# Scientific Report 08-05

# Enviro-RISKS:

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

Alexander Baklanov and Evgeny Gordov, Editors

# Volume 4: Terrestrial Ecosystems and Hydrology

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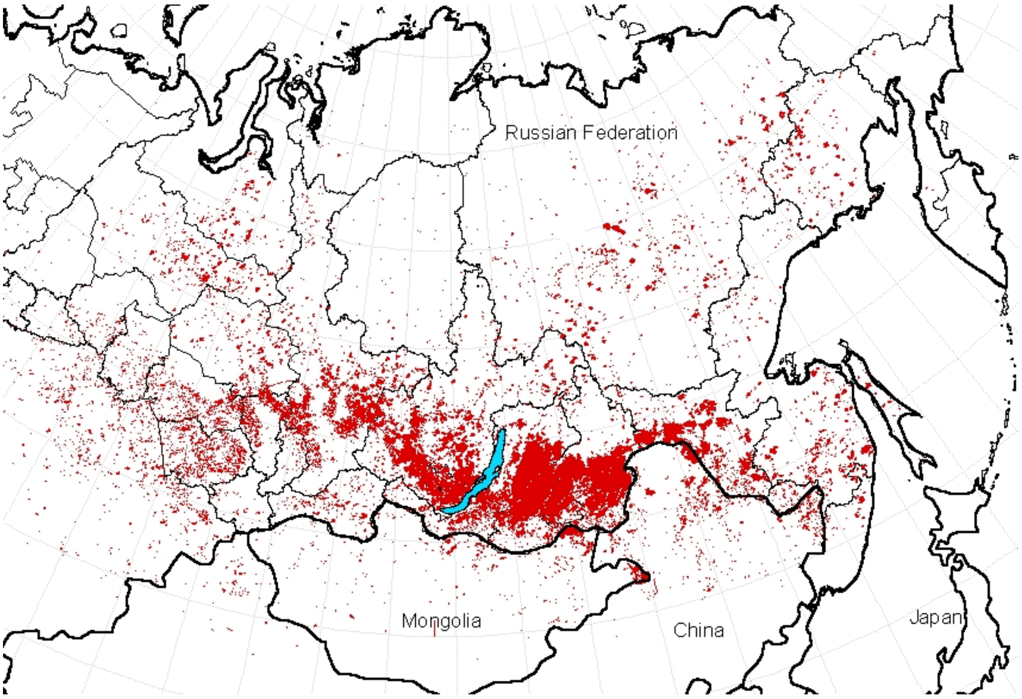

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# Enviro-RISKS Report Content:

**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 a separate Volume 3:* www.dmi.dk/dmi/sr08-05-3.pdf*)*

**Thematic Focus 3: Terrestrial Ecosystems and Hydrology and Risks** *(in this Volume 4)*

**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 4:

# Abstract

Siberia, the land mass of the continental scale, is represented by huge diversity of climatic conditions and terrestrial ecosystems. The most dramatic climatic change over the globe is expected here. Fragility of ecosystems which evolutionary developed under a rather stable cold climate is an inherent feature of high latitudes. Ecological thresholds and buffering capacity of the region's ecosystems under substantial warming have no analogues and are poorly understood. This generates major challenges for understanding the current and future state, vitality and resilience of ecosystems. In addition, Siberia is a region of intensive and insufficiently regulated anthropogenic impacts which may accelerate the impacts of climate change on natural landscapes and terrestrial ecosystems. Current state and recent tendencies of dynamics of terrestrial ecosystems, particularly forests, are negatively impacted by increasing anthropogenic pressure and insufficient governance of natural resources.

Recent developments of industry in Siberia, man-made changes of environment and ecosystems, as well as ongoing and expected climate change generate many risks for ecosystems and stable hydrological regimes dealt with (1) negative processes connected to permafrost destruction including aridization of vast areas, physical destruction of sites, thermocarst, soliflucation, as well as acceleration of emissions of greenhouse gases; (2) loss of soil fertility due to water erosion, soil compaction, desertification, lack of nutrients, solinization, increasing water table and other changes of water regime, air pollution and soil contamination; (3) impoverishment of soil biota, decline of productivity of lands; (4) lack of water resources in arid regions; (5) damage of agriculture lands in river valleys due to increase of inundation; (6) outbreaks of traditional pests and microorganisms; (7) alteration of forest fire regime; (8) anomalous outbreaks and spatial distribution of traditional and new insects; (9) loss of biodiversity; and (9) "green" desertification. In spite of many studies on the topic in Siberia, there are a number of fundamental problems which require urgent investigation: thresholds of acceptable (not destructing) impacts on ecosystems taking into account non-linear and multi-variant responses of ecosystems to long-term accumulation of stresses; system (holistic) analysis of complicated systems which contain components of different nature – biophysical, ecological, social and economic; theory and practice of decision making under uncertainties; development of integrated observing systems; others. The region requires development of an anticipatory strategy of adaptation to, and mitigation of negative impacts of global change.

# 1. Introduction

Siberia, a vast territory of Northern Eurasia, bounded by 60 and 130 $^{o}$EL and 50 and 80 $^{o}$NLat, plays a substantial role in the global climate machine through complex interactions among atmospheric circulation patterns, temperature regimes, permafrost behaviour, river discharge, functioning of terrestrial ecosystems, and sea ice formation (Mysack, 1995). In the global view, Siberia substantially impacts the Earth system as a whole, and, particularly, its climatic and hydrological components. From other side, the most dramatic climatic change over the globe is expected in this region. In addition, Siberia is a region of intensive and insufficiently regulated anthropogenic impacts which may accelerate the impacts of climate change on natural landscapes and terrestrial ecosystems.

Ongoing global change is an integral and inherent feature of the dynamics of Siberian ecosystems. Under current conditions, Siberian vegetation should be considered as a heterogeneous socio-natural system. This is revealed in the sophisticated interplay and mutual conditionality of impacts, responses and feedbacks of natural, economic and social components, environment and human society. An important feature of the region is fragility of ecosystems which evolutionary developed under a rather stable cold climate. Ecological thresholds and buffering capacity of ecosystems under substantial warming have no analogues and are poorly understood. This generates major challenges for understanding the current and future state, vitality and resilience of ecosystems of high latitudes.

