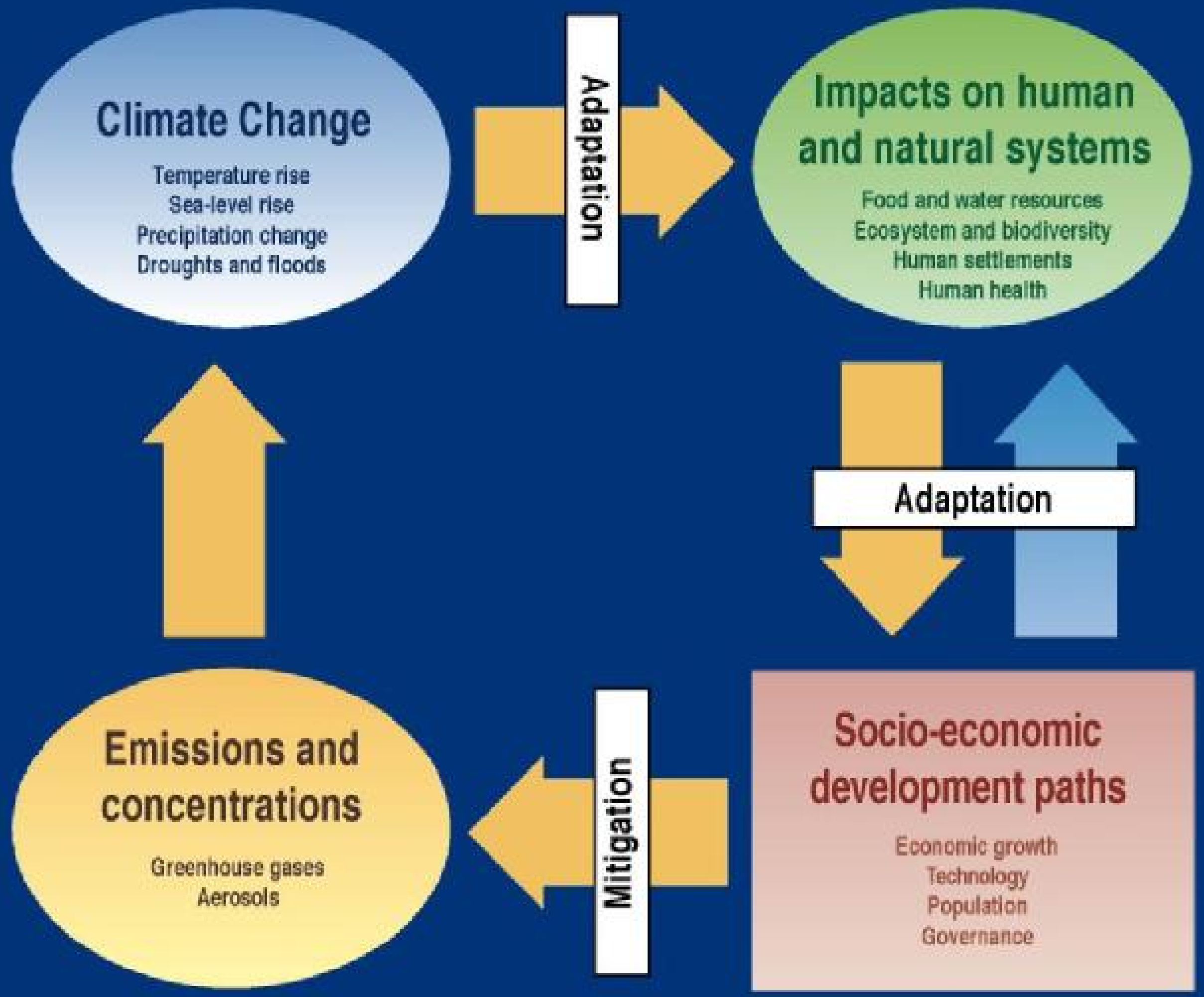
Annually mean air temperature in Khanty-Mansiisk for the time period from 1937 to 1999 (Khanty-Mansiisk Hydrometeocenter).
0
-0,5
-1
-1,5
-2,5
-3
C degrees
1937-46
1939-48
1941-50
1943-52
1945-54
1947-56
1949-58
1951-60
1953-62
1955-64
1957-66
1959-68
1961-70
1963-72
1965-74
1967-76
1969-78
1971-80
1973-82
1975-84
1977-86
1979-88
1981-90
1983-92
1985-94
1987-96
1989-98
Decades

Indicators of the human influence on the atmosphere during the Industrial era

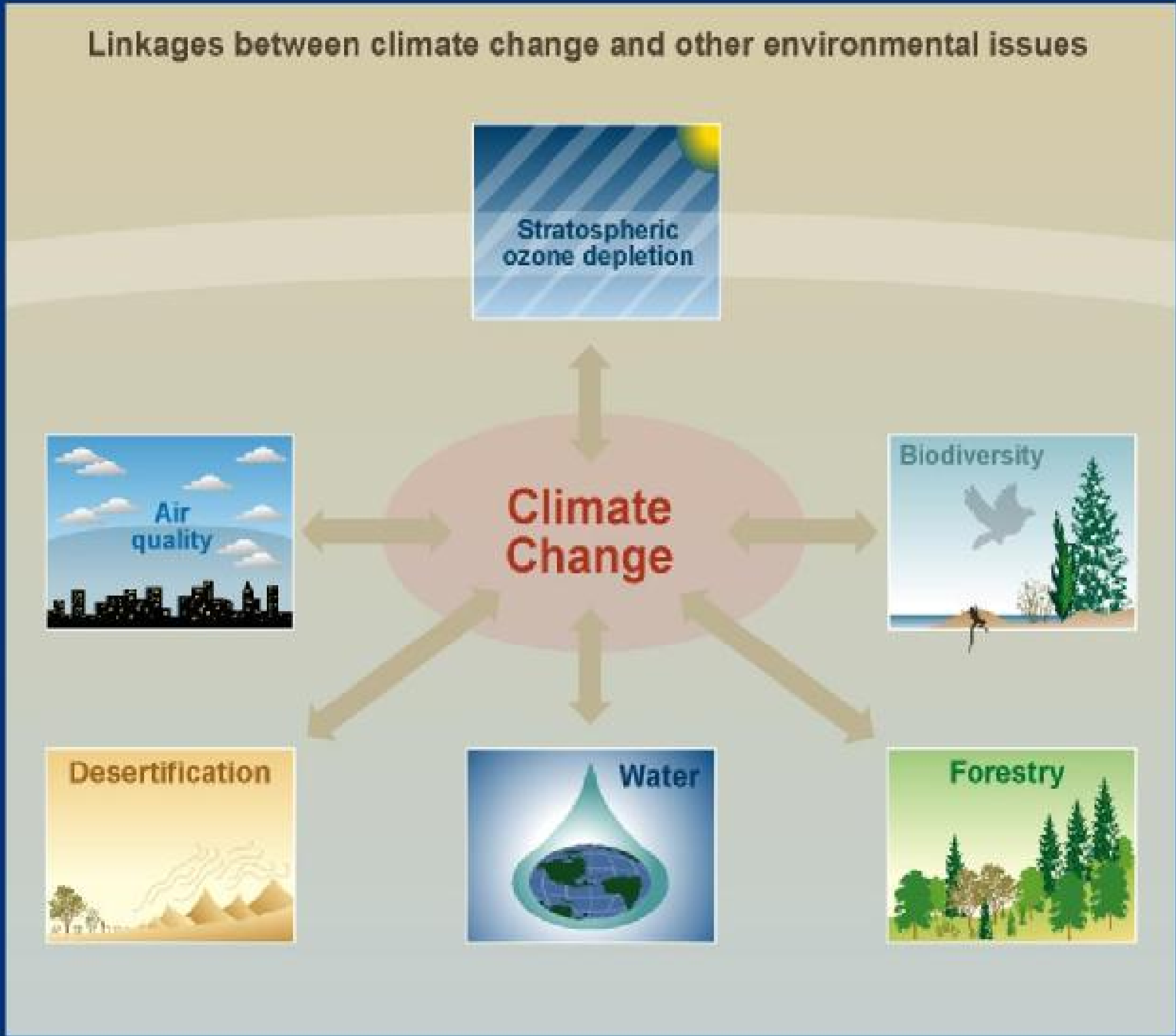


SYR - FIGURE 2-1
WG1 FIGURE SPM-2

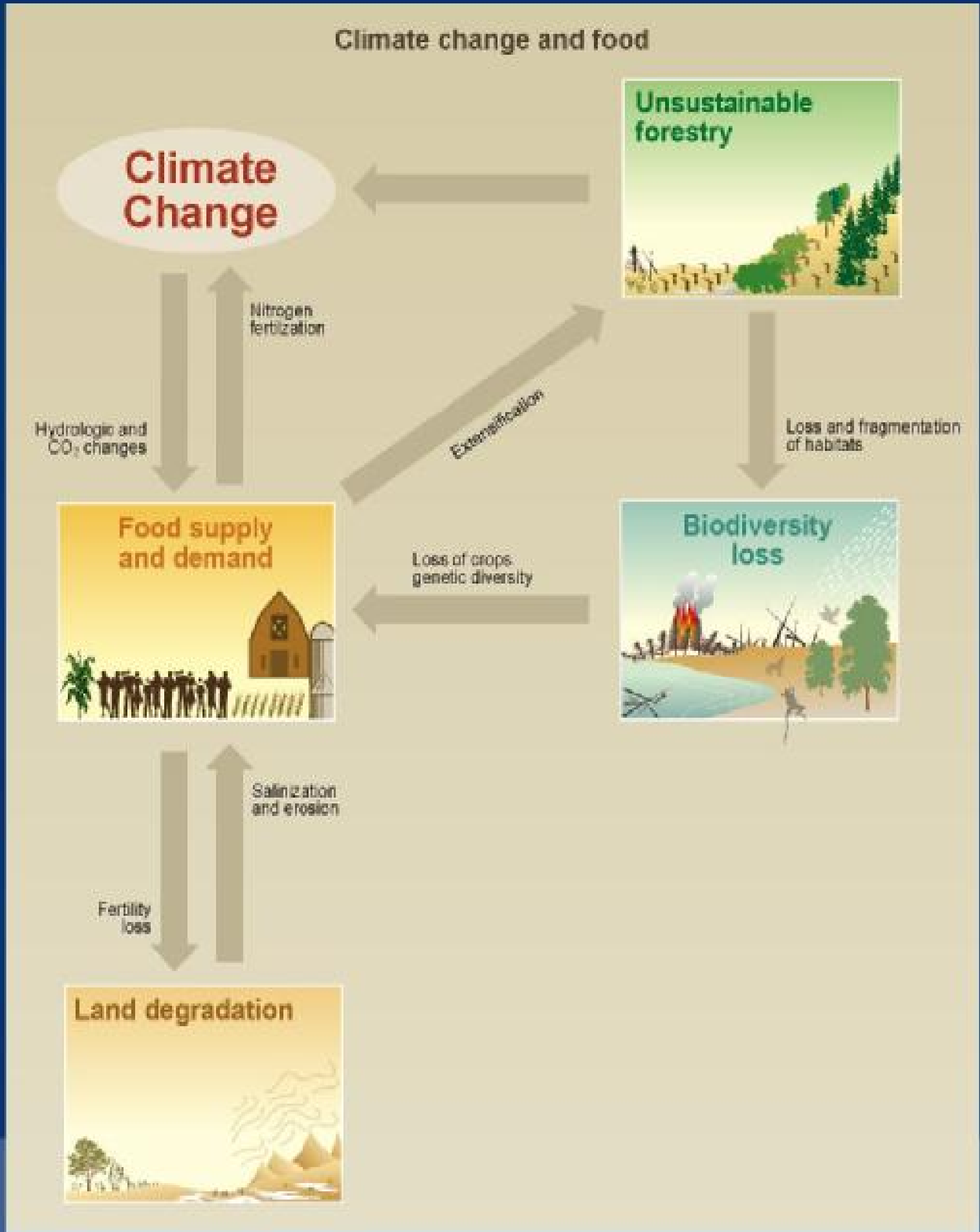
Climate Change - an integrated framework



SYR FIGURE 1-1



SYR - FIGURE 8-1



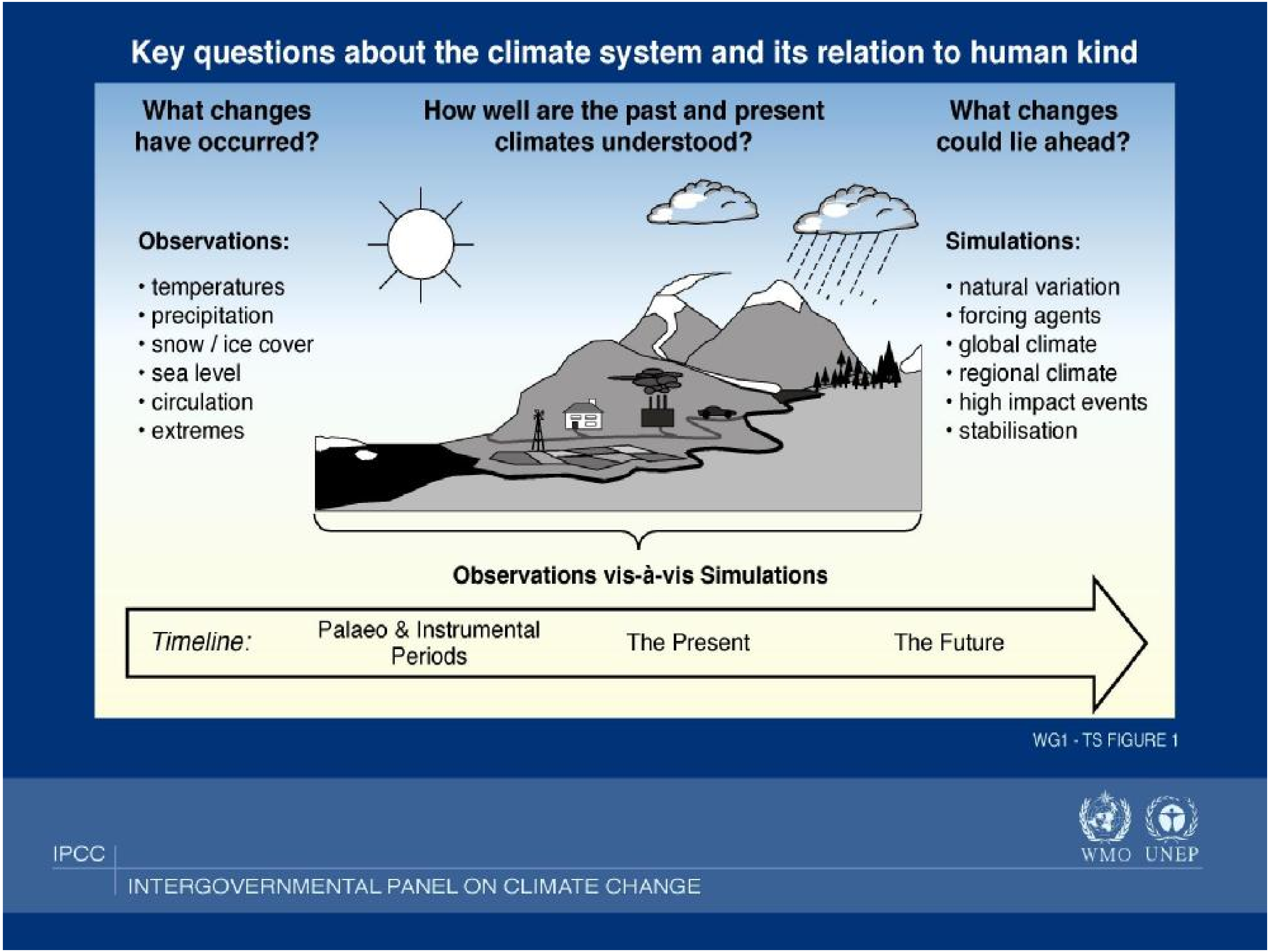
SYR - FIGURE 8-2

Features of the climate system as physical object-I

- Basic components of the climate system – atmosphere and ocean – are thin films with the ratio of vertical scale to horizontal scale about 0.01-0.001.
- On global and also regional spatial scales, the system can be considered as quasi-twodimensional one. However, its density vertical stratification is very important for correct description of energy cycle.
- Characteristic time scales of energetically important physical processes cover the interval from 1 second (turbulence) to tens and hundreds years (climate and environment variability).
- Laboratory modelling of such system is very difficult.

Features of the climate system as physical object-II

- It is practically impossible to carry out specialized physical experiments with the climate system.
- For example, we have no possibility to “pump” the atmosphere by the carbon dioxide and, keeping other conditions, to measure the system response.
- We have shirt–term series of observational data for some of components of the climate system.
- Conclusion: the basic (but not single) tool to study the climate system dynamics is mathematical (numerical) modeling.
- Hydrodynamic climate models should be based on global models of the atmosphere and ocean circulation.