A major paradigm of the interaction of humanity and nature in the contemporary world is transition to sustainable development. One of most important prerequisites of sustainable development is maintenance of regional stability of the biosphere (in particular, balancing major biogeochemical cycles within ecological regions). In many countries (including Russia) this transition is declared as a background of national and regional policy of nature resources management. However, the reality is far from such declarations. The ecological and environment situation in large regions of Northern Eurasia could be characterized as the on-going global ecological crisis initiated by the unregulated anthropogenic pressure on nature and explosive increase of consumption of fossil fuels. All together, this results in the decreasing quality of major components of the environment – air, water, soil, and vegetation. Siberia is a typical and illustrative example of such negative processes.

Recent developments of industry in Siberia, man-made changes of environment and ecosystems, as well as ongoing and expected climate change generate many risks. The region is one of the most vulnerable vast territories of the planet. For instance, it is estimated as a “hot spot” by the IGBP Global Carbon Project. The impacts of global change on the Siberian environment and human health, as well as on the social and economic safety of human well-being, are very likely in the short-term impacts, and are crucial in assessing the long-term consequences. However, environmental monitoring in the region is organized only partially, and governance of natural resources’ use is mostly insufficient.

This report summarizes results and activities related to *ecosystems* and *hydrology* (WP 03-04 and WP 07-08 of the Enviro-RISKS Project). It includes major natural and anthropogenic drivers and impacts on terrestrial ecosystems and hydrological cycle of the region, recognized responses and feedbacks, and expected risks. Major topics of this report have been analyzed and were widely discussed in the framework of different events and activities that were organized by the Project, particularly at special events in the framework of the International Conferences ENVIROMIS-2006, CITES-2007 and ENVIROMIS-2008, as well as at thematic sessions of Annual Assembles of the European Geophysical Union in 2007 and 2008.

# 2. Regional Specifics of Global Change in Siberia

## 2.1. Introductory notes

Recent years have substantially improved the knowledge of past, on-going and future climate change in the region. The aggregated characteristics of past and future climate dynamics of Northern Eurasia have been presented in the IV Assessment Report of the Intergovernmental Panel on Climate Change. A number of detailed analyses of historical and on-going climate change in Siberia has been provided by scientists of the Russian Academy of Sciences during recent years (see report of the focus group on climate change). Interesting results have been received on the regional specifics of the hydrological cycle of the region (IF SB RAS). A number of publications reported new results on productivity of terrestrial biota and budgets of terrestrial biota major greenhouse gases under changing growth conditions (IIASA, IF SB RAS, IMCES). These findings have been presented at the Conferences ENIVIROMIS-2006 and 2008 and CITES-2007 (Tomsk, Russia). Major results with an emphasis to the impacts on terrestrial ecosystems and hydrological cycle of the region are briefly discussed in this Section.

Studying both global and regional climatic changes, as well as their impacts on ecosystems, presents a difficult problem due to the fact that changes of climate and environment reveal a dynamic, complicated and multidimensional interplay of diverse impacts and cannot be understood within the simple “cause-and-effect” paradigm. Understanding and appropriate description of these changes requires to take into account many climate-forming factors of cosmophysical (including heliospheric), geospheric, biospheric and anthropogenic origin, to determine not only changes of states of the climatic system, but also evolution of these physical processes and phenomena, which are regionally specific. Recent results on the topic that were obtained in the framework of international, national and regional research programs led to the conclusion that integrated (multidisciplinary) regional studies should be recognized as most relevant and of high priorities. In such studies, regionalization of the present global climatic models, organization of comprehensive networks of instrumental observations, development of integrated models, which would include climatic, environmental, ecological and social processes, become necessary. So far, integrated studies of global change, environment and biota face a number of unsolved problems.

## 2.2. Spatial and temporal regularities of air temperature dynamics in Northern Eurasia

In spite of increasing resolution and accuracy of GCMs, geographical and altitudinal specifics of territories can substantially impact the global tendencies. Thus, empirical studies of regional climatic regularities are of a crucial interest for understanding of cause-effect relations and the impacts of climate change on environment and vegetation.

Based on results of instrumental measurements of air temperature on 73 meteorological stations from 1950 to 2005, a recent regional study (Onuchin, 2008) suggested four geographical types of seasonal temperature trends (STT) in Siberia which are inherent to different geographical regions. Scenarios of climatic change and their impacts on ecosystems within the latter have evident specifics.

The first – Arctic type – is divided in two subtypes: Arctic marine and Arctic continental. The Arctic marine subtype of STT resides arctic islands and the coast of the Arctic Ocean. The Arctic continental subtype is typical for regions stretching along the coast and those situated in wide valleys of large rivers, i.e. the areas which are open for penetrating the air mass from the Arctic side, even if they are distant from the ocean. The second type of STT is the continental one. This is divided in two subtypes – continental-depression-plain and continental mountain ones. The first one reveals in the vast continental area of Northern Eurasia stretching from West Siberia to Chukot, and from north to south – from the Putorana plateau to Altay mountains, and from mountains of North-Eastern Asia to Manchuria. The mountain subtype of STT is typical in mountains of south of Siberia and Altay, as well in mountain systems of Northern-Eastern Asia (Chersky's range, Oimjakon plateau etc.).The third type of STT – Northern Pacific (Chukot) one - also includes two subtypes – marine and continental. The marine subtype relates to the Pacific coast northward from Kamchatka, and the second – to continental area of the Chukchi peninsula. The fourth one – the Far Eastern type - characterizes the coast of Okhotsk Sea and Northern Prymorie.

*Arctic type of SST*. For the marine subtype, the maximal warming is observed from March to May at the rate 2.5 $^{o}$C/100 years; from June to January the trend is weak and does not exceed 1.0 $^{o}$C/100 years (Fig. 1). The marine and continental trends have a good seasonal synchronism. However, the continental trend is more clear. It reaches 5 $^{o}$C/100 years in April but decreases practically to 0 $^{o}$C/100 years in June similarly to the continental trend. The higher continental trends are probably explained by the specifics of geographical environment. In opposite, large water mass provide the larger inertia. The latter likely causes a shift of the maximal trends from February for the continental trend to March and April in the Arctic.

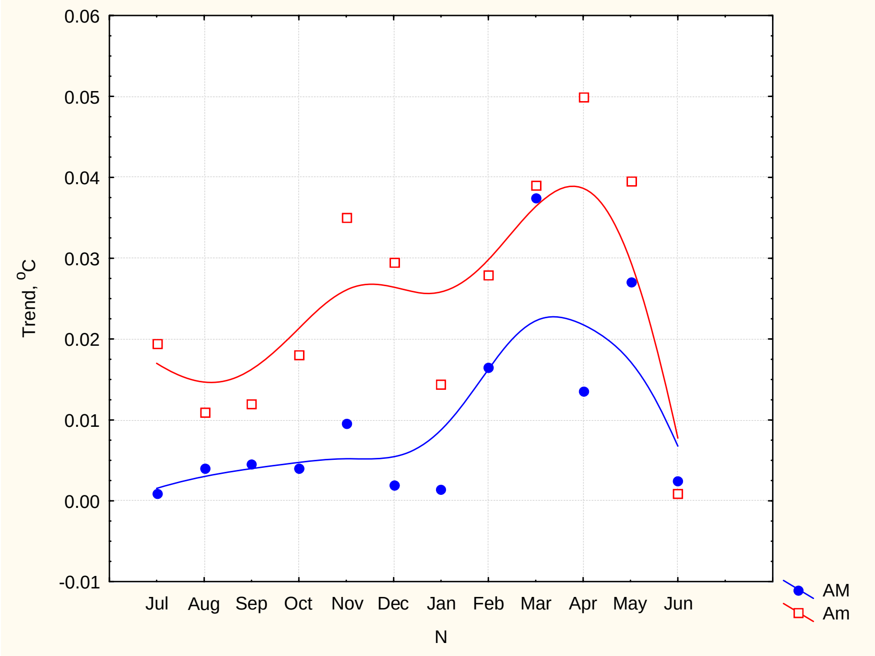


**Fig. 1.** *Arctic type of differentiation of seasonal temperature trends: AM – marine subtype, Am – continental subtype.*

*Continental types of SST*. The maximal warming for continental plain subtype is observed in February and on average is estimated at 9.3 $^{o}$C/100 years. For this subtype, monthly rate of the trend decrease by Summer to 0.7 $^{o}$C/100 years and reach zero in September with the following increase to 5.4 $^{o}$C/100 years by late fall. The mountain subtype has similar regularities. However, the monthly differentiation is less expressed (Fig. 2). Thus, warming under continental conditions is the highest at end of winter and early spring. Likely, it is caused by the greenhouse effect because during winter time, when solar radiation is minimal, greenhouse gases hinder from the cooling of land surface. This effect is clearer in depressions and on plains.

Territories of the Chukchi Peninsula and its coast have very specific STT. *The Northern Pacific type* of STT is an exact antithesis of the continental type. Here, the cooling during winter time is observed and the negative temperature trend of January reaches -10 $^{o}$C/100 years. For rest of months, a moderate warming (from 1.5 to 5 $^{o}$C/100 years) is observed (Fig. 3).

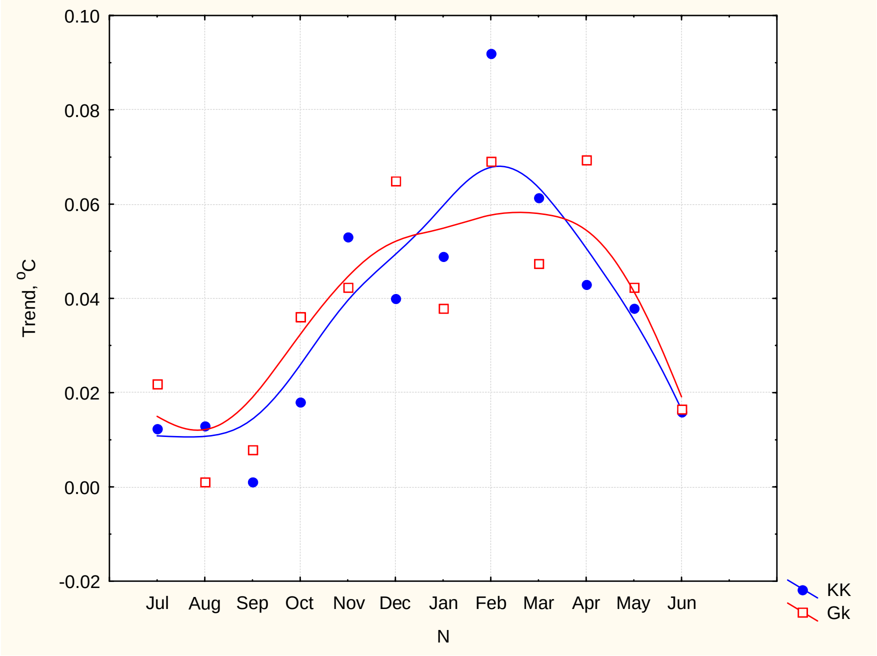


***Fig. 2.*** *Continental type of seasonal temperature trends: KK- depression-plain subtype; Gk – mountain subtype.*

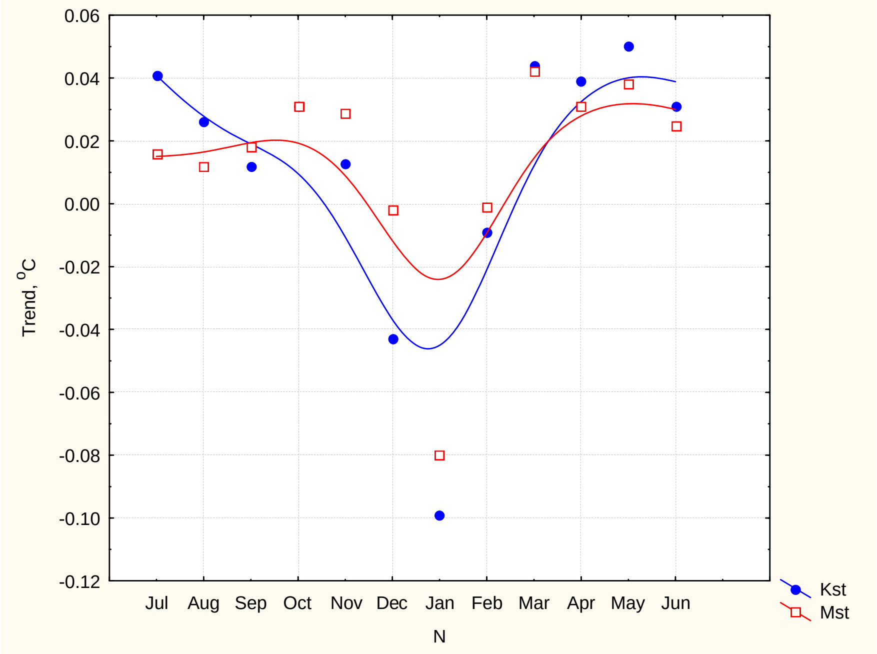


***Fig. 3.*** *Northern Pacific type of seasonal differentiation of temperature trends. Kst – continental subtype; Mst – marine subtype.*

In the Chukchi territories, as well in the Arctic, the trends are more evident in regions distant from sea territories. The supposed reasons of this are similar to the Arctic. Evidently, the negative temperature trends in the Chukchi Peninsula cannot be direct consequence of the greenhouse gas effects. Probably, the recognized cooling is caused by changes of the cyclonic activity, as well as sea currents, particularly by prohibition of warm currents which reached Chukchi coast before. In turn, the latter could be a consequence of the greenhouse gas effect realized in other territories. Up to now, there are no data about reorganization of sea currents in the Bering Sea although their interim dynamics is very complicated there (Chrapchenkov, 2007). However, the directional changes of the climatic system of Northern-West Pacific have been reported (Plotnikov, 2007).