Key questions about the climate system and its relation to human kind
What changes have occurred?
How well are the past and present climates understood?
What changes could lie ahead?
Observations:
• temperatures
• precipitation
• snow / ice cover
• sea level
• circulation
• extremes
Simulations:
• natural variation
• forcing agents
• global climate
• regional climate
• high impact events
• stabilisation
Observations vis-à-vis Simulations
Timeline:
Palaeo & Instrumental Periods
The Present
The Future
WG1 - TS FIGURE 1
WMO UNEP
IPCC
INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

Objectives of climate modeling

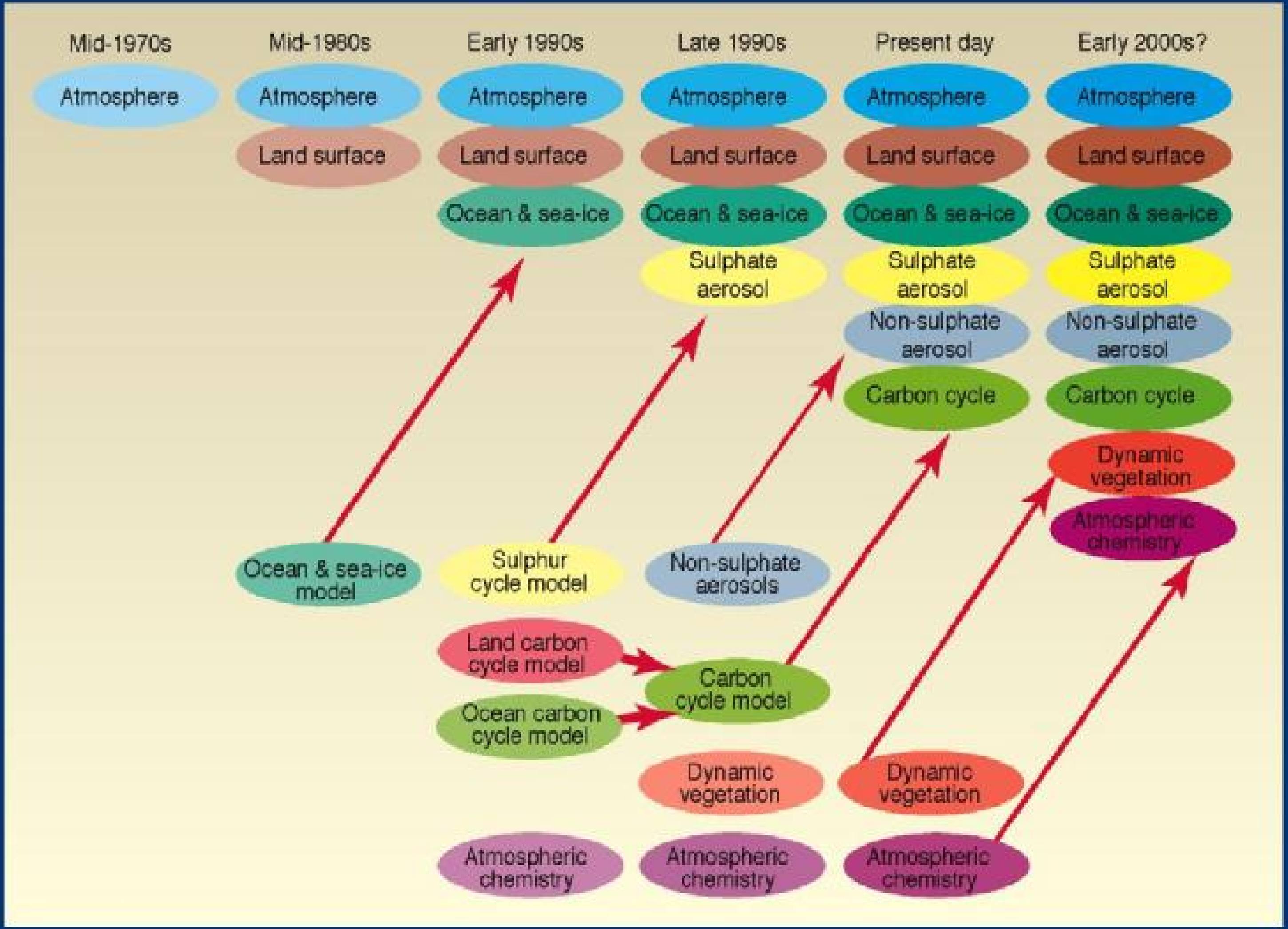
- **To reproduce both “climatology” (seasonal and monthly means) and statistics of variability: intra-seasonal (monsoon cycle, characteristics of storm-tracks, etc.) and climatic (dominated modes of inter-annual variability such as El-Nino phenomenon or Arctic Oscillation)**

- **To estimate climate change due to anthropogenic activity**

- **To reproduce with high degree of details regional climate: features of hydrological cycle, extreme events, impact of global climate change on regional climate, environment and socio-economic relationships**

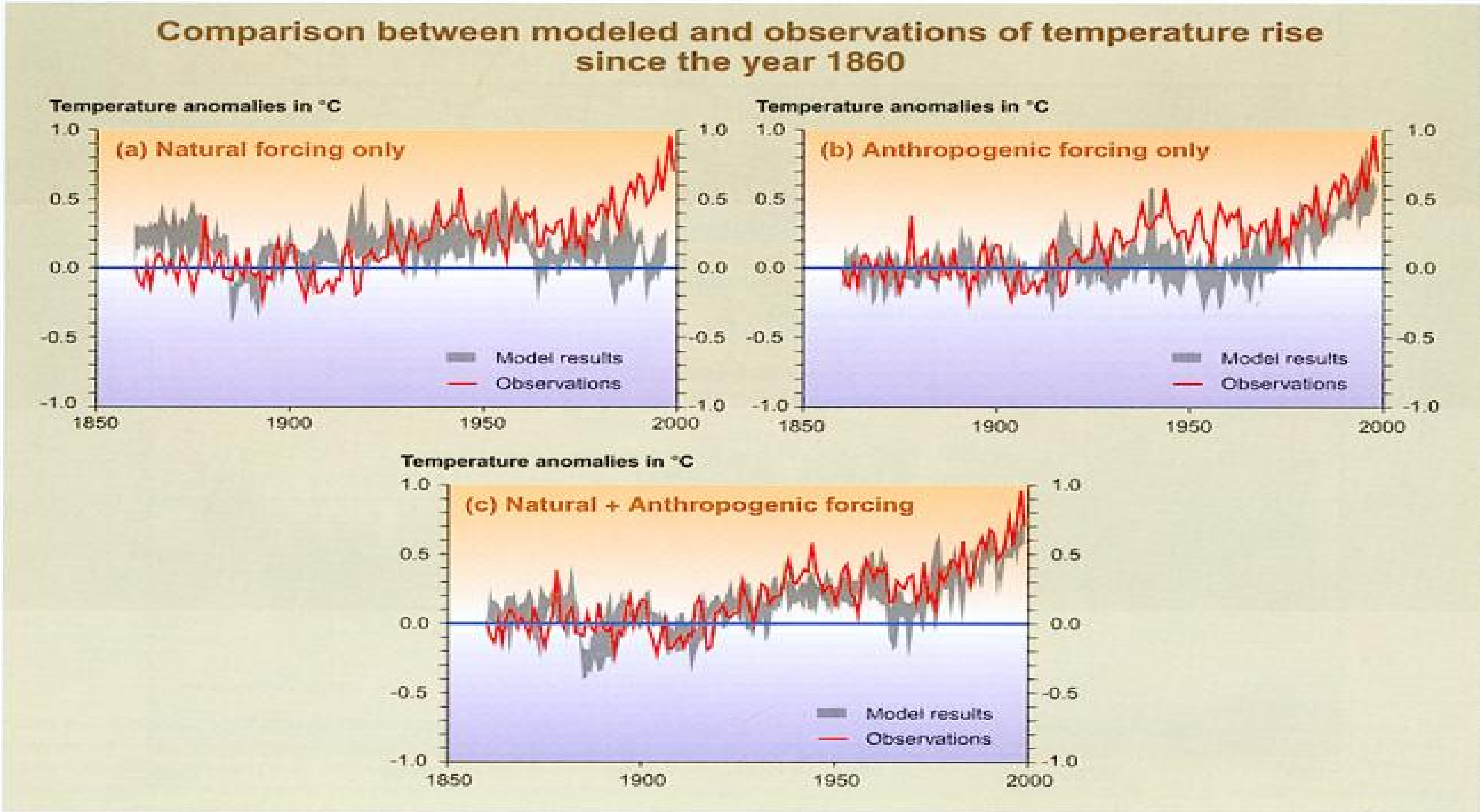
- **Fundamental question (V.P. Dymnikov): what climatic parameters and in what accuracy must by reproduced by a mathematical model of the climate system to make its sensitivity to small perturbations of external forcing close to the sensitivity of the actual climate system?**

The development of climate models, past, present and future



WG1 - TS BOX 3
FIGURE 1

Comparison of observed changes
in global-average surface air temperature over the 20-th century
with that from an ensemble of climate model simulations
(http://www.grida.no/climate/ipcc_tar/vol4/english/022.htm)



INM climate model and experiments

(Dymnikov et al., 2005, Volodin & Diansky, 2006)

http://ksv.inm.ras.ru/index

AGCM

- Finite difference model with spatial resolution 5°x4° and 21 levels in sigma-coordinates from the surface up to 10 hPa.

- In radiation absorption of water vapour, clouds, CO_2, O_3, CH_4, N_2O, O_2 and aerosol are taken into account. Solar spectrum is divided by 18 intervals, while infrared spectrum is divided by 10 intervals.

- Deep convection, orographic and non-orographic gravity wave drag are considered in the model. Soil and vegetation processes are taken into account.

||

Non-flux-adjusted coupling

||

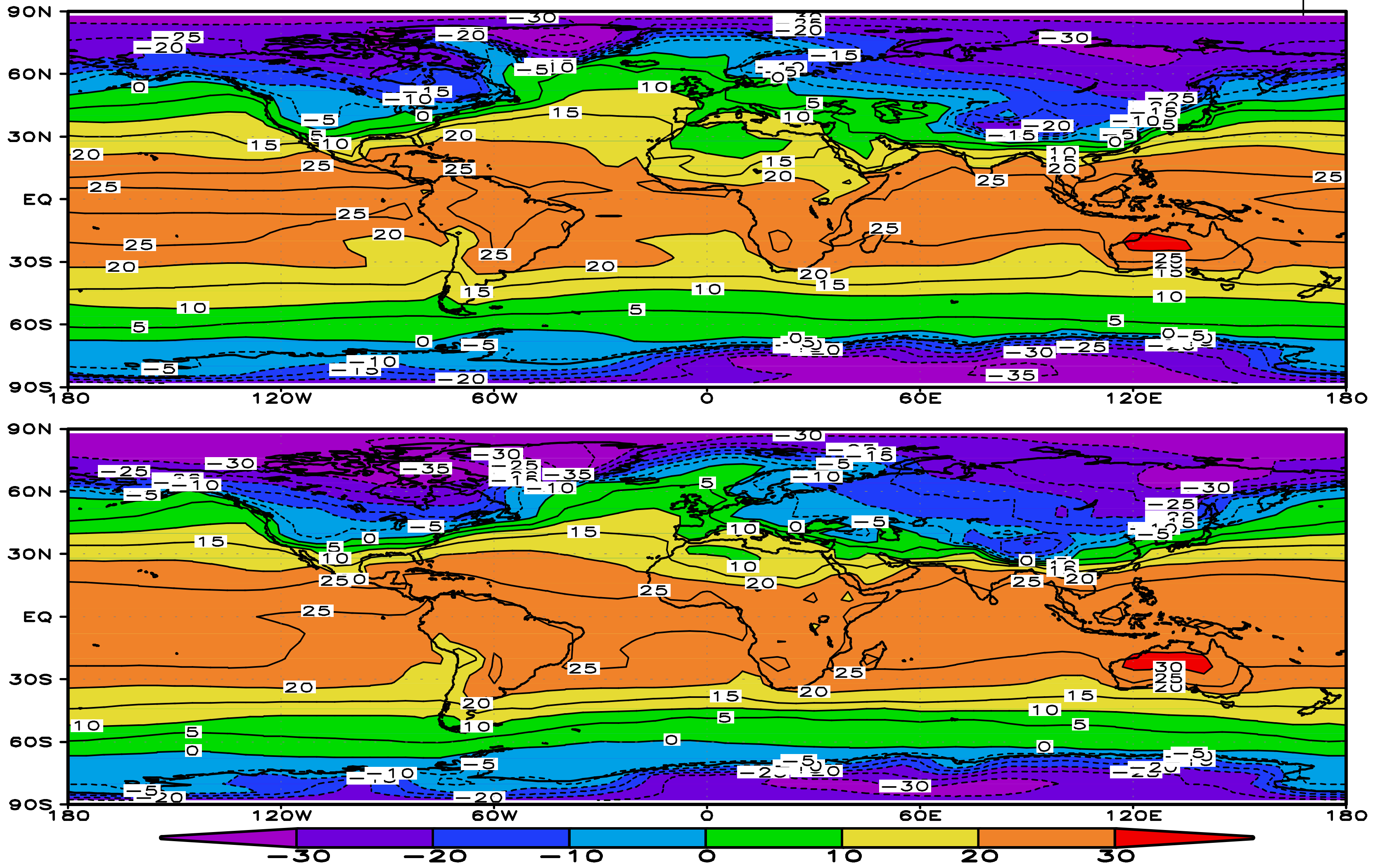
OGCM

-The model is based on the primitive equations of the ocean dynamics in spherical *sigma*-coordinate system. It uses the splitting-up method in physical processes and spatial coordinates. Model horizontal resolution is 2.5°x2°, it has 33 unequal levels in the vertical with an exponential distribution.

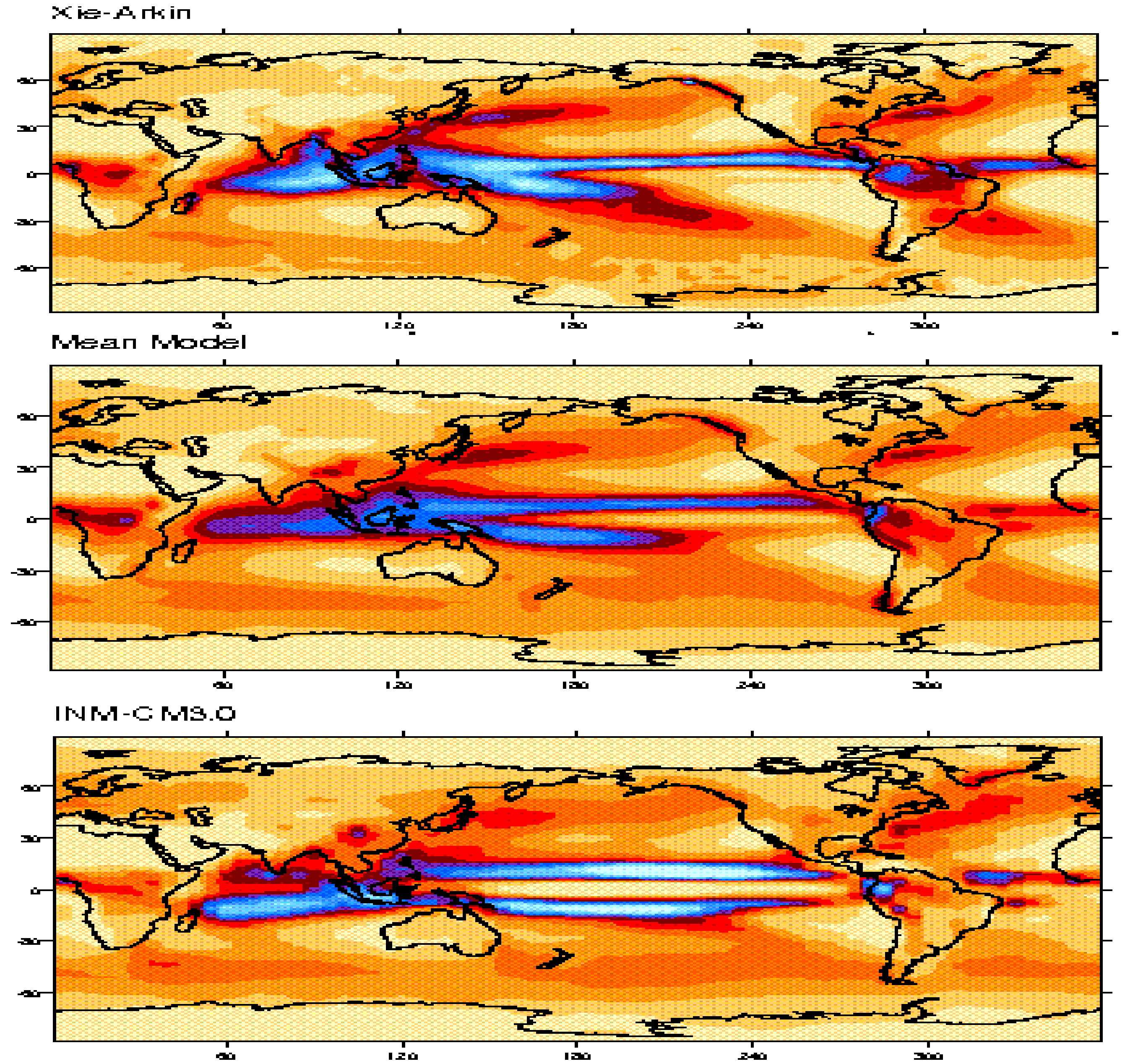
-An other version: 50m upper ocean layer with ice

Experiments: http://ksv.inm.ras.ru/index	Abbreviation	1-st year	Last year	Initial conditions
Preindustrial (Control) Forcing: 1871	CNT	1871	2200	
XX century case Forcing: 1871-2000	XX	1871	2000	
XXI century case Forcing: 2000	COMM	2001	2100	CNT
Forcing: scenario A2	A2	2001	2200	CNT
Forcing: scenario A1B	A1B	2001	2200	CNT
Forcing: scenario B1	B1	2001	2200	CNT
Doubling CO2 from 1871 to 1940, then fixed double CO2	2CO2	1871	2090	
Quadrupling CO2 from 1871 to 2010, then fixed quadruple CO2	4CO2	1871	2160	
GCMA+50 m ocean upper layer. Forcing: 2000 Control + double CO2	CNT50m 2CO250m	2000	2059	
GCMA with SST and sea ice boundaries prescibed	AMIP	1979	2003	

Near-the-surface winter air temperature: simulation (top) and observations (bottom)



Annually mean precipitation (mm/day) as follows from observations (top), CMIP models averaged results (middle) and INM simulation (bottom).