The fourth type of STT – *Far Eastern type* - is characterized by the maximal warming in January (on average 6 °C/100 years (Fig. 4). This type of STT is similar to the continental type but differ by smaller values of the trends and their seasonal flatness.

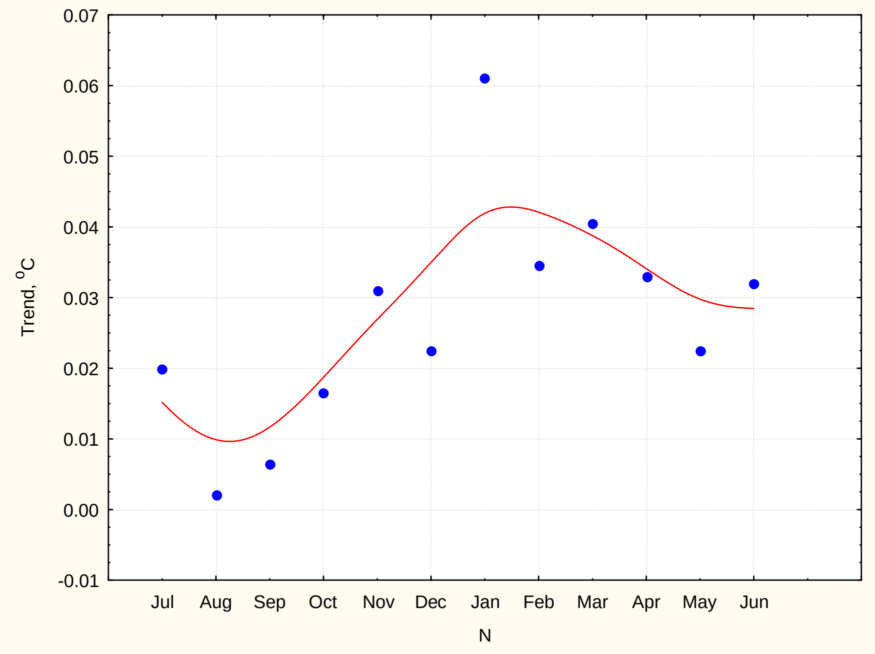


***Fig. 4.*** *Far Eastern type of seasonal temperature trend.*

This analysis of geographical regularities of STT shows that the maximal warming took place in continental regions and is observed during winter time. The warming is less pronounced in the Arctic and across the Chukchi Peninsula and is more expressed in March-April. Winter became colder on the Chukchi Peninsula, and moderate warming (+2 to +5 °C/100 years) was observed during the rest of year.

Overall, the trends of July temperatures decrease with increasing of latitude of territories. The similar regularity is also observed for temperature in February, while the trends of temperature in May are practically not changed over different latitudes. From west to east, the trends of July temperatures increase. However, such regularity is observed only to the meridian which goes through the eastern edge of the Middle Siberian tableland. In Saha Republic and Chukot, the July trend dos not depend upon the latitudes. The trends of February temperatures slightly increase towards the east. But in Yakutia and Chukot, this regularity changes into the opposite one. The trends substantially decrease with increasing the latitudes there. The trends of May temperatures do practically not depend on the latitudes and on average vary from +2 to +5 °C/100 years for the entire territory of Northern Eurasia.

Remoteness of areas from Arctic coast towards the continent, altitudinal marks and availability of the territories for air mass moving from the Arctic Ocean – these are major factors which define the temperature trends over the central regions of Yakutia. It was shown that the temperature trends increase with increase of distance from the coast and decrease with increase of height above the sea level. Isolation of territories by orographic barriers from the northside also increases the temperature trends.

*Conclusion.* The global warming which is observed in major part of the Northern Eurasian territory could be caused by both greenhouse gas effect and cosmic reasons. The temperature trends are most presented in the continental conditions, particularly in depressions which are isolated by orographic barriers from the atmospheric fronts of the Arctic and Pacific oceans (Fig. 5). The positive temperature trends in continental conditions correspond to the hypothesis of greenhouse gas nature of the warming. Very likely, the greenhouse gas warming hypothesis is also supported the fact that the warming trends decrease with increasing the altitudinal levels of territories.

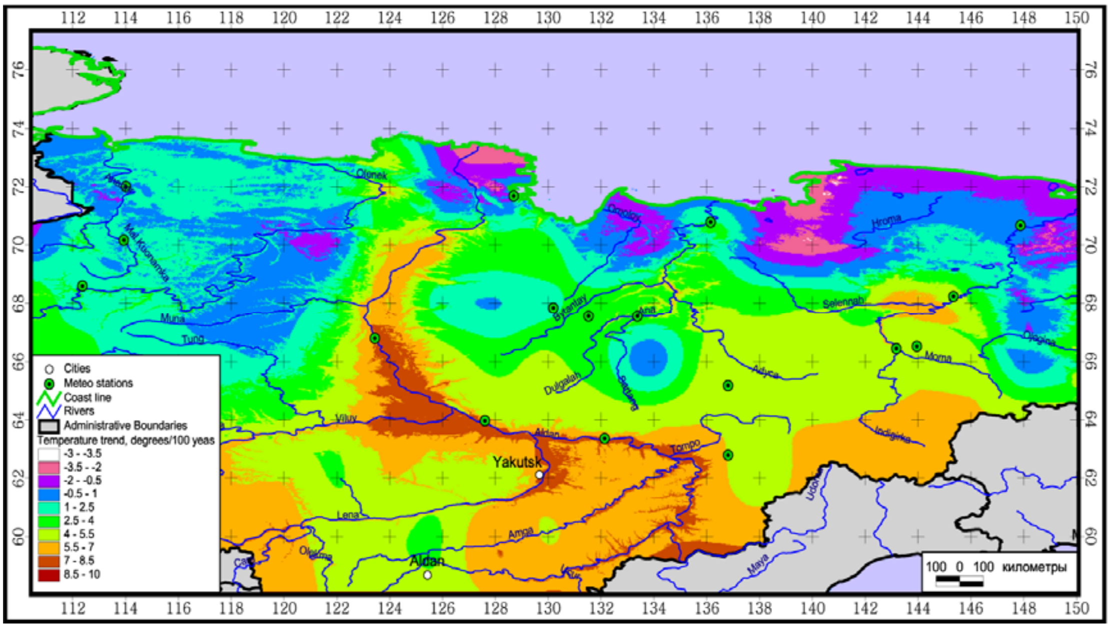


*Fig. 5. Map of temperature trends in Northern Asian Russia. Source Onuchin (2007)*

The climatic change is clearly impacted by the processes of energy-mass transfer in the system *ocean-land-atmosphere*. Very likely, the ocean is responsible for climate changes which are observed inside the continent. Over the Arctic coast the warming trends are less expressed due to the warming inertia of huge amount of water. Similar regularity is also observed in valleys of large rivers which are open to the atmospheric oceanic mass. The decrease of winter temperature is observed in coastal regions of northern Pacific, and the increase – in the southern ones. The maximal warming is observed in February and March (at 6.5 and 5.3 $^{o}$C/100 years, respectively). After, the trends decrease, and the minimum is observed in summer and early autumn (on average at 1.6-0.7 $^{o}$C/100 years), and again increase by winter. The highest spatial variation of the temperature trends is observed in January and February, the lowest – in August and September. The summer and early fall warming, which is the weakest among seasonal changes of temperature, is most evenly distributed over the entire territories of Northern Eurasia. The January trend average for the entire territory is less expressed than the February's one because the increase of January temperature in continental regions to some extent is compensated the temperature's decrease over the north-east Pacific coast. These regularities have been expressed in form of regression models that allows to estimate the spatial differentiation of temperature trends taking into account parameters of relief of territories.

An important conclusion of this study is that for better understanding of nature of global climate change, estimation of its intensity, scales and spatial peculiarities of climatic trends, it is necessary to provide analyses of the impact of these processes on ecosystems in connections with geographical specifics of territories and seasonal manifestation of the changes. These specifics substantially impact regional specifics of global climate change.

Other analysis of spatial heterogeneity of warming observed in Siberia have been provided based on linear trend of annual mean surface temperature. This linear trend has been calculated using accumulated series of monthly mean temperatures over second half of 20th century. The data have been obtained from 134 meteorological stations located in Siberia and Far East (Ippolitov *et al*., 2004). Warming rates on the Siberian territory during the second half of 20$^{th}$ century were quite high (more than 0.2 $^{o}$C/10 years), and in some "hot spot" regions – up to 0.5 $^{o}$C /10 years. These hot spots are mostly located in East Siberia and are caused by temperature increase in winter months (Ippolitov *et* *al*., 2004). However, the zoning of temperature regime in Siberia was realigned in recent decades. This tendency is explained by evolution of atmospheric circulation in recent decades (Vakulenko *et al*., 2000), particularly by the decreasing of the pressure (at the rate of 0.2 to 0.4 hPa/10 years). This is sufficient for intensification of cyclonic activity (Ippolitov *et al.*, 2005, Byshev *et al.*, 2002). Annual average ratio between the number of cyclones and anticyclones was 1.4 in 1976 to 2004, while it was 1.7 before 1975.

Scales of time variability of warming that is observed in Siberia have been revealed using procedures based on application of wavelet analysis that is efficient when processing multiscale signals and fields (Astaf'eva, 1996). Based on wavelet spectrum of 120 years long time series for annual mean surface temperatures in Tomsk (Ippolitov *et al*., 2007), statistically significant periodicity scales in the time series have been analyzed. For example, decadal periodicities have transformed into periodicities with the scales of 5 to7 years at the end of 19th century and in the second half of the 20th century. Periodicities with the scales of 20 to 30 years during 20th century gradually transformed into periodicities of 15 years having tendency toward decrease and also into periodicities with the scales of 30 to 40 years by the end of the century. It also follows from comparison of analogous wavelet spectra for surface temperature series obtained in different Siberian cities (Ippolitov *et al*., 2002), that continued transformation of statistically significant periodicities occurred in 20th century simultaneously in all Siberian region.

In order to recognize functions of global natural processes in transformation of time periodicities of warming observed in the region, a correlation analysis was performed between wavelet spectra of annual mean temperatures in Siberia and wavelet spectra of the planetary index characterizing North-Atlantic Oscillation (NAO). It has been shown that there were no phase shifts for small-scale periodicities (5-7 years), phase shifts for middle-scale periodicities (10-15 years) are equal to 1-3 years, while for large-scale periodicities (30-40 years) phase shifts increase up to 7 years. Time correlation for single periodicity of 30 to 40 years scale is of particular interest. This periodicity, having high wavelet correlation in 1940 to 1980s, can be considered as climatic phenomenon for this period. This phenomenon is very important from the methodical point of view because it evidences necessity of differentiate description of climate-forming and weather-forming processes.

## 2.3. Sub-regional specifics of climate change in Siberia

As following from the above analysis, climatic change in Siberia is an on-going and clearly observed process. The huge area of the region predetermines a significant diversity of climatic processes and their dynamics patterns. On average, current trends of climate change are characterized by significant warming (Table 1) that – in the major part of the region – are accompanied by relatively stable or slightly decreasing amount of precipitation. Both these trends have intensified during recent decades.