The climate model sensitivity to the increasing of CO_2

CMIP - Coupled Model Intercomparison Project

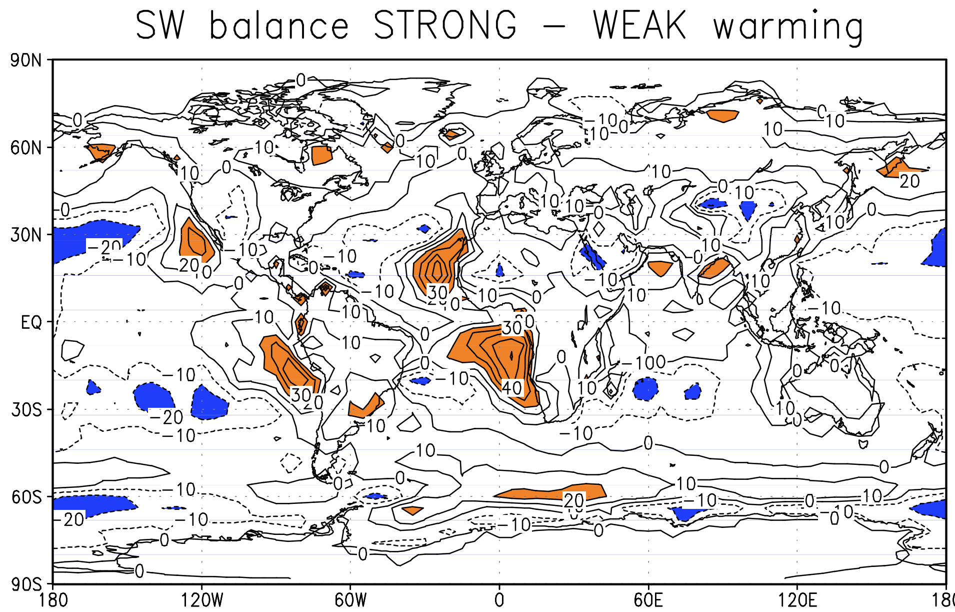
http://www-pcmdi.llnl.gov/cmip

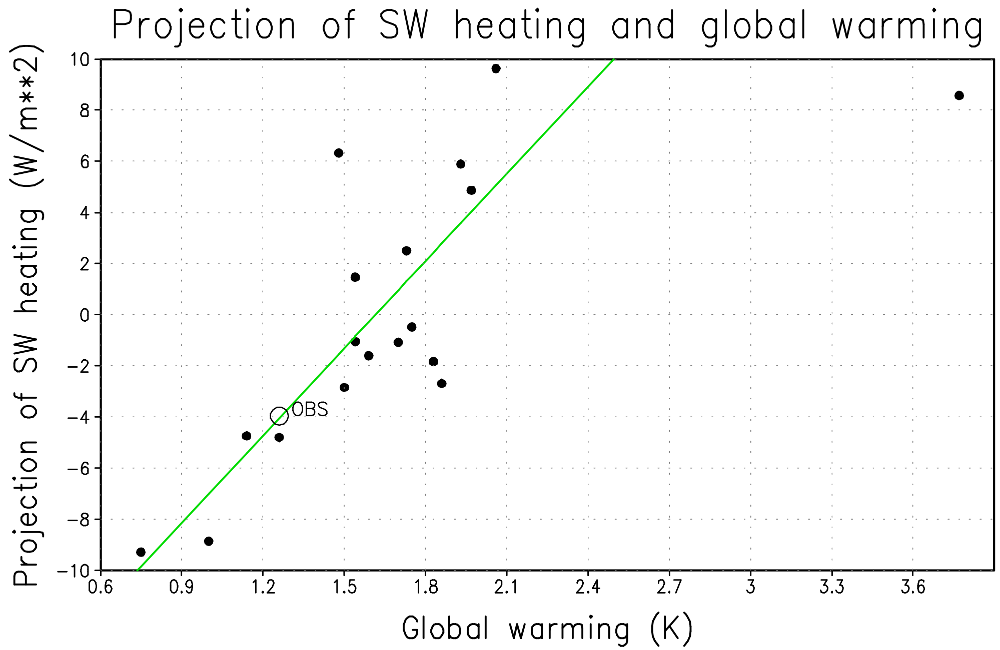
CMIP collects output from global coupled ocean-atmosphere general circulation models (about 30 coupled GCMs). Among other usage, such models are employed both to detect anthropogenic effects in the climate record of the past century and to project future climatic changes due to human production of greenhouse gases and aerosols.

Global warming in CMIP models in CO_2 run and parameterization of lower inversion clouds

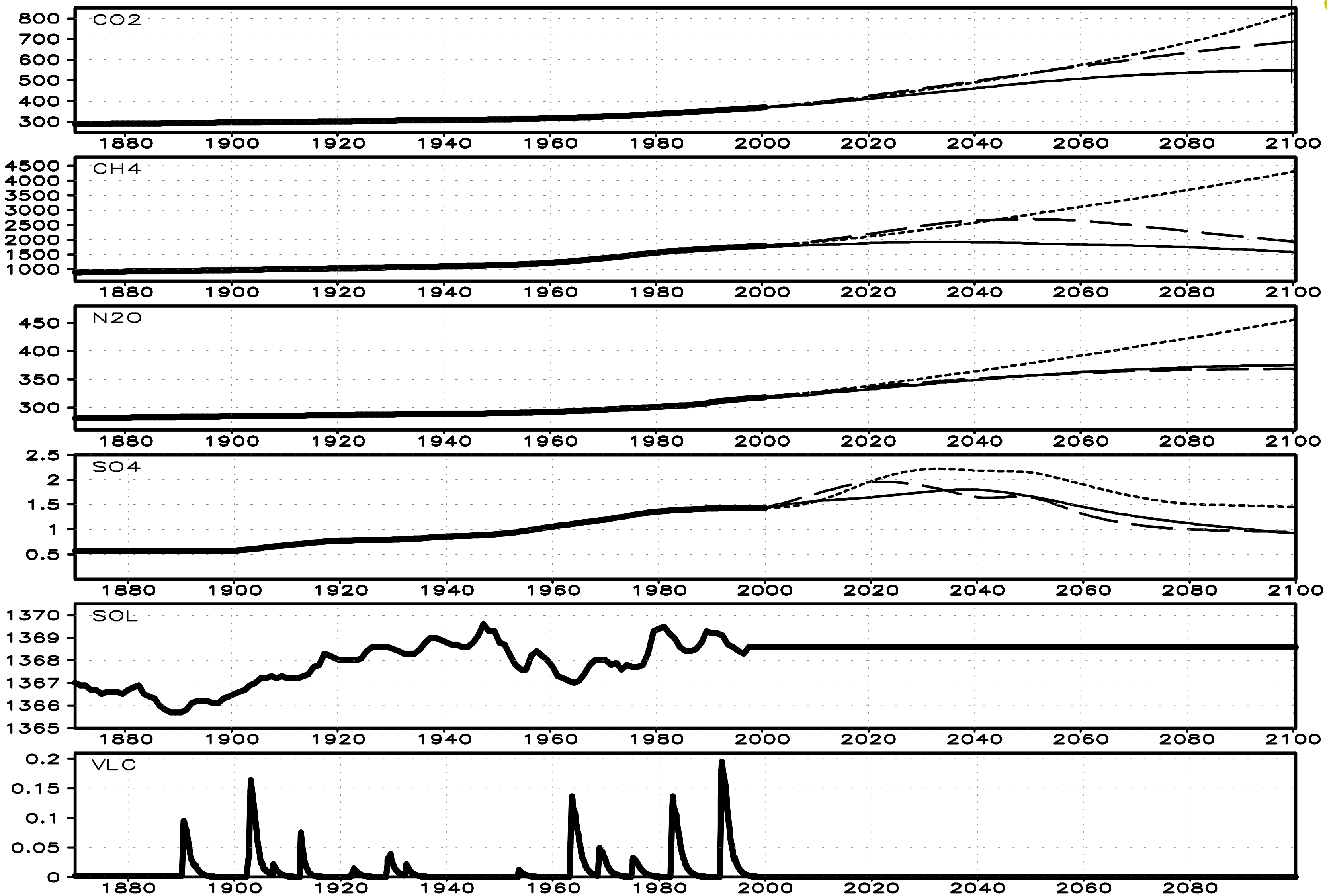
T - global warming (K), *LC* - parameterization of lower inversion clouds (+ parameterization was included, - no parameterization, ? - model description is not available). Models are ordered by reduction of global warming.

Model	T	*LC*
NCAR-WM	3.77	?
GFDL	2.06	-
LMD	1.97	-
CCC	1.93	-
UKM03	1.86	-
CERF	1.83	-
CCSR	1.75	-
CSIRO	1.73	+
GISS	1.70	-
UKMO	1.59	-
BMRC	1.54	+
ECHAM3	1.54	-
MRI	1.50	-
IAP	1.48	+
NCAR-CSM	1.26	+
PCM	1.14	+
INM	0.99	+
NRL	0.75	+

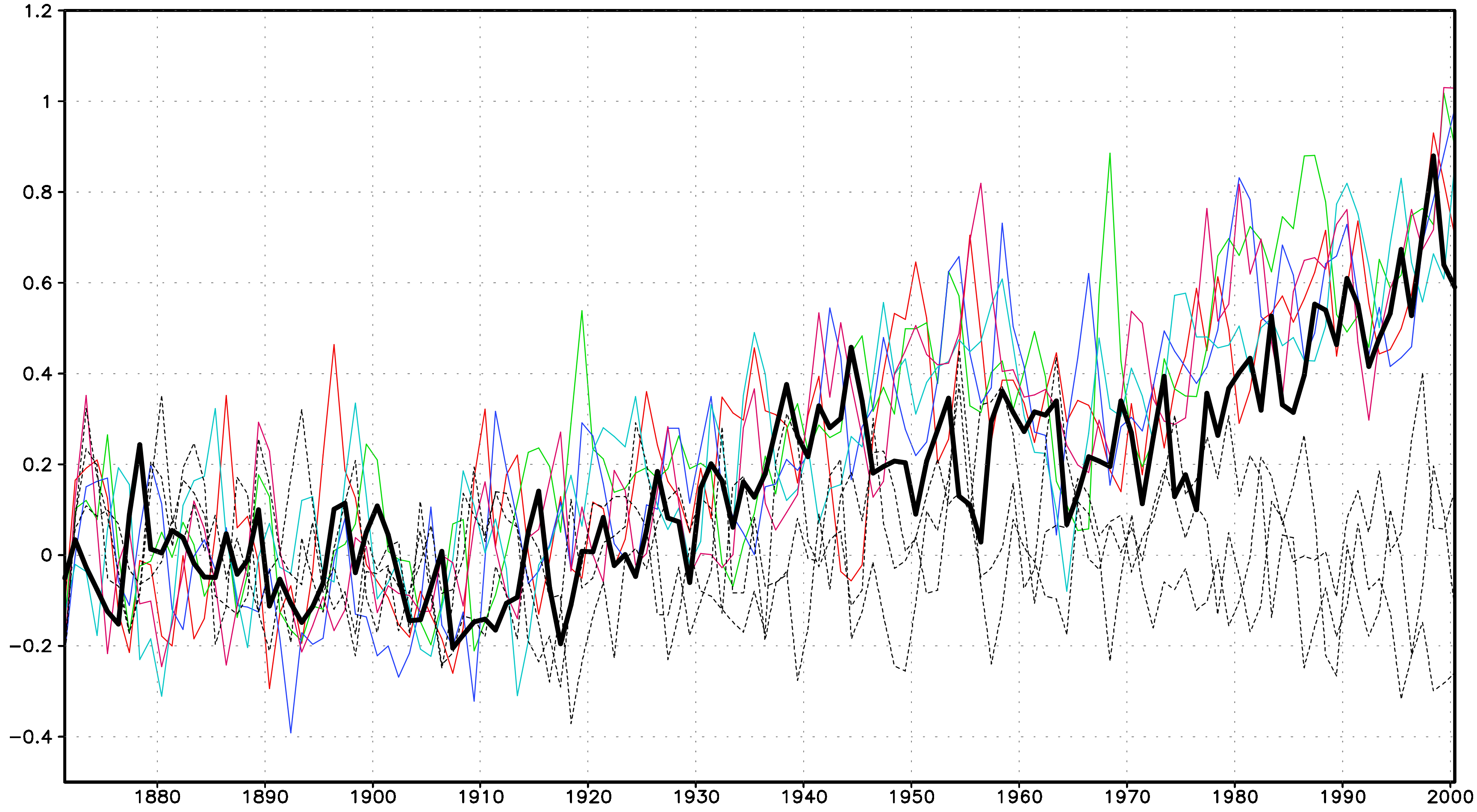




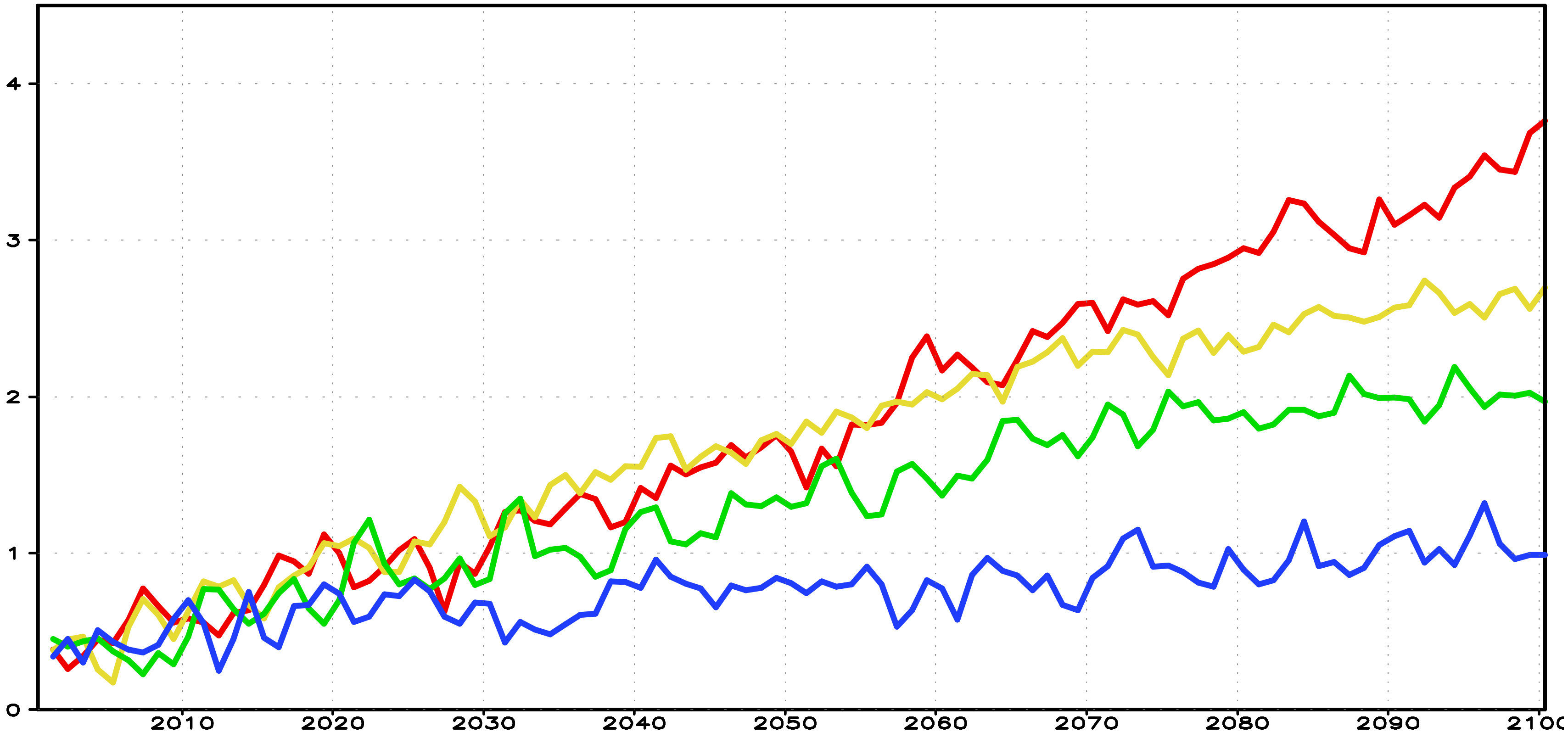
From top to bottom: time variations of carbon dioxide concentration (ppm), methane (ppb), nitrous oxide (ppb), sulphate aerosol (mg/m^2), solar constant (W/m^2), optical depth of volcanic aerosol (non-dim). Solid line – observations (1871-2000), thin solid line – scenario B1, long-dashed line – scenario A1B, dashed line – scenario A2.



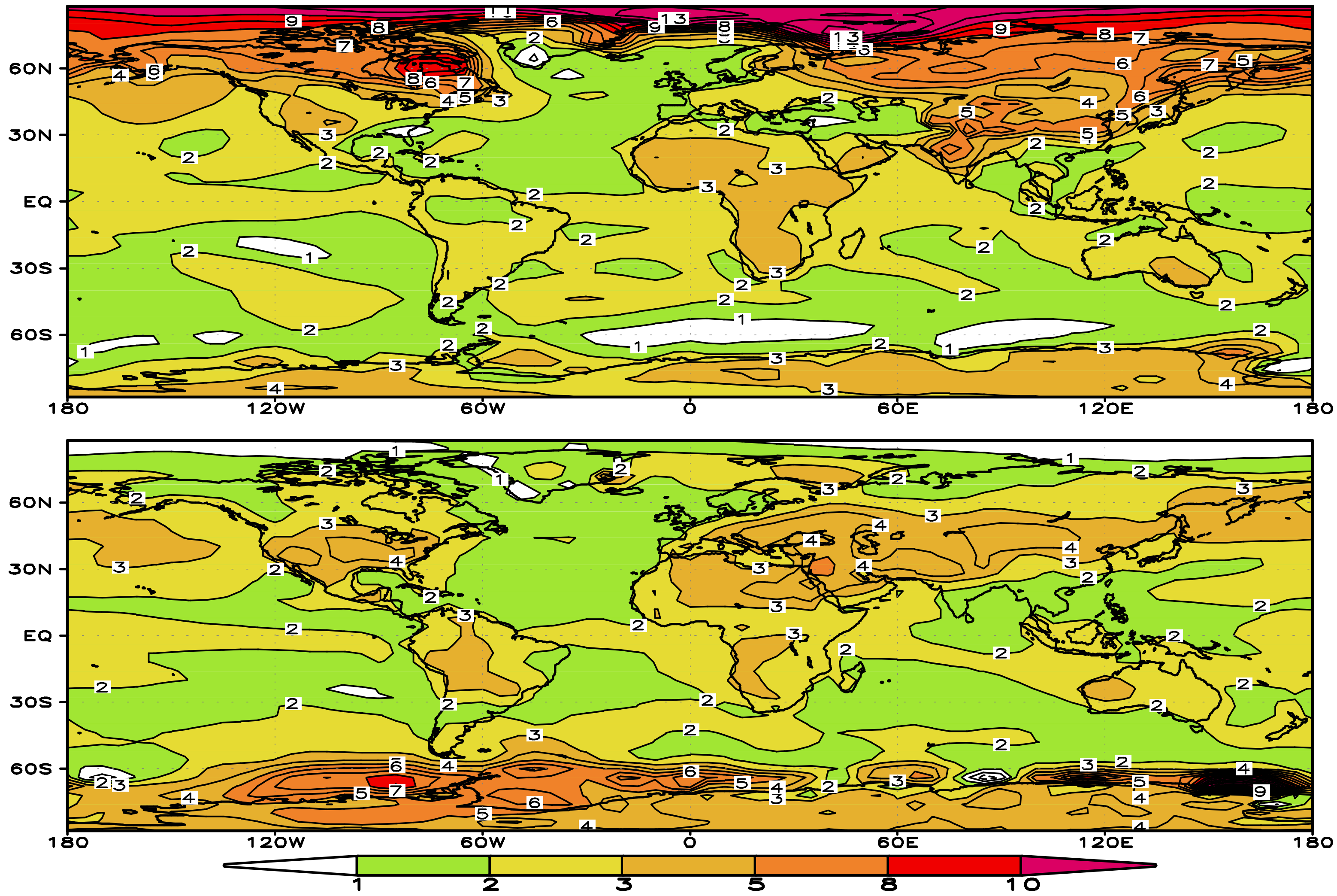
Variations of global-average near-the-surface air temperature (K degrees) in 1871-2000 as follows from: observations (solid black line), results of 5 numerical experiments with observed variations of atmospheric forcing (thin solid color lines) and results of 3 numerical experiments with external forcing fixed at 1871 value. Averaged for 1871-1920 extracted.



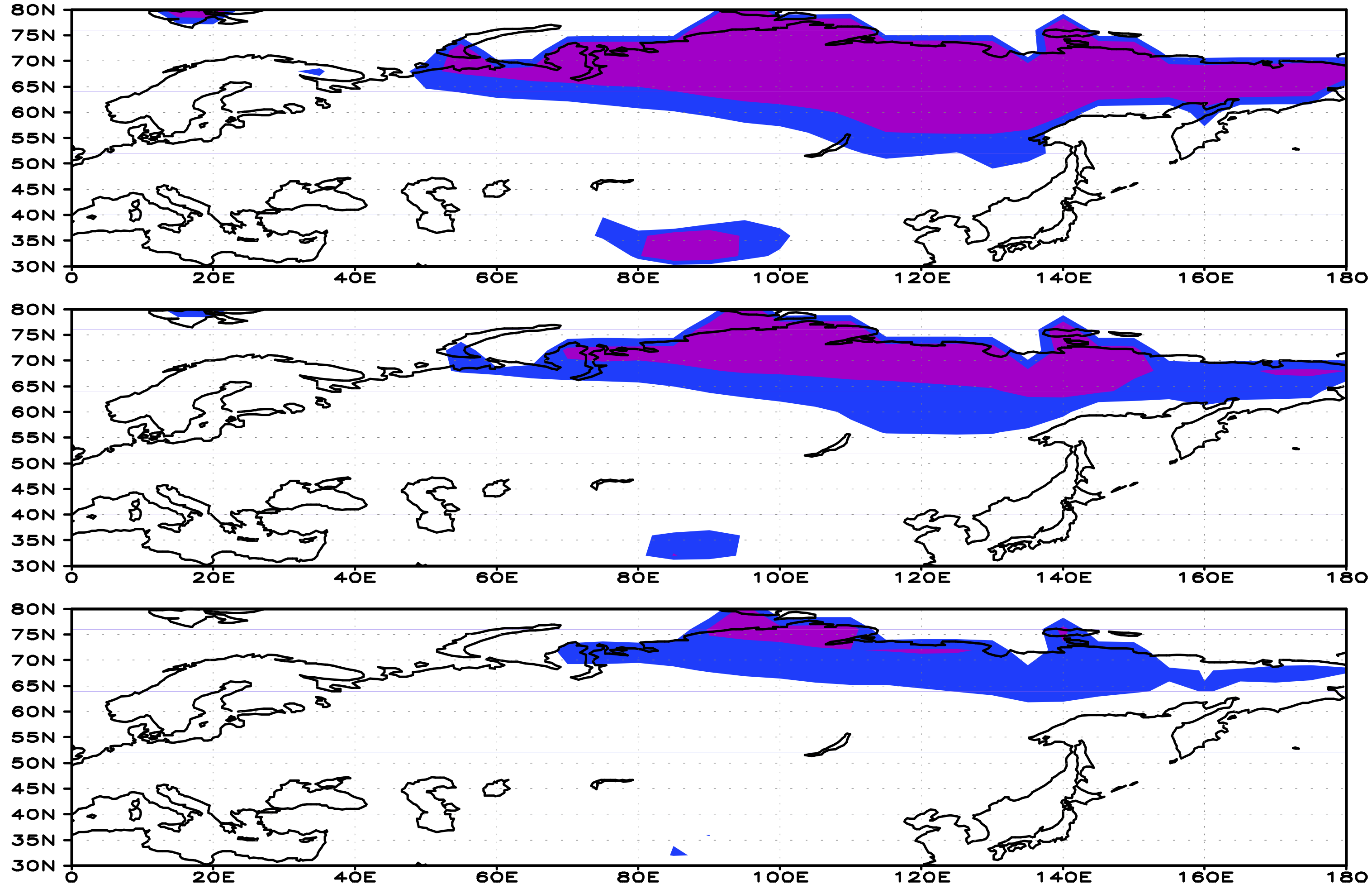
Global-average temperature change in 21 century relatively to 1981-2000 as follows from INM climate model experiments A2 (red), A1B (yellow), B1 (green) и 2000 (blue).



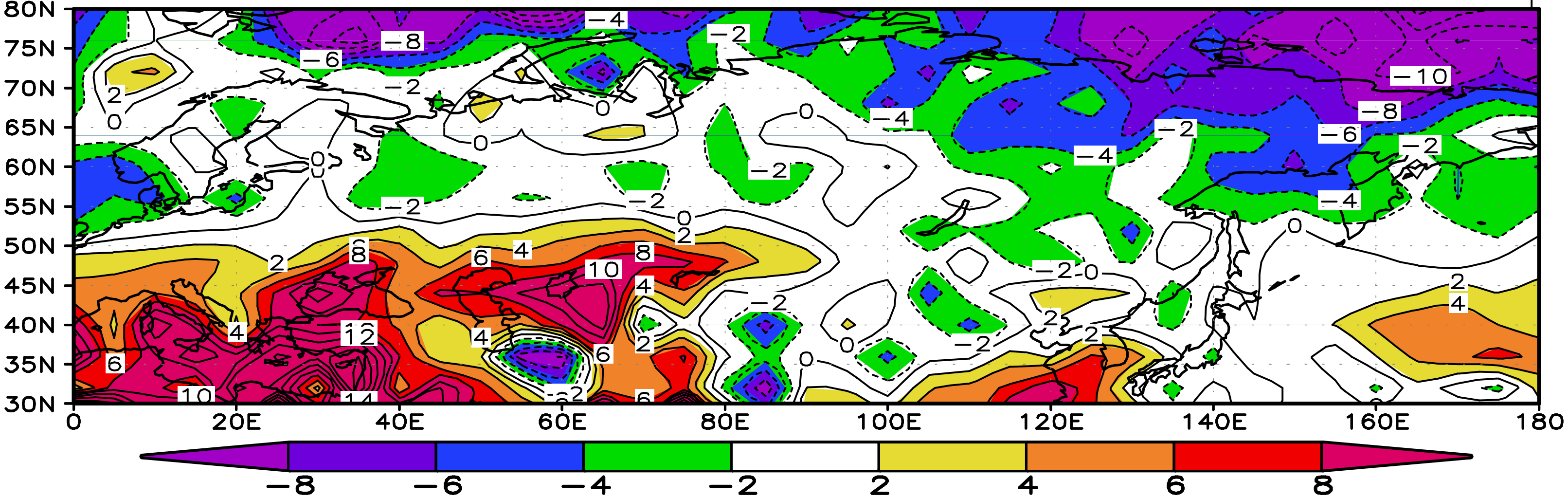
Near-the-surface air temperature change in 2081-2100 relatively to 1981-2000 under scenario A1B in winter (top) and summer (bottom).

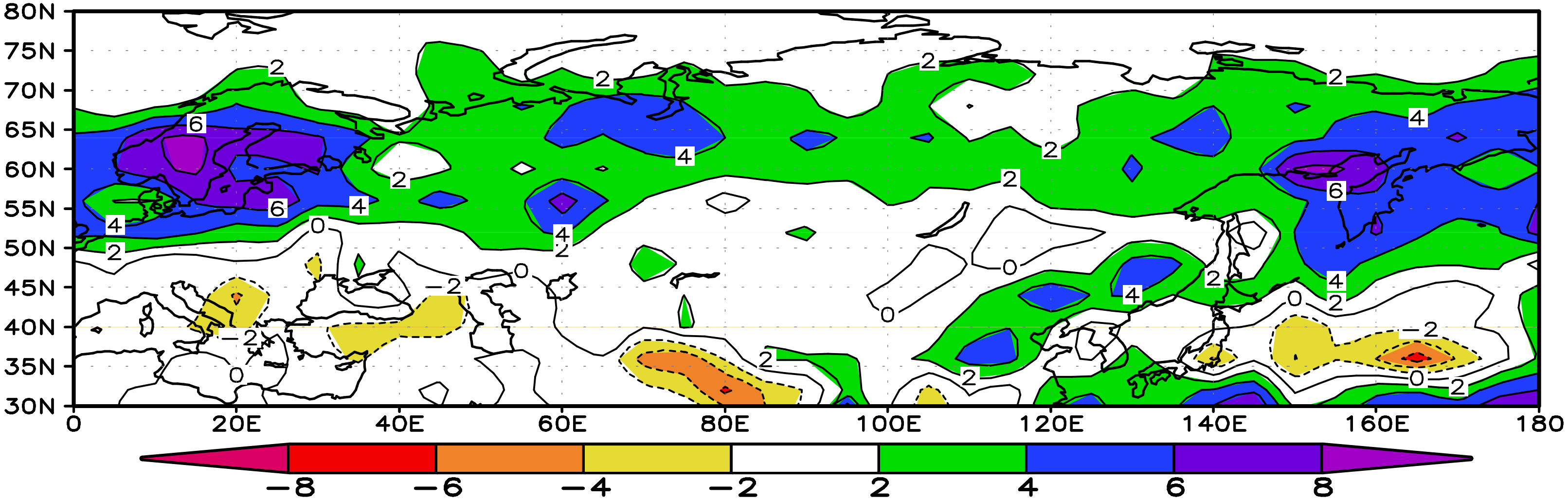


Spatial distribution of continuous (violet) and sporadic (blue) permafrost as follows from INM climate model experiments: in 1981-2000 (top), 2081-2100 under scenario B1 (middle) and in 2081-2100 under scenario A2 (bottom).

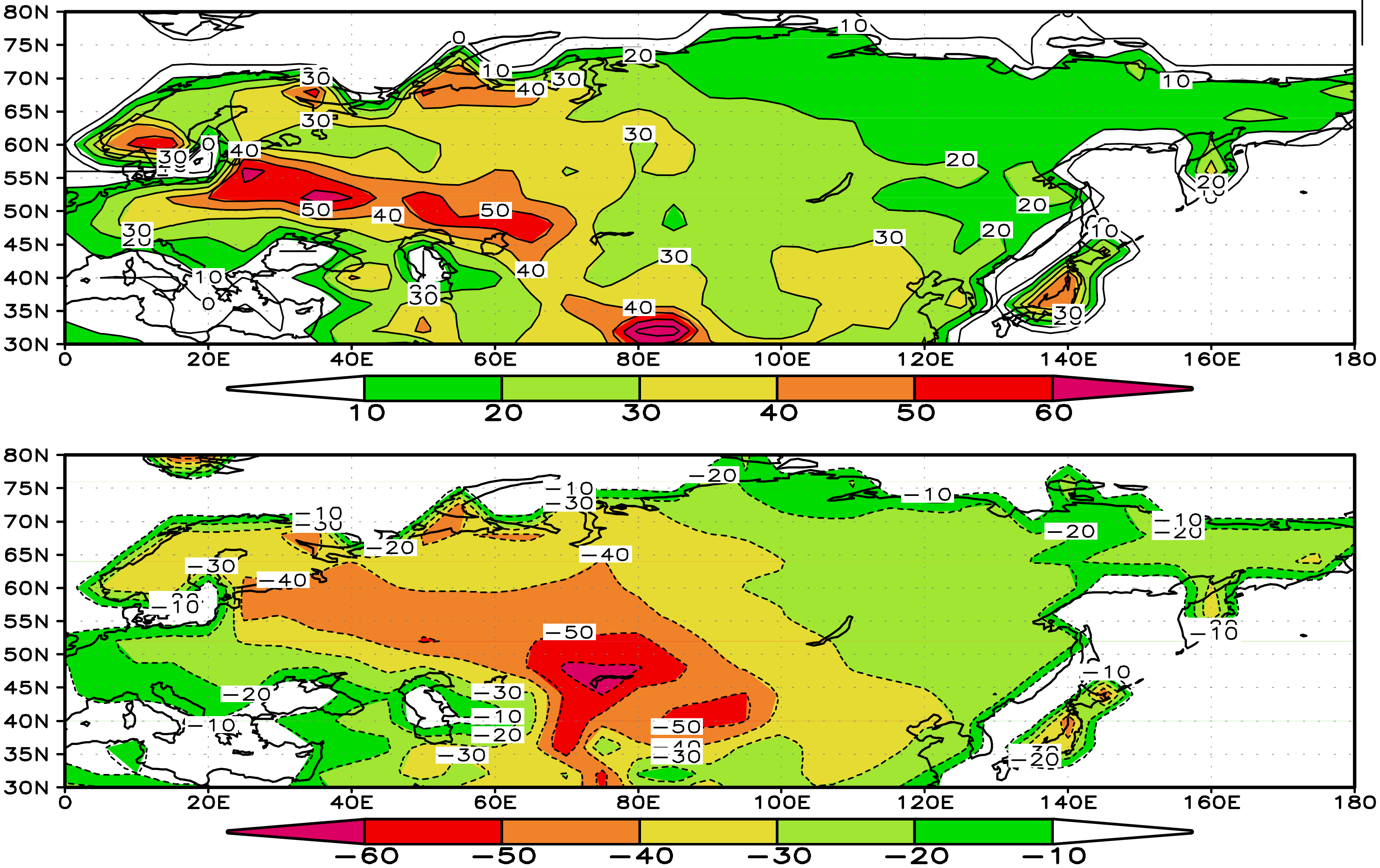


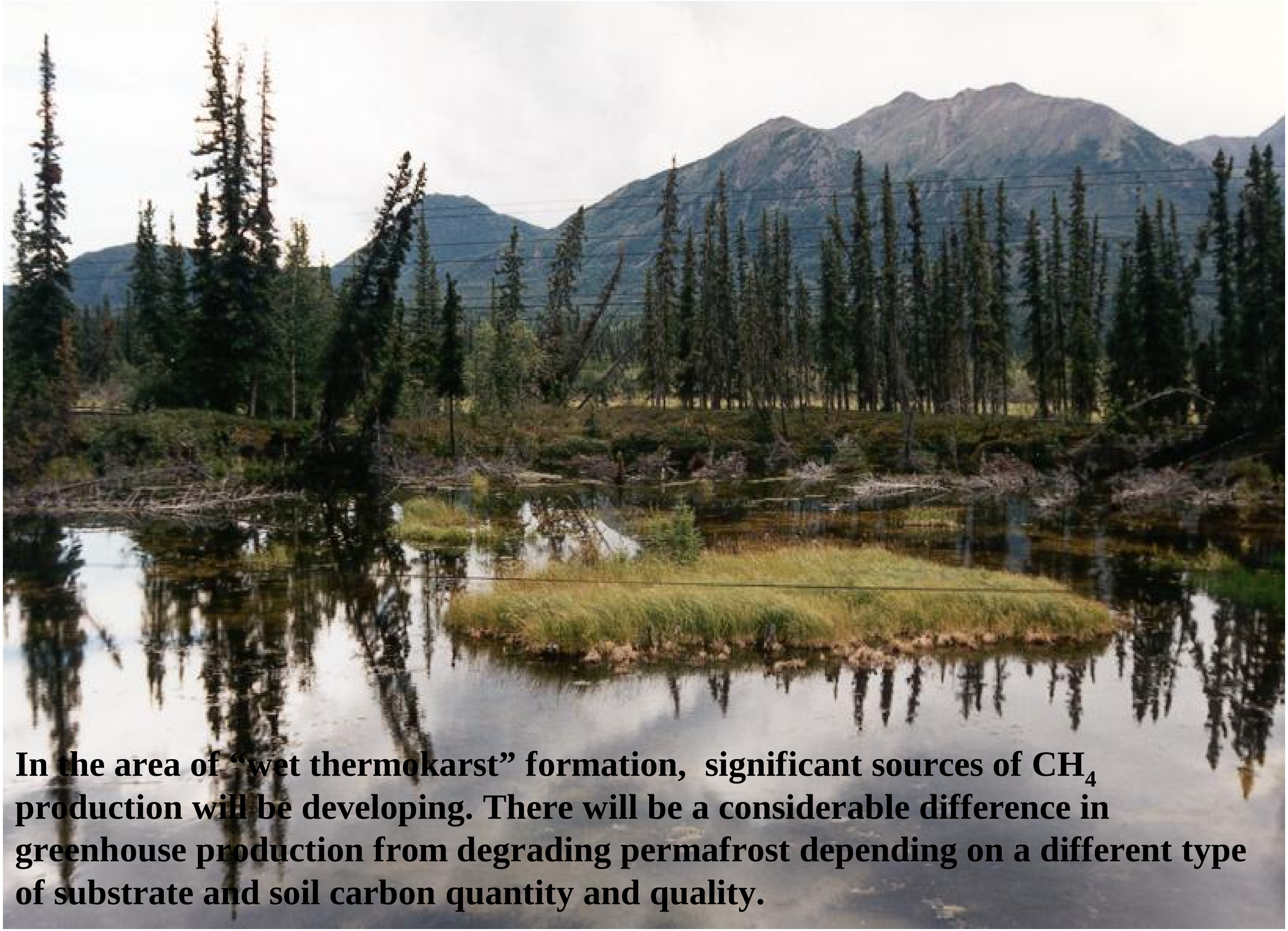
Changes in maximal duration of dry period, days (top) and in number of days with precipitation more than 10 mm/day (bottom) in 2081-2100 under scenario A1B with respect to 1981-2000.