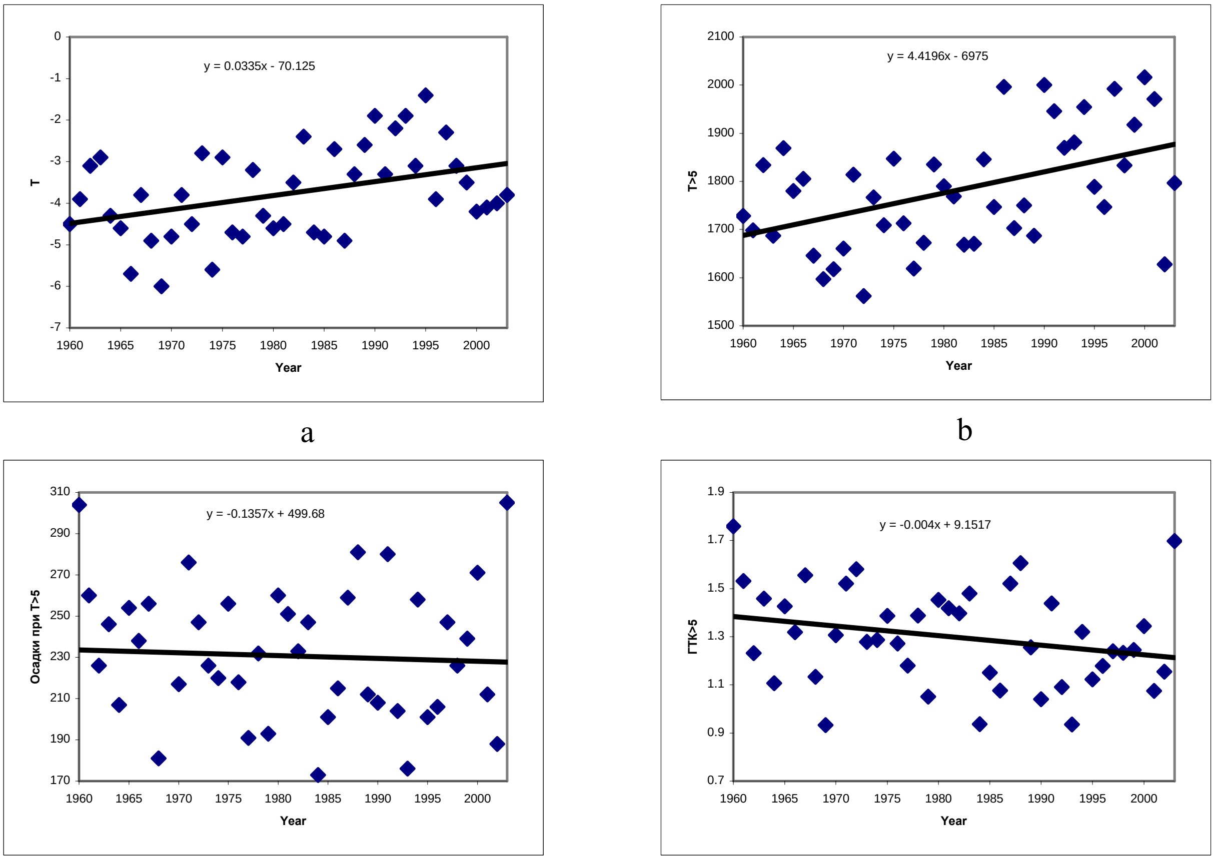
***Table 1.*** *Linear trend of temperature ($^{o}$C/100 year) for Siberia for the period 1976-2002. Source Garuza et al. (2002).*

| **Region** | **Year** | **Winter** | **Spring** | **Summer** | **Autumn** |
|---|---|---|---|---|---|
| **Western Siberia** | 3.7 | 6.8 | 8.5 | 1.2 | -1.3 |
| **Central Siberia** | 5.3 | 7.3 | 7.7 | 5.9 | 0.5 |
| **Baikal Region** | 6.3 | 8.3 | 9.5 | 7.5 | 0.2 |
| **North-East** | 4.4 | -0.8 | 8.2 | 4.4 | 5.5 |
| **Russian Federation** | 4.9 | 6.7 | 7.1 | 4.6 | 1.6 |

The average annual temperature has been growing at the expense of winter warming. On average, maximal warming is recorded in continental regions, less – in maritime regions; average warming in high latitudes is 1.5 fold higher than in Southern Siberia and 3 fold higher than in Mongolia. The highest rate of warming is indicated in East Siberia: during the last century winter temperature increased by 10 °C in Jakutia, 7°C in Pribaikalie, and 5 °C in Mongolia. The increase of the annual average temperature has been at 2-3.5 °C in these regions. After the 1970s, the intensity of warming is 1.5-2 times higher than during the first half of the 20th century. The growth period (> 5 °C) increased by 1-2 weeks over the region, more in the south than in the north, less in more humid climate than in dry climate.

Trends of the annual and seasonal amount of precipitation as a rule have different direction by seasons: there is a positive trend in winter (of 2-5 mm/10 years) and a negative one in summer (about –2 to -7 mm/10 years). The annual amount of precipitation, particularly, in continental regions of Middle and East Siberia has a tendency to decrease (e.g., -4.1mm/100 years for areas around Baikal Lake). The increase of snow depth in some regions of East Siberia shifts to the south. It may indicate a weakening of the Siberian anticyclone. The runoff of large Siberian rivers has increased. All climatic models predict a substantial acceleration of the above tendencies during the 21st century: while the increase of annual average temperature is expected by 4-10 °C, water supply of vast areas will decrease substantially.

In spite of a large heterogeneity of spatial distribution of climatic indicators over the region (as it has been discussed above), the increase of temperature in major part of Siberia is not compensated by the increase of precipitation. It leads to increasing aridity of region climates. Examples for Irkutsk oblast’ and Republic Saha (Yakutia) are presented in Figures 6 and 7.



a b

c d

***Fig. 6**. Linear trends of climatic indicators in southern taiga ecoregions of Irkutsk oblast’ in 1960-2003: a – annual temperature, b, c and d – sum of effective temperature, amount of precipitation and Selyaninov hydro-thermal coefficient for the period with daily temperature >5 °C, respectively. Source Vashchuk and Shvidenko (2006).*