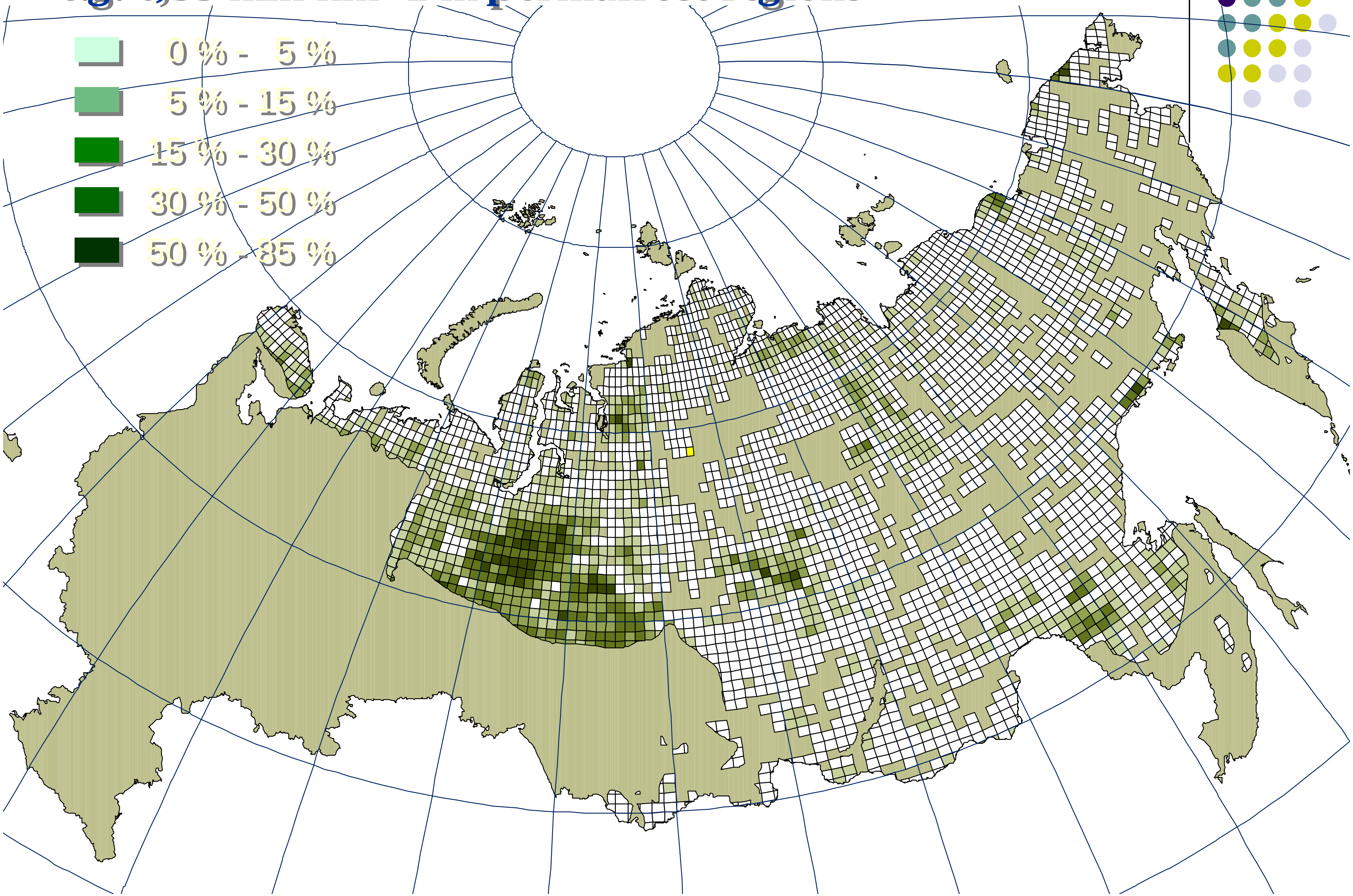
Changes in length of vegetation period, days (top) and in number of frosty days (bottom) in 2081-2100 under scenario A1B with respect to 1981-2000 as follows from INM climate model experiments





In the area of “wet thermokarst” formation, significant sources of CH_4 production will be developing. There will be a considerable difference in greenhouse production from degrading permafrost depending on a different type of substrate and soil carbon quantity and quality.

Fraction of wetlands in Russia: 0,76 mln km^2, e.g. 0,35 mln km^2 in permafrost regions



Large-scale hydrothermodynamics of the atmosphere

$$\frac{du}{dt} - \left(f + \frac{u}{a}\operatorname{tg}\varphi \right) v + \frac{1}{a\cos\varphi}\left(\frac{\partial \Phi}{\partial \lambda} + \frac{RT}{p}\frac{\partial p}{\partial \lambda} \right) = F_u ,$$

$$\frac{dv}{dt} + \left(f + \frac{u}{a}\operatorname{tg}\varphi \right) u + \frac{1}{a}\left(\frac{\partial \Phi}{\partial \varphi} + \frac{RT}{p}\frac{\partial p}{\partial \varphi} \right) = F_v ,$$

$$\frac{\partial \Phi}{\partial \sigma} = -\frac{RT}{\sigma} ,$$

$$\frac{\partial p}{\partial t} + \frac{1}{a\cos\varphi}\left(\frac{\partial p u}{\partial \lambda} + \frac{\partial p v \cos\varphi}{\partial \varphi} \right) + \frac{\partial p \dot{\sigma}}{\partial \sigma} = 0 ,$$

$$\frac{dT}{dt} - \frac{RT}{c_p \sigma p}\left[p\dot{\sigma} + \sigma\left(\frac{\partial p}{\partial t} + \frac{u}{a\cos\varphi}\frac{\partial p}{\partial \lambda} + \frac{v}{a}\frac{\partial p}{\partial \varphi} \right) \right] = F_T + \varepsilon ,$$

$$\frac{dq}{dt} = F_q - (C - E),$$

where

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \frac{u}{a\cos\varphi}\frac{\partial}{\partial \lambda} + \frac{v}{a}\frac{\partial}{\partial \varphi} + \dot{\sigma}\frac{\partial}{\partial \sigma} .$$

Subgrid-scale processes parameterization

Parameterization of subgrid-scale processes

- **Turbulence in the atmospheric boundary layer, upper ocean layer and bottom boundary layer**
- **Convection and orographic waves**
- **Diabatic heat sources (radiative and phase changes, cloudiness, precipitation, etc.)**
- **Carbon dioxide cycle and photochemical transformations**
- **Heat, moisture and solute transport in the vegetation and snow cover**
- **Production and transport of the soil methane**
- **Etc.**

Regional scale modeling and assessment

- **Atmospheric modeling, e.g. using global climate model with improved spatial resolution in the region under consideration and non-hydrostatic mesoscale models: parameterization of mesoscale variability**
- **Catchment modeling, e.g. constructing models of river dynamics: parameterization of hydrological cycle**
- **Vegetation modeling, e.g. models of vegetation dynamics: parameterization of biogeochemical and hydrological cycles**
- **Soil (including permafrost) modeling, e.g. models of snow and frozen ground mechanics: parameterization of hydrological and biogeochemical cycles**
- **Coupled regional models**
- **Air and water quality modeling**
- **Statistical and dynamic downscaling (e.g. regional projections of global climate change patterns)**

Assessment of climate change impact on regional environment

- **RAS/NASA Northern Eurasia (NEA) Earth Science Partnership Initiative (NEESPI):**

  - are mathematical models capable of simulating observed climate changes in NEA and their feedback effects on global climate?

  - what are the direct and feedback effects on environmental changes in NEA on the Earth climate system?

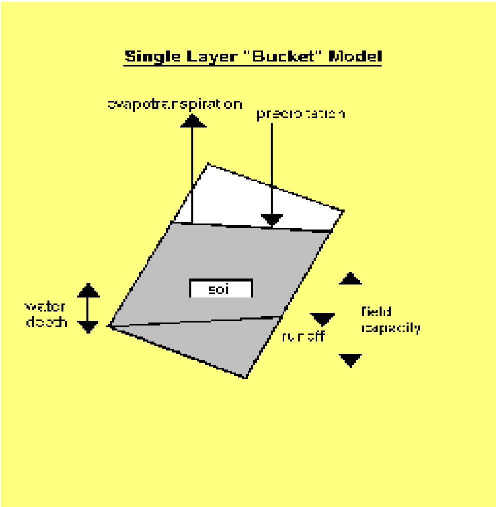
- **Permafrost changes in Siberia may have a substantial effect on the chemical deposition of the atmosphere such as carbon dioxide and methane**

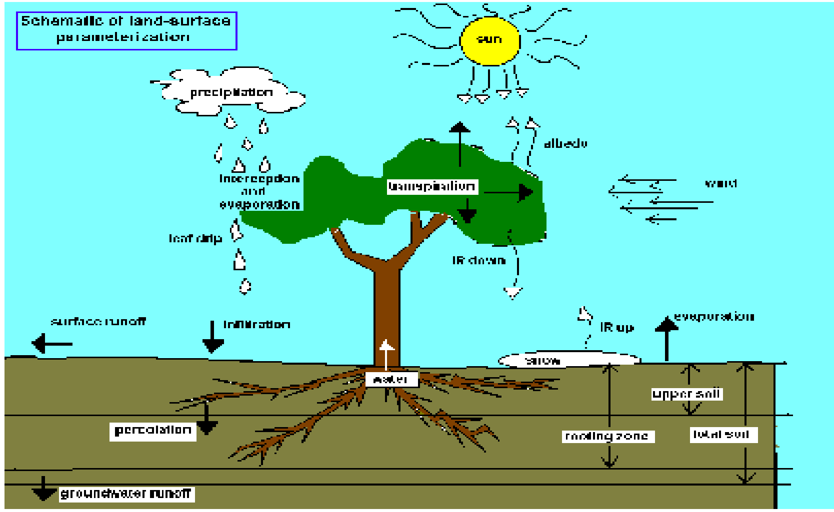
- **Are stand-alone permafrost models forced by climate change scenarios produced by global climate models (which, in general, do not describe explicitly processes in the frozen ground) capable of correct assessing environmental changes in Siberia?**

T.J. Philips et al. (2002). Large-Scale Validation of AMIP II Land-Surface Simulations

The Overarching Question:

What degree of LSS complexity is *essential* for climate simulation?





“Bucket” Scheme

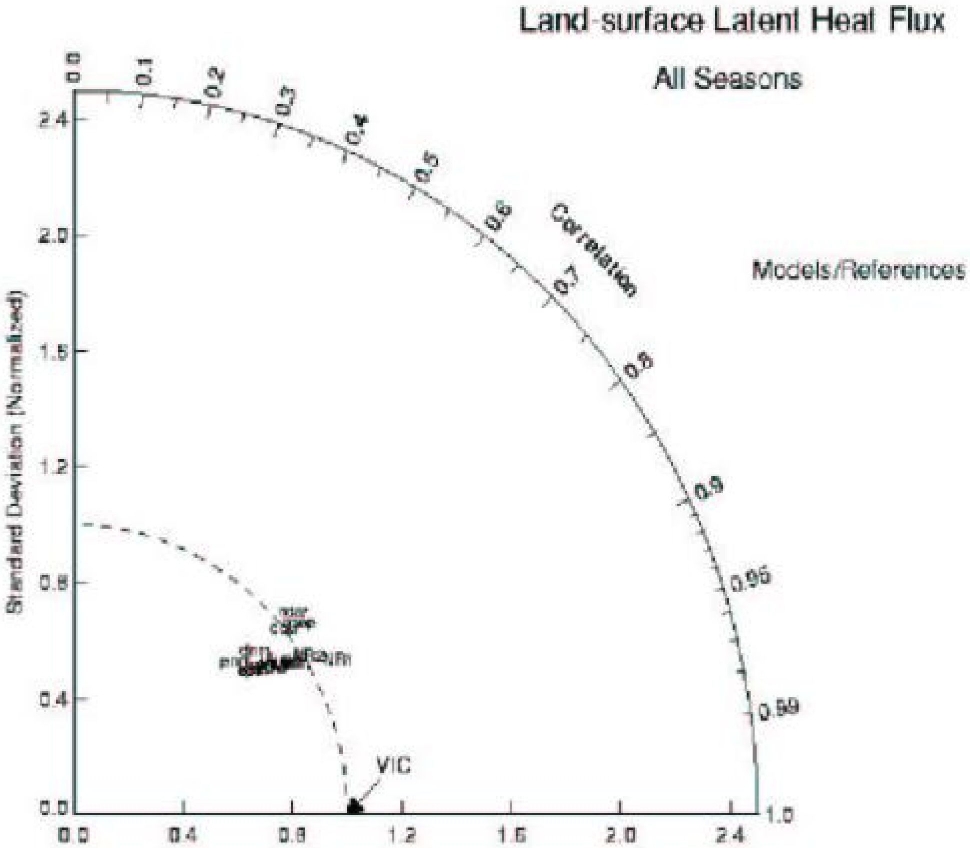
- No explicit vegetation
- Little soil physics
- Overflow runoff
- Few free parameters
- Computationally cheap

Complex Biophysical Scheme

- Vegetation canopy(interception, resistance)
- Soil moisture percolation/diffusion
- Surface and gravitational runoff
- Many free parameters
- Computationally expensive

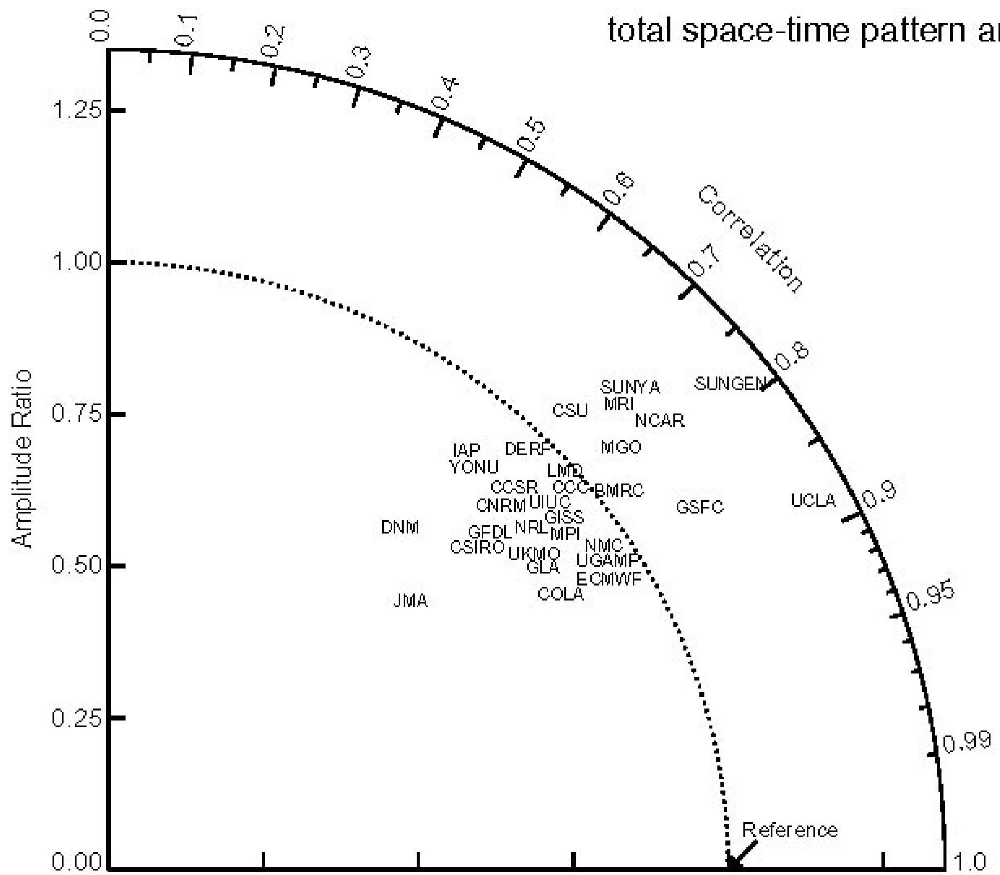
The Taylor diagram for the variability of the latent heat flux at the land surface as follows from results of AMIP-II experiments

(Irannejad et al., 2002).

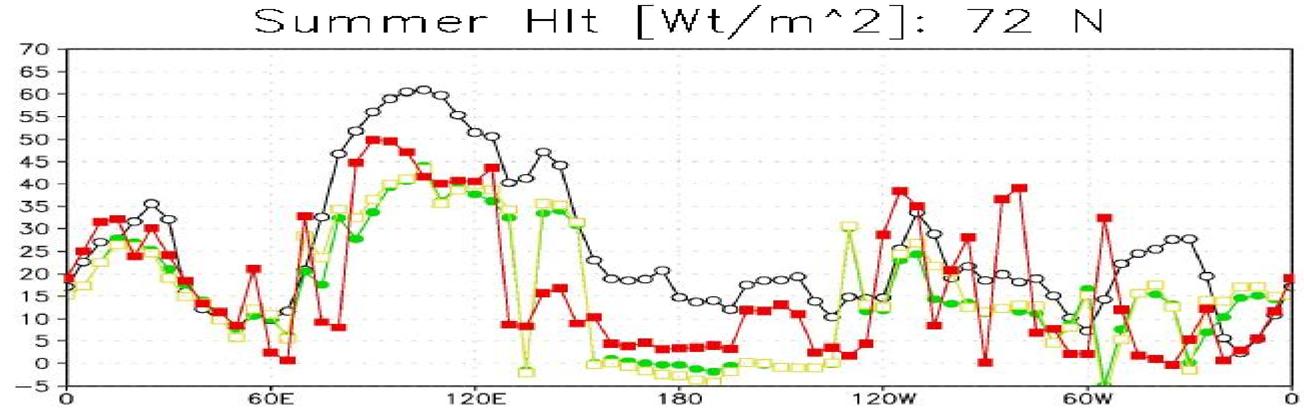


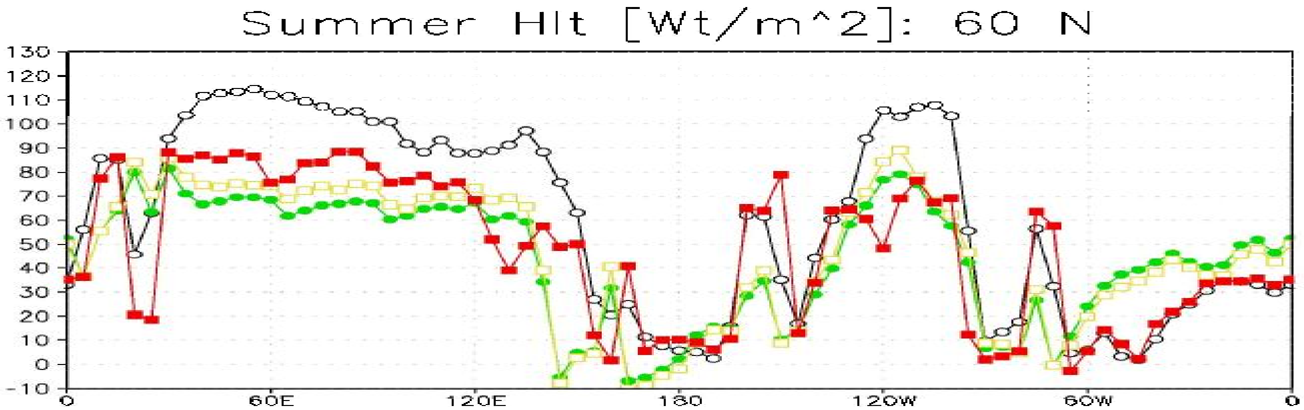
Land-surface Evaporation: AMIP I Models vs NCEP Reanalysis

total space-time pattern analysis

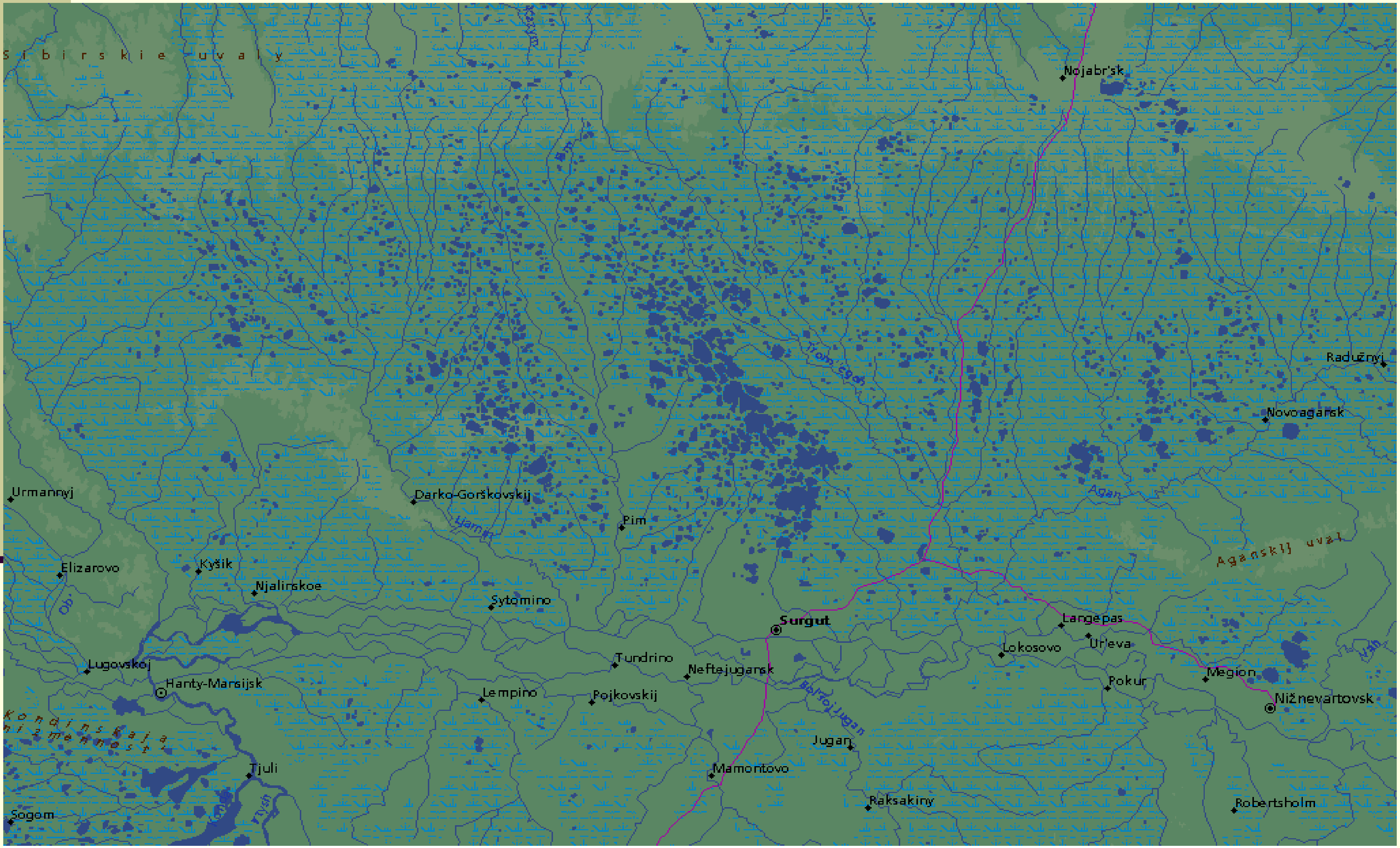


Latent heat flux: gray line - NCAR/NCEP reanalys, red line – ECMWF reanalys, green line – simulation of the present-day climate, yellow line – climate with double CO2

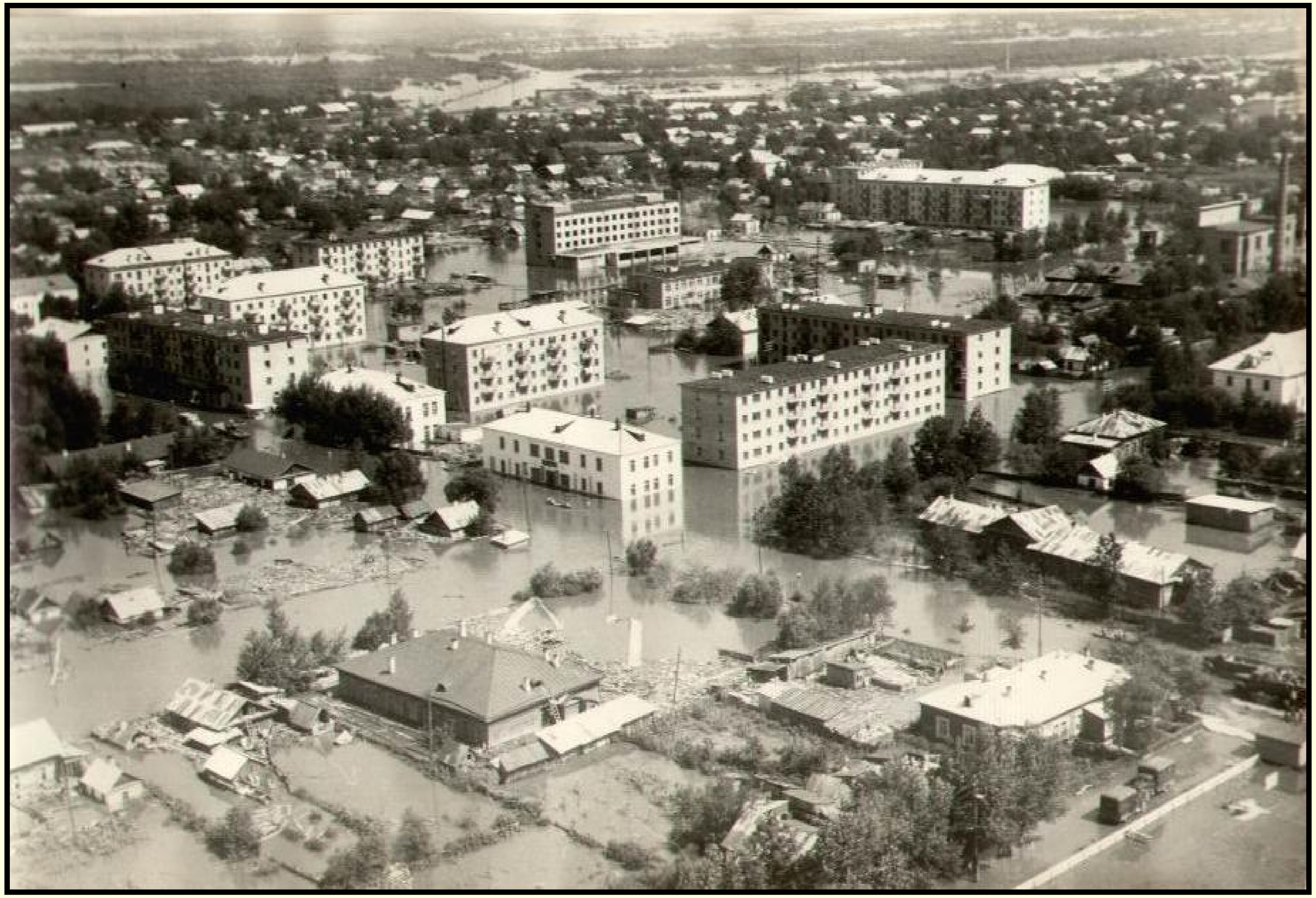




An example of “hydrological” heterogeneity: middle Ob’ river



Flood in city Dal’norechensk of Primorskii region



Instruction Report EL-02-1
August 2002

CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.1

User Manual

by Thomas M. Cole
Environmental Laboratory
U.S. Army Corps of Engineers
Waterways Experiment Station
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and

Scott A. Wells
Department of Civil and Environmental Engineering
Portland State University
Portland, OR 97207-0751

Draft Report
Not approved for public release
(Supersedes Instruction Report E-95-1

DRAFT

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

where B_η is the width at the surface.

Equation of State

The density must be known for solution of the momentum equations. The equation of state is an equation that relates density to temperature and concentration of dissolved substances. This equation is given by:

$$\rho = f(T_w, \Phi_{TDS}, \Phi_{ISS}) \tag{A-50}$$

where $f(T_w, \Phi_{TDS}, \Phi_{ISS})$ is a density function dependent upon temperature, total dissolved solids or salinity, and inorganic suspended solids.

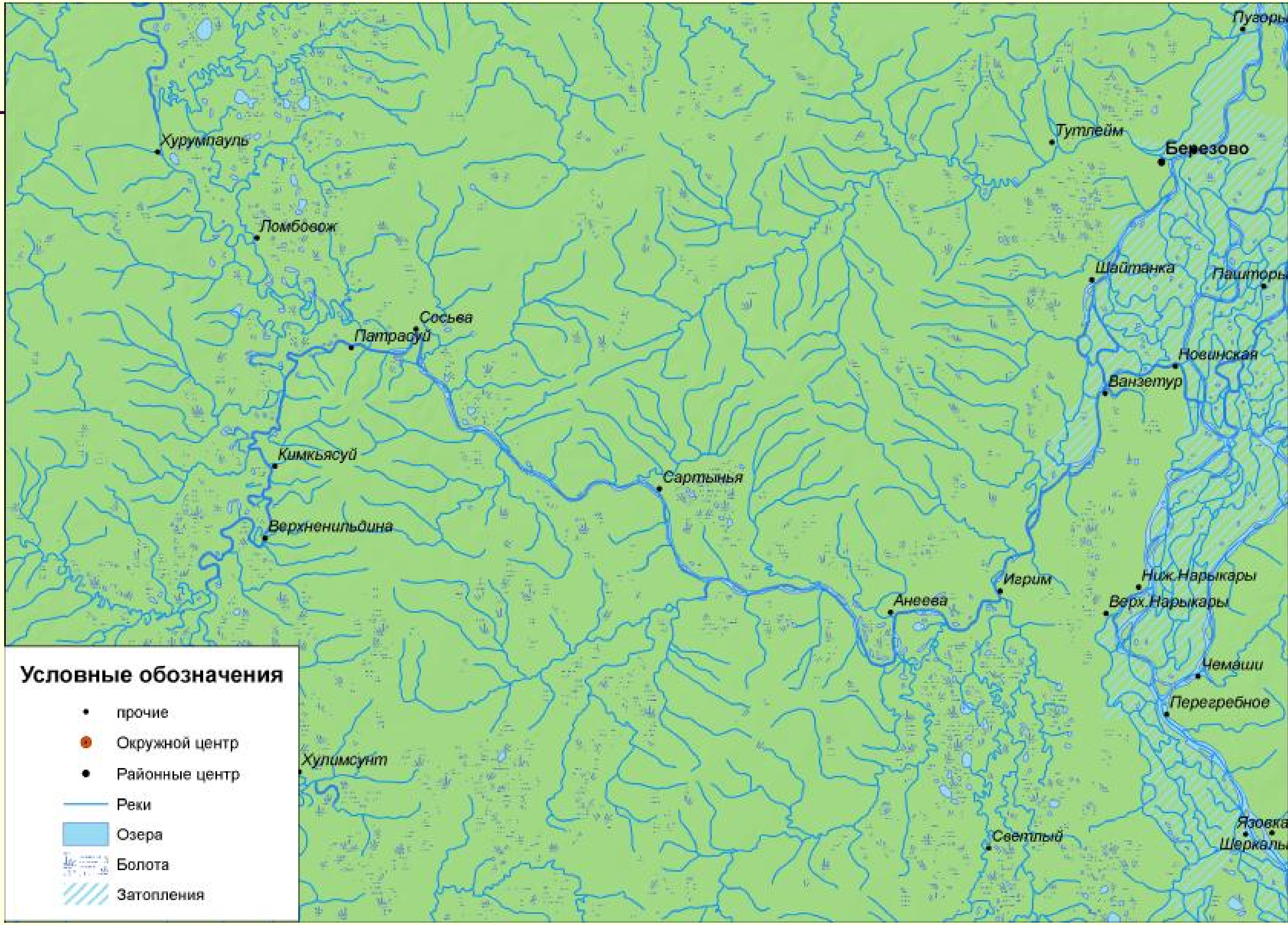
Summary of Governing Equations

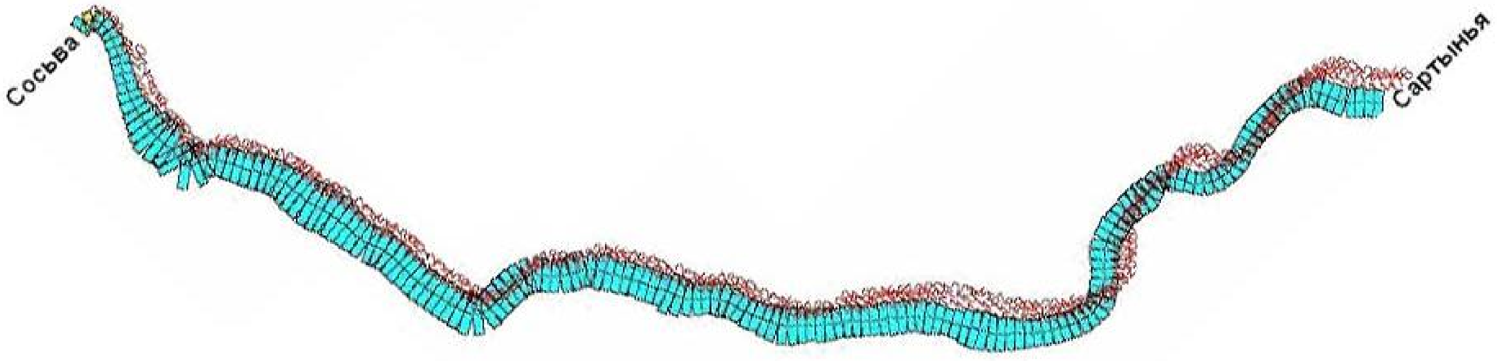
Table A-1 shows the governing equations after lateral averaging for a channel slope of zero (original model formulation) and for an arbitrary channel slope. Parameters used in **Table A-1** are illustrated in **Figure A-12**.