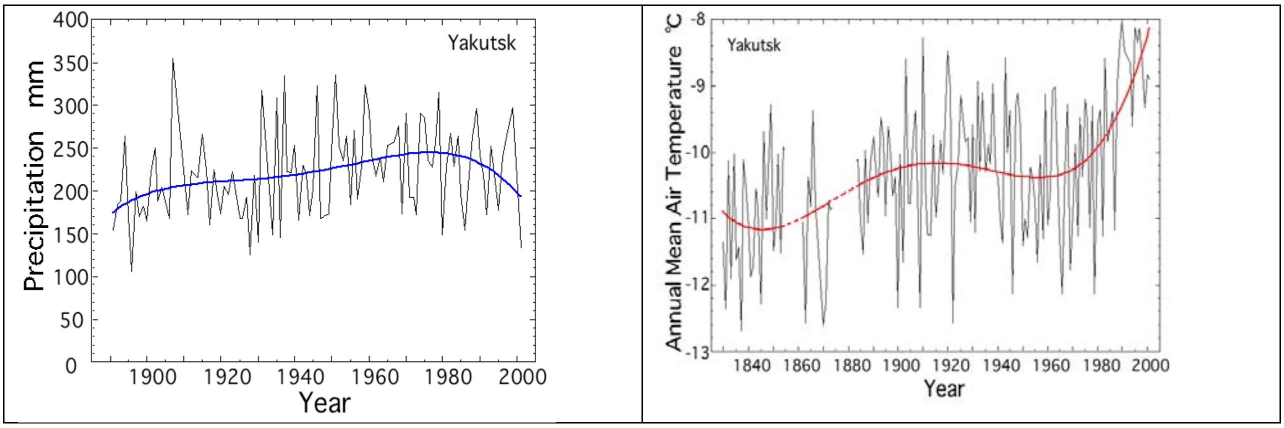


***Fig. 7.*** *Recent dynamics of annual average temperature and precipitation in territories of Yakutia*

## 2.4. Future climate due to GCMs predictions

Table 2 contains maximal and minimal changes of temperature and precipitation during the 21st century estimated by an ensemble of a number of GCM (HadCM3, CSIRO, NCAR-PCM, ECHAM4, CGCM2, GFDL and CCSRNIES) which are used in the framework of IPCC Scenarios A1F1, A2, B2, B1) for two region – Arctic land and Northern Asia (Ruosteenoja *et al*. 2003). The second region is limited by 50 and 67.5 °C of northern latitude and stretches from Ural mountains to the Pacific. The diversity of forecasts by individual models is high – up to 10 times by temperature and precipitation (the maximal increase of temperature up to 16-18°C during some periods is predicted by model CCSRNIES and by precipitation – up to100%, model ECHAM4).

***Table 2.*** *Forecast of changes of temperature and precipitation by different GCMs for the 21st century*

| Period | December-February | | March-May | | June-August | | September-November | |
|---|---|---|---|---|---|---|---|---|
| | ΔT, °C | ΔP, %% | ΔT, °C | ΔP, %% | ΔT, °C | ΔP, %% | ΔT, °C | ΔP, %% |
| **Arctic Land (67.5 S Lat, 90 N Lat)** | | | | | | | | |
| 2010-2039 | +1.6; +3.6 | +4; +24 | +1.3; +3.0 | +2; +19 | +0.7; +3.0 | +3; +16 | +2.1; +4.7 | +2; +17 |
| 2040-2069 | +2.7; +8.7 | +6; +55 | +2.1; +5.6 | +7; +37 | +0.9; +5.5 | +6; +32 | +2.6; +9.3 | +5; +40 |
| 2970-2099 | +5.0; +18 | +9; +81 | +3.0; +11 | +10; +62 | +1.0; +8.0 | +5; +51 | +3.8; +14 | +9; +62 |
| **Northern Asia (50.0 S Lat, 67.5 N Lat, 40.0 W Lon, -170.0 E Lon)** | | | | | | | | |
| 2010-2039 | +0.9; +5.5 | +3.0; +36 | +0.7; +3.8 | +3.0; +17 | +0.7; +2.9 | +1.0; +10 | +1.0; +3.9 | +3.0; +16 |
| 2040-2069 | +1.8; +9.6 | +7.0; +70 | +1.2; +6.5 | +9.0; +39 | +1.1; +5.2 | +1.0; +15 | +1.9; +7.1 | +5.0; +20 |
| 2970-2099 | +3.0; +16 | +9; +105 | +2.0; +13 | +10; +71 | +1.6; +9.1 | +3.0; +28 | +2.1; +12 | +9.0; +31 |

In spite of the high variability of the forecasts, some trends could be clearly recognized:

- the maximal increasing of temperature is predicted for most cold months (December-February); both regions indicate the average increase by end of the century about 10 °C; maximal increase of precipitation is also expected for this period;
- the minimal increase of temperature is expected for spring and summer (March to August) – about 6 °C by 2100; the precipitation also grows, but substantially slower;
- increase of precipitation is expected mostly during wintertime;
- increase of climate aridity is expected toward the southern continental regions.

## 2.5. Climatic peculiarities of bog ecosystems (an example of Great Vasyugan Bog)

The next example presents interesting evidences of impacts of large specific ecosystems on regional climate. From this point of view, wetlands and water-bog complexes, occupying vast territory in Siberia, are of particular interest due to the feedbacks which these formations could make on regional and global climatic processes. Great Vasyugan Bog (GVB), considered below as a research object, is the largest bog of the world by its territory (Table 3).

***Table 3.*** *Parameters of the Great Vasyugan Bog.*

| № | Parameter | Estimates |
|---|---|---|
| 1 | Total area in Tomsk, Omsk and Novosibirsk *oblasts* | 53 thousand km$^2$ |
| 2 | Dominating bog type | ridge-hollow, sphagnum |
| 3 | Bog age, including 25% of territory | 6-10 thousand years, more than 500 years |
| 4 | Water reserves in lakes | 400 km$^3$ |
| 5 | Peat deposits:<br>explored reserves<br>average depth<br>maximum depth | <br>More than 1 billion t<br>2.4 m<br>10 m |

Results of interdisciplinary research carried out in 1990s by a number of research groups of Siberian Branch of RAS and Siberian universities have been summarized in a monograph (Kabanov, 2002) which contains:

- general characteristics of the GVB and adjacent territories that includes description of the main stages of the bog-forming processes, as well as cultural and historical processes over this territory during recent;
- methodological basis for regional monitoring and modeling, as well as modeling climatic processes on the GVB territory;
- present-day climatic changes on the GVB territory including analysis of climatic, hydrological, geochemical and atmospheric processes observed;
- state and evolution processes of the GVB natural and refuge potential, that includes dynamic aspects of peat and soil formation and landscape structures on the GVB territory;
- environment reclamation and protection including analysis of hydrocarbon and lipids compositions in peat deposits, as well as grounds for establishing a landscape reserve in the GVB ecosystem as a world natural heritage.

A number of interesting findings are worth to be indicated.

(1) Bog-forming processes are cyclic due to climatogenic nature of peat accumulation during past millennia. Based on stratigraphic column dating, the dynamics of carbon accumulation rate has been obtained for the past 7 thousand years. Based on wavelet analysis, the basic cycles that were observed throughout all time period, changed from 500 years in the past to 1500 years now. The evolution of periodicity scale for carbon accumulation in the GVB peat is associated with climatogenic nature of peat accumulation and coincides with results obtained for Europe (Blundell and Barberk, 2005) and Canada (Yu *et al.*, 2001). This result indicates a planetary character of the evolution processes observed, at least for the Northern hemisphere.

(2) The temperature field on the GVB territory has some peculiarities. Since ground hydrometeorological observation net is absent there, in order to reveal temperature heterogeneities, available satellite data were used. Monthly mean temperatures on the GVB territory for some months differ from adjacent territories up to 6°C. The largest difference is in June (cooling effect of wetlands) and

in spring months (warming effect), for both surface layer and at high altitudes (up to 10 km). Analysis of temperature distribution at different altitudes obtained from MODIS spectrometer in February 2004 confirms warming effect of the bog ecosystem in winter months that occurs up to high altitudes. As a whole, these effects (Fig. 8) are not completely understood. They are rather connected to thermal characteristics of peat deposits then to regional emissions of greenhouse gases.