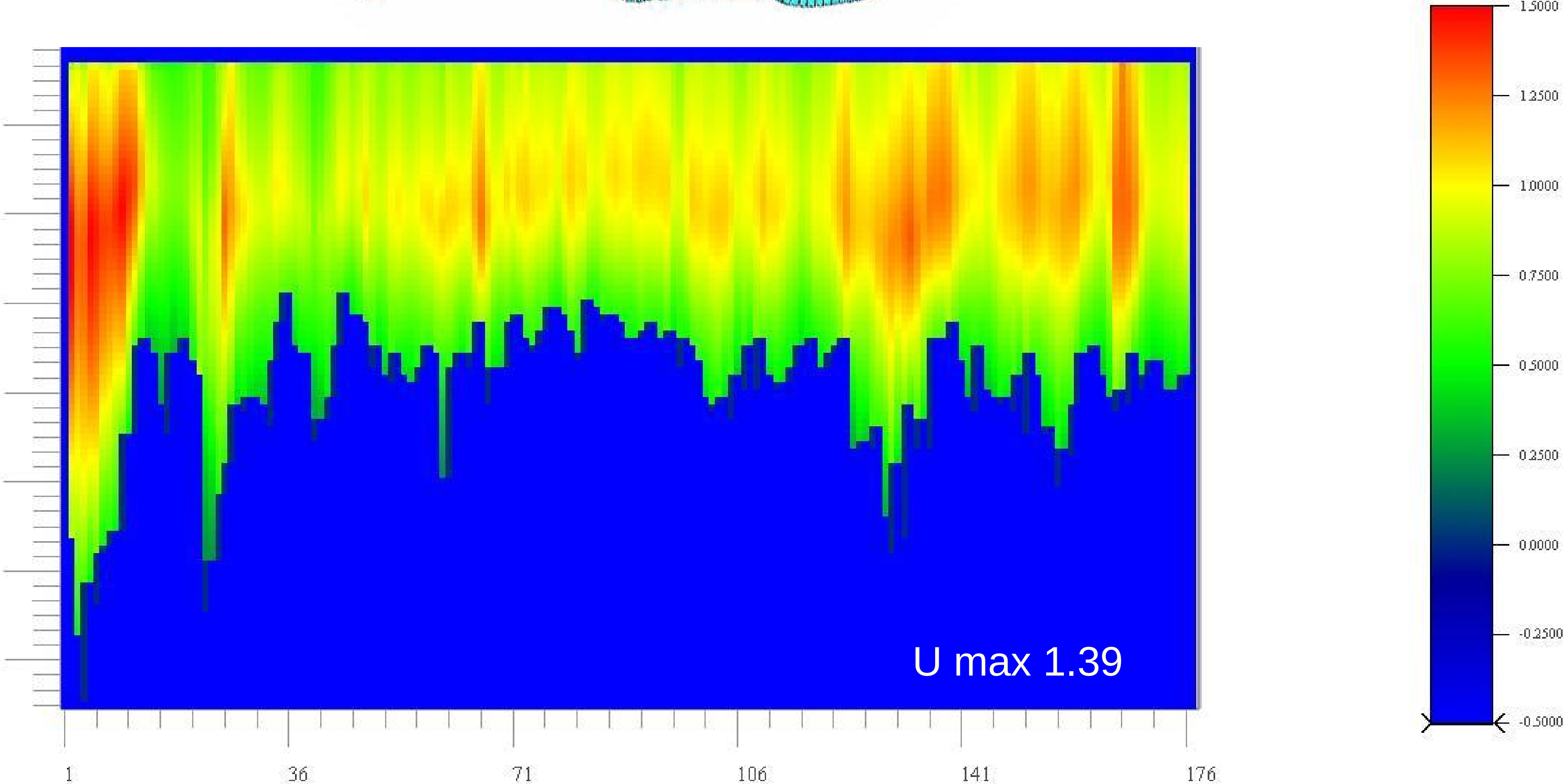
Table A-1. Governing equations with and without channel slope.

Equation	Governing equation assuming no channel slope	Governing equation assuming an arbitrary channel slope and conservation of momentum at branch intersections
x-momentum	$\frac{\partial UB}{\partial t} + \frac{\partial UUB}{\partial x} + \frac{\partial WUB}{\partial z} = gB\frac{\partial \eta}{\partial x} - \frac{gB}{\rho}\int_\eta^z \frac{\partial \rho}{\partial x} dz + \frac{1}{\rho}\frac{\partial B\tau_{xx}}{\partial x} + \frac{1}{\rho}\frac{\partial B\tau_{xz}}{\partial z}$	$\frac{\partial UB}{\partial t} + \frac{\partial UUB}{\partial x} + \frac{\partial WUB}{\partial z} = gB\sin\alpha + g\cos\alpha B\frac{\partial \eta}{\partial x} - \frac{g\cos\alpha B}{\rho}\int_\eta^z \frac{\partial \rho}{\partial x} dz + \frac{1}{\rho}\frac{\partial B\tau_{xx}}{\partial x} + \frac{1}{\rho}\frac{\partial B\tau_{xz}}{\partial z} + qBU_x$
z-momentum	$0 = g - \frac{1}{\rho}\frac{\partial P}{\partial z}$	$0 = g\cos\alpha - \frac{1}{\rho}\frac{\partial P}{\partial z}$
continuity	$\frac{\partial UB}{\partial x} + \frac{\partial WB}{\partial z} = qB$	$\frac{\partial UB}{\partial x} + \frac{\partial WB}{\partial z} = qB$
state	$\rho = f(T_w, \Phi_{TDS}, \Phi_{ss})$	$\rho = f(T_w, \Phi_{TDS}, \Phi_{ss})$
free surface	$B_\eta \frac{\partial \eta}{\partial t} = \frac{\partial}{\partial x}\int_\eta^h UB dz - \int_\eta^h qB dz$	$B_\eta \frac{\partial \eta}{\partial t} = \frac{\partial}{\partial x}\int_\eta^h UB dz - \int_\eta^h qB dz$

Pushistov et al.:
Modeling of hydrodynamics of Severnaya Sos'va river







Streamwise velocity

Thermodynamics of shallow reservoir

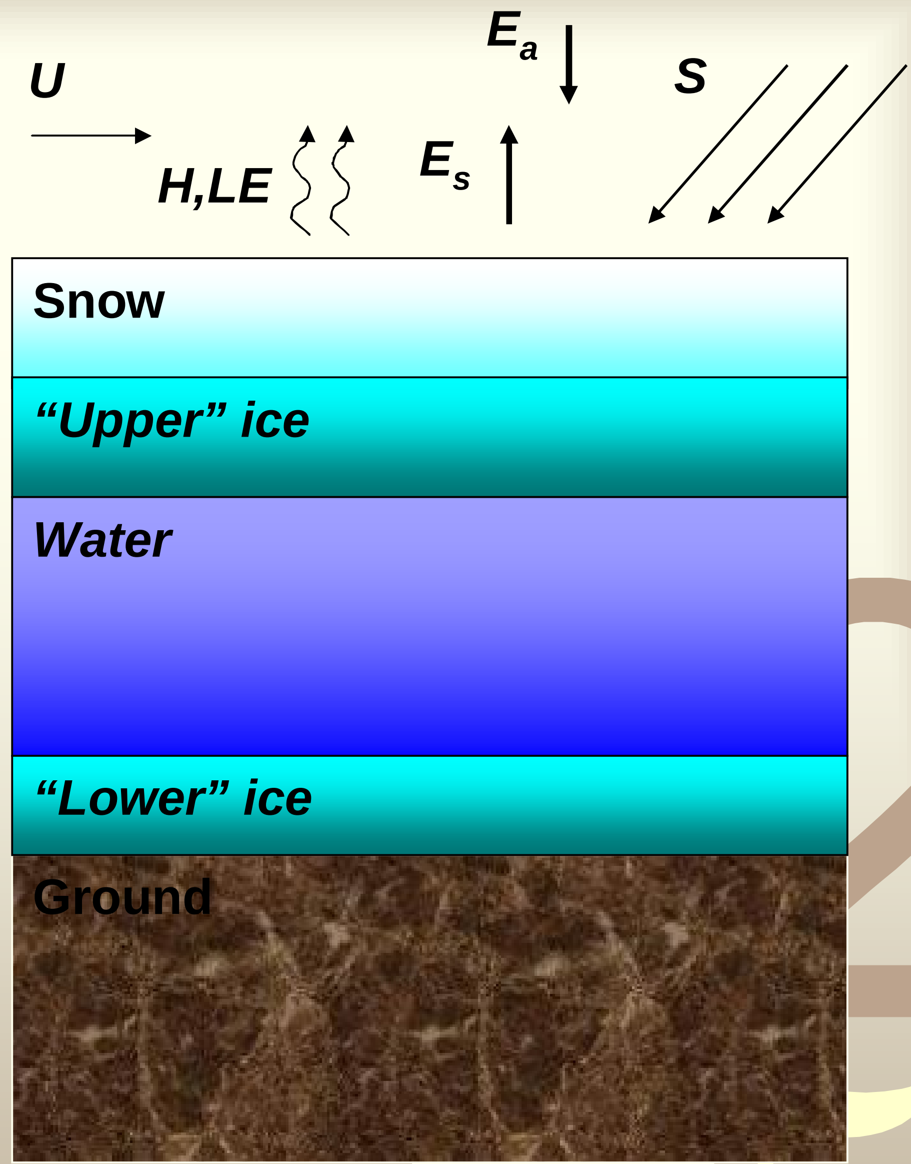
1) **One-dimensional** approximation.

2) On the **upper boundary**: fluxes of momentum, sensible and latent heat, solar and long-wave radiation are calculated

On the **lower boundary**: fluxes are prescribed

3) Water and ice: **heat transport**

Snow and ground: **heat- and moisture transport**



U – wind velocity
H – sensible heat flux
LE – latent heat flux
S – shirt-wave radiation
E_a – incoming long-wave radiation
E_s – outgoing long-wave radiation

Mathematical formulation

- for water and ice:

$$\tilde{n}r\frac{\partial T}{\partial t}=\frac{l}{h^2}\frac{\partial^2 T}{\partial x^2}+cr\frac{dh}{dt}\frac{x}{h}\frac{\partial T}{\partial x}-cr\frac{1}{h}\frac{dh}{dt}\frac{\partial T}{\partial x}-\frac{\partial I}{\partial z},\quad x=\frac{z}{h}$$

- heat conductivity

- for snow:

$$cr\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}l\frac{\partial T}{\partial z}+rLF_{fr},$$

- temperature

$$\frac{\partial W}{\partial t}=-\frac{\partial g}{\partial z}-F_{fr}.$$

- liquid water

- for ground:

$$rc\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left(l_T\frac{\partial T}{\partial z}+crT\left(l_W\frac{\partial W}{\partial z}-g\right)\right)+rL_iF_i,$$

- temperature

$$\frac{\partial W}{\partial t}=\frac{\partial}{\partial z}l_W\frac{\partial W}{\partial z}-\frac{\partial g}{\partial z}-F_i,$$

- liquid water

$$\frac{\partial I}{\partial t}=F_i.$$

- ice

Mesoscale atmospheric model NH3D *(Miranda, 1991)*

Governing equations in σ-coordinates *(Miller, White, 1984)*

$$\frac{\partial up_*}{\partial t}+\frac{\partial u^2 p_*}{\partial x}+\frac{\partial vup_*}{\partial y}+\frac{\partial \dot{\sigma} up_*}{\partial \sigma}=-p_*\frac{\partial \phi'}{\partial x}+\sigma\frac{\partial p_*}{\partial x}\frac{\partial \phi'}{\partial \sigma}+fvp_*+p_*\left(D_u+R_u\right),$$

$$\frac{\partial vp_*}{\partial t}+\frac{\partial uvp_*}{\partial x}+\frac{\partial v^2 p_*}{\partial y}+\frac{\partial \dot{\sigma} vp_*}{\partial \sigma}=-p_*\frac{\partial \phi'}{\partial y}+\sigma\frac{\partial p_*}{\partial y}\frac{\partial \phi'}{\partial \sigma}-fup_*+p_*\left(D_v+R_v\right),$$

$$\frac{\partial \tilde{w}p_*}{\partial t}+\frac{\partial u\tilde{w}p_*}{\partial x}+\frac{\partial v\tilde{w}p_*}{\partial y}+\frac{\partial \dot{\sigma}\tilde{w}p_*}{\partial \sigma}=-S_v p_*\frac{\partial \phi'}{\partial \sigma}+p_*g\left(\frac{q'}{q_s}-q_r\right)+p_*\left(D_w+R_w\right),$$

$$\frac{\partial q' p_*}{\partial t}+\frac{\partial uq' p_*}{\partial x}+\frac{\partial vq' p_*}{\partial y}+\frac{\partial \dot{\sigma} q' p_*}{\partial \sigma}=-S_v\tilde{w}p_*\frac{\partial q_s}{\partial \sigma}+p_*\frac{L_v}{c_p}\left(\frac{p_0}{p}\right)^k\left(COND-EVAP\right)+p_*\left(D_q+R_q\right),$$

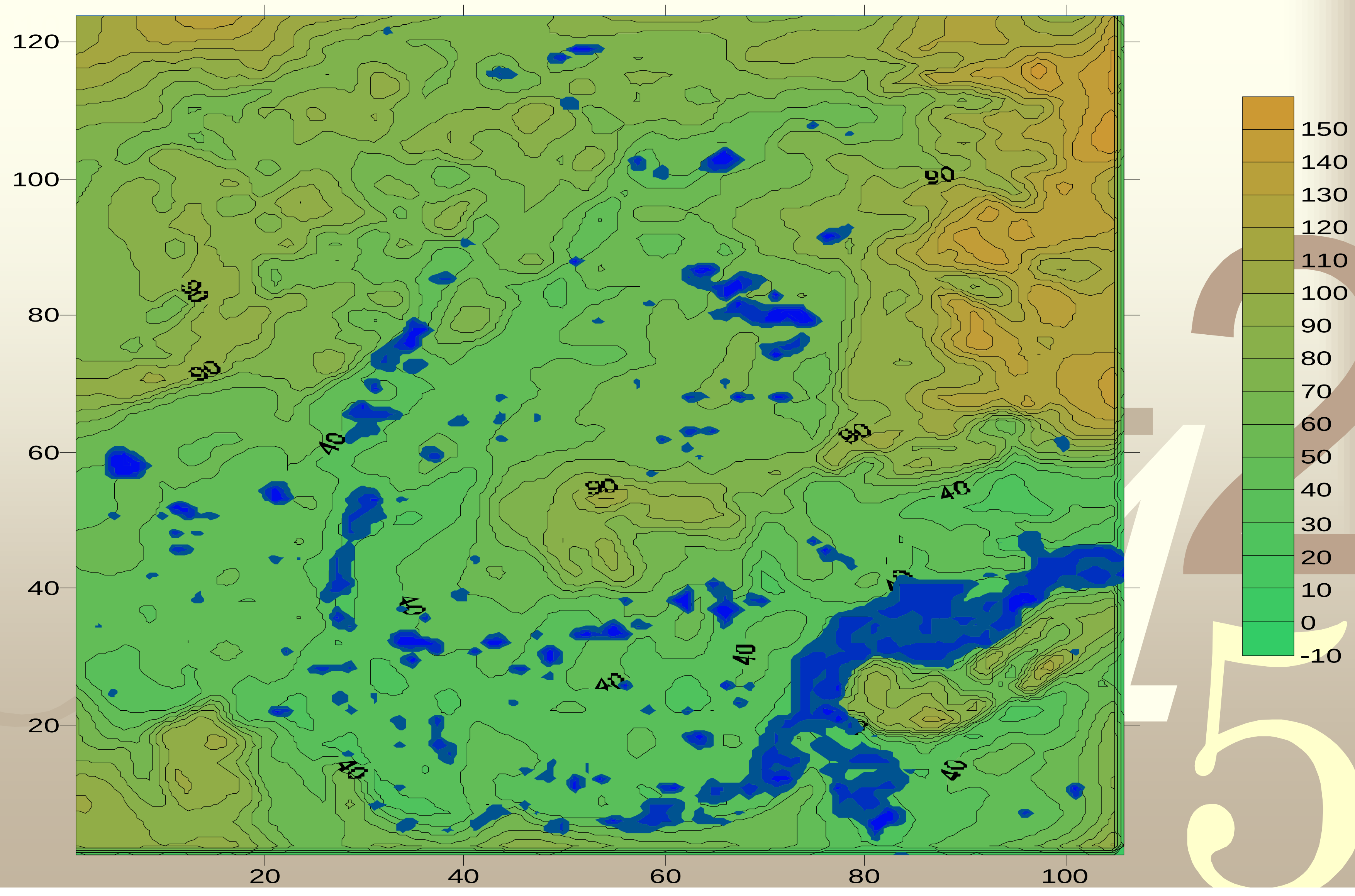
$$\frac{\partial p_*}{\partial t}+\frac{\partial up_*}{\partial x}+\frac{\partial vp_*}{\partial y}+\frac{\partial \dot{\sigma} p_*}{\partial \sigma}=0,$$

$$\frac{\partial q_v p_*}{\partial t}+\frac{\partial uq_v p_*}{\partial x}+\frac{\partial vq_v p_*}{\partial y}+\frac{\partial \dot{\sigma} q_v p_*}{\partial \sigma}=p_*\left(EVAP-COND\right)+p_*\left(D_{q_v}+R_{q_v}\right),$$

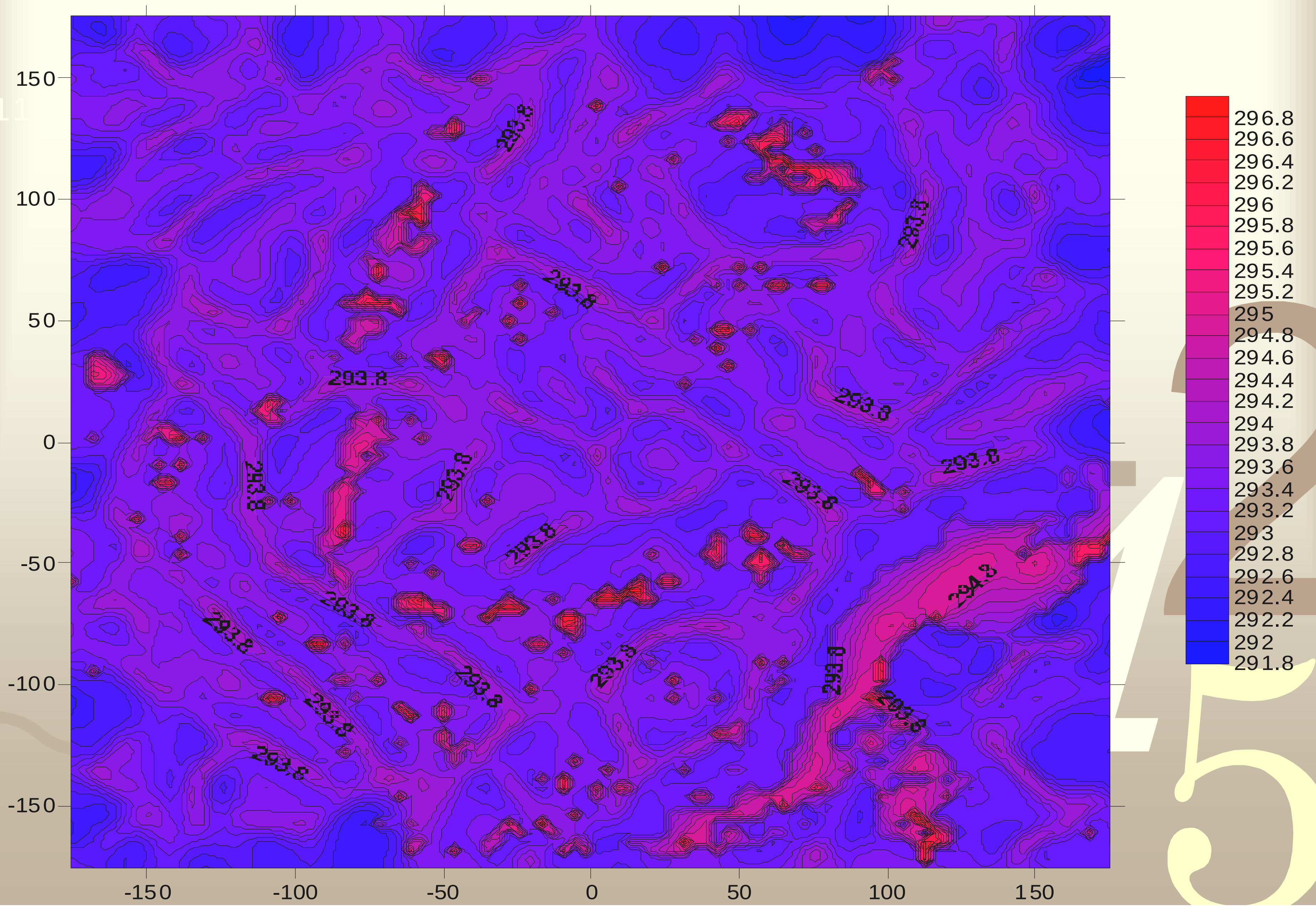
$$\frac{\partial q_c p_*}{\partial t}+\frac{\partial uq_c p_*}{\partial x}+\frac{\partial vq_c p_*}{\partial y}+\frac{\partial \dot{\sigma} q_c p_*}{\partial \sigma}=p_*\left(COND-AUTO-COL\right)+p_*\left(D_{q_c}+R_{q_c}\right),$$

$$\frac{\partial q_r p_*}{\partial t}+\frac{\partial uq_r p_*}{\partial x}+\frac{\partial vq_r p_*}{\partial y}+\frac{\partial \dot{\sigma} q_r p_*}{\partial \sigma}=p_*\left(AUTO+COL-EVAP\right)-g\frac{\partial \rho V_r q_r}{\partial \sigma}+p_*\left(D_{q_r}+R_{q_r}\right).$$

West Siberia, 54.5-58.6° N, 63.1-66.6 ° E, topography and inland waters, grid resolution 3.7 km



Surface temperature calculated by Nh3d model



Geophysical Boundary Layers (GBLs) as elements of the Earth climate system

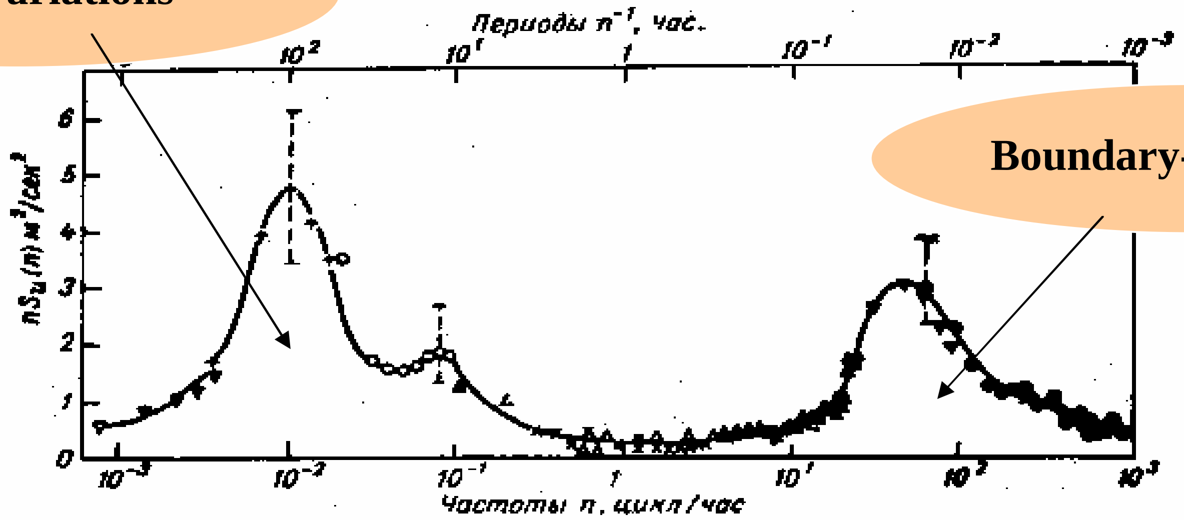
- Atmospheric Boundary Layer $H_{ABL} \sim 10^2 - 10^3$ m
- Oceanic Upper Layer $H_{UOL} \sim 10^1 - 10^2$ m
- Oceanic Bottom Layer $H_{OBL} \sim 10^0 - 10^1$ m

GBL processes control:

- 1) transformation of the solar radiation energy at the atmosphere-Earth interface into energy of atmospheric and oceanic motions
- 2) dissipation of the whole Earth climate system kinetic energy
- 3) heat- and moisture transport between atmosphere and soil (e.g. permafrost), sea and underlying ground (e.g. frozen one).

Synoptical variations

Boundary-Layer flows

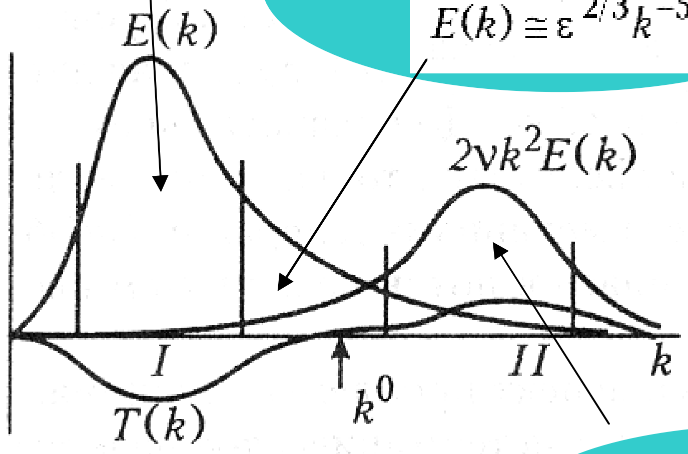


Спектр скорости ветра в приземном слое атмосферы [по Ван дер Ховену (1957)], n — частота, $S_u(n)$ — спектральная плотность.

Energy range

Inertial range

$E(k) \cong \varepsilon^{2/3} k^{-5/3}$



Dissipation range

$$a(x_i, t) = \tilde{a}(x_i, t) + a'(x_i, t) + a''(x_i, t)$$

$$\overline{a}(x_i, t) = \int G(x_i - x_i') a(x_i', t) dx_i'$$

$$\overline{a}(x_i, t) = \tilde{a}(x_i, t) + a'(x_i, t)$$

Differential formulation of models

Models are based on Reynolds' type equations obtained after spatial averaging of Navier-Stokes equations and added by equations of heat and moisture (or salt):

$$\frac{\partial \overline{u}_i}{\partial t} =$$
$$-\frac{\partial}{\partial x_j}\overline{u}_i\overline{u}_j - \frac{\partial}{\partial x_j}\overline{u_i''u_j''} - \frac{1}{\rho_0}\frac{\partial \overline{p}}{\partial x_i} + \nu\frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} + \frac{g}{\rho_0}\overline{\rho}\delta_{i3} - 2\varepsilon_{ijk}\Omega_j\overline{u}_k,$$

$$\frac{\partial \overline{\theta}}{\partial t} + \frac{\partial}{\partial x_j}\overline{u}_j\overline{\theta} = -\frac{\partial}{\partial x_j}\overline{u_j''\theta''} + \chi\Delta\overline{\theta},$$
$$\frac{\partial \overline{s}}{\partial t} + \frac{\partial}{\partial x_j}\overline{u}_j\overline{s} = -\frac{\partial}{\partial x_j}\overline{u_j''s''} + D\Delta\overline{s},$$

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0, \qquad \Delta p = F,$$

$$\overline{\rho_o} = \overline{\rho_o}(\overline{\theta}, \overline{s}, \overline{p}) \qquad \overline{\rho_a} = \frac{\overline{p}}{R\overline{T}_v}$$

PARALLEL IMPLEMENTATION

- **Parallel version of models is developed to be mainly used on supercomputers with distributed memory**

- **Procesor-to-processor data exchange is realized with the use of MPI standard**

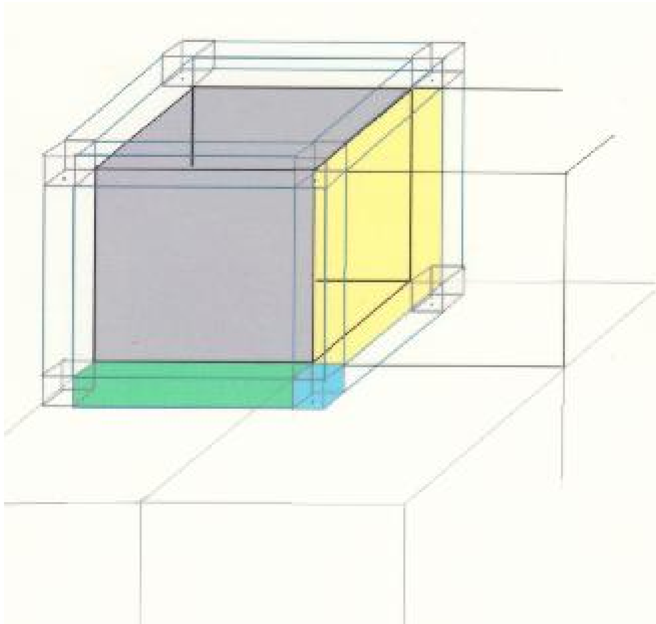
- **non-blocked functions of the data transfer-receive**

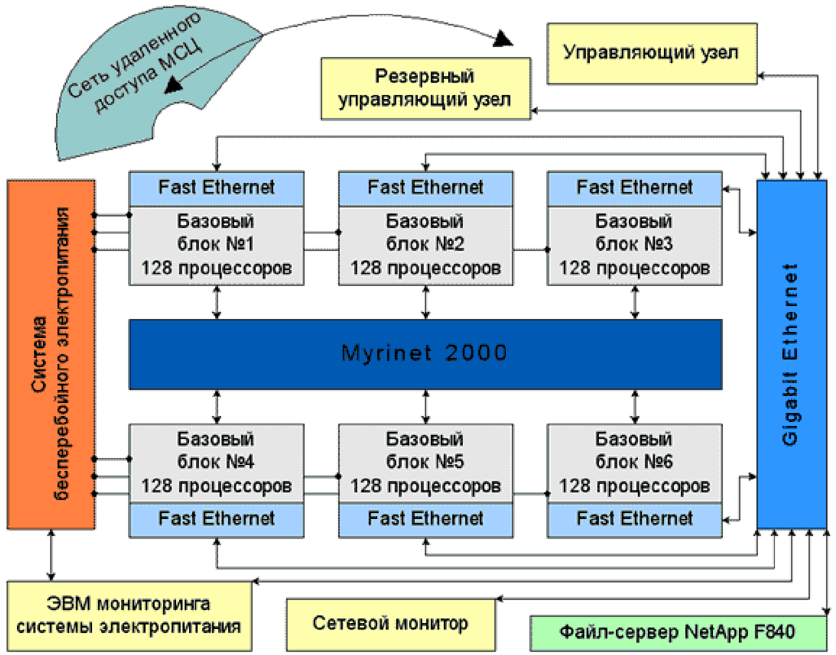
- **3-D decomposition of computational domain**

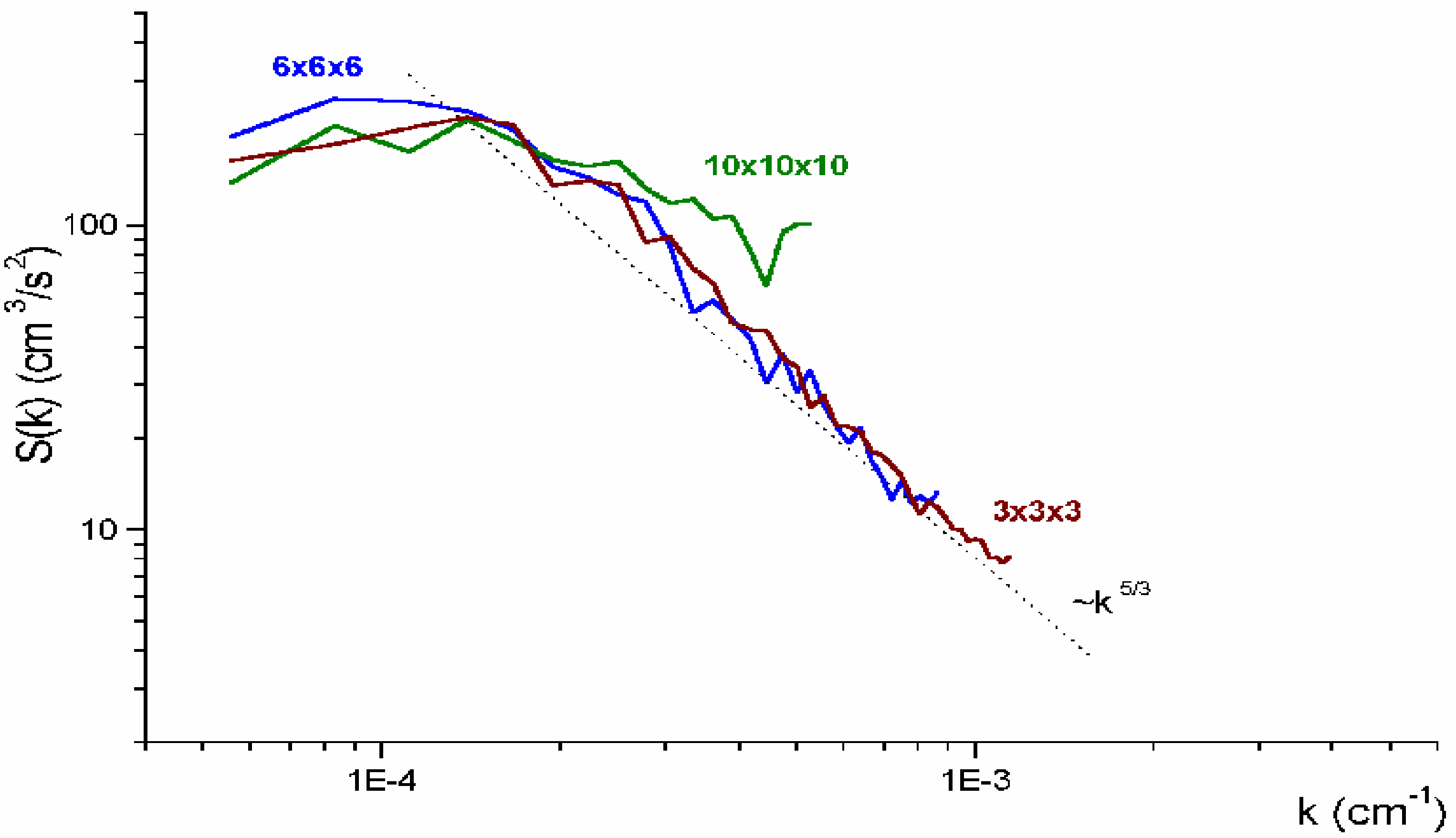
- **on each time step, processes are co-exchanged only by data which belongs to boundary grid cells of decomposition domains**

- **The Random Access Memory (operative memory) is dynamically distributed between processors (the features of FORTRAN-90 are used)**

- **Debuging and testing of parallel versions of models is executed on supercomputer MVS1000-M of Joint Supercomputer Center (768 processors, peak productivity - 1Tflops)**







Spectra of kinetic energy calculated using results of large-eddy simulation of the convective upper oceanic layer under different spatial resolution (m^3)


THANK YOU
for YOUR ATTENTION