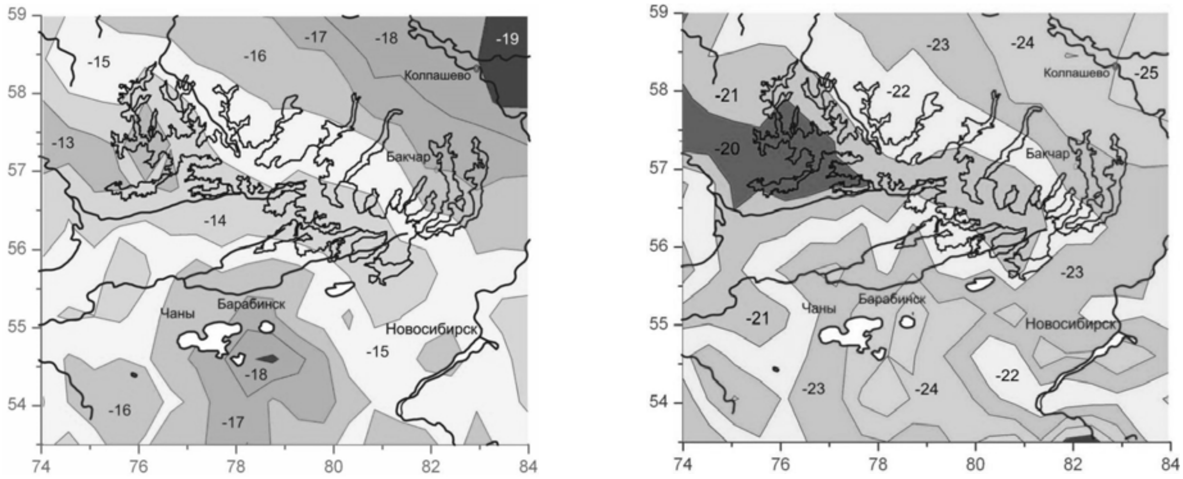


***Fig. 8.*** *Temperature distribution at different altitudes over GVB territory (GVB contour is in the Figure center)*

(3) Based on the long-term ground observations, it has been shown that $CO_2$ emission fluxes depend on landscape and meteorological conditions. Statistical analysis showed that $CO_2$ emission fluxes $F$ (mg/m$^2$ hour) from peat deposit surface at the GVB northern area depends on air temperature $T(°C)$ and $CO_2$ concentration in the atmosphere $C_{CO_2}$ (*ppm*),

$$F = 26.7 + 2.5T - 0.004C_{CO_2},$$

while $CO_2$ emission fluxes simultaneously measured at forest sites and at open fen differ more that twice (lesser for an open fen). However, net carbon sink has been recognized at all observation sites. Moreover, predictive estimates for some IPCC scenarios have shown that positive carbon balance on $CO_2$ will be kept until 2080, even taken into account a limited potential of $CO_2$ accumulation.

Applying statistical analysis to instrumental meteorological data, regularities of climatic changes have been recognized for Siberian region. The warming, observed in Siberia over last 30 years, is characterized by heterogeneous subregional structure with mesoscale spots that have increased warming rates up to 0.5°C/10 years. Trends of surface pressure for the same period was less contrast (the decrease of annual mean pressure was at 0.2-0.4 hPa/10 years).

Wavelet analysis of time variability of climatic parameters over the past century indicated periodicities with the scales of 10-12 and 30-50 years. The correlation between wavelet spectra of surface temperature in West Siberia and North-Atlantic Oscillation index during 1940-1990 has time shift up to 7 years. This climatic phenomenon could be explained by possible inertia mechanisms in oceanic heat transfer.

# 3. Hydrological Regime of the Region’s Territory

Major characteristics of hydrological regimes of the region are considered in the report of the climatic focus group. Here we present aggregated information and some examples which are important for understanding current state and future impacts of hydrological regimes on ecosystems.

(1) Observations and climate models show that the present-day changes in the radiation forcing affect the surface heat and moisture budgets, thereby involving the hydrologic cycle. As it is stated in the Fourth IPCC Assessment (IPCC, 2007), on average, the general trend in river and lake ice over the past 150 years indicates that in the Northern Hemisphere the freeze-up date has became later, while the break-up date has occurred earlier. For instance, the climate warming led to change of ice conditions on the Lake Baikal: later freezing (at an average rate of 11 days per century); earlier ice breakup (7 days per century); the ice-free period duration increased, and the ice-cover period duration decreased at an average rate of 18 days per century; during 1949-2000 the maximal ice thickness decreased with the trend of 2.4 cm per decade. It is known also that annual average arctic sea ice extent has shrunk by about 2.7% per decade since 1978 (IPCC, 2007).

(2) Permafrost and seasonally frozen ground in most regions (and, especially, in Siberia) show large changes in recent decades. Accordingly to Pavlov (1996), permafrost temperature increased approximately at 1˚C at the depth 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 the 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. Results of monitoring studies of the active layer, glacial phenomena, permafrost and wedge ices (the upper layer up to the depth of annual heat exchange, i.e., 10-15 m) in different zones and for different landscape locations provided by the Permafrost Institute (Yakutsk) in 1989-2002 indicated a present-day degradation in the upper part of ice-rich soils of both undisturbed and disturbed permafrost landscapes with 5-30% losses of cold and ground ice resources over a short period of time under present-day warming ($\Delta t_0 = 0.06\text{-}0.09^{o}$C yr$^{-1}$), and the degradation on disturbed sites was much more intensive (Gavriliev, 2003). Siberian data on permafrost degradation are similar to other parts of polar domain. Due to research in Alaska, in Tanana River basin, permafrost degradation causes substantial changes of vegetation – mostly from birch forests to fens and bogs. In the region, where 83% are covered by permafrost, ~42% has been affected by thermokarst development. From 1949 to 1995, the area of birch forests have decreased by 35% and of fens have increased by 29%. The area with totally degraded permafrost (collapse-scar fens and bogs) has increased from 30 to 47% during 46 years. If current conditions persist, it is expected that the remaining birch forests will be eliminated by the end of this century (Jorgenson *et al*., 2001).

(3) Seasonal variability of snow in Northern Hemisphere is high: about 50 million km$^2$ in midwinter and 4 million m$^2$ in August. Interannual variability comprises at 10 million km$^2$. Snow accumulation over Russia accounts for about 65% of freshwater discharge to the Arctic Ocean. From 1936 to 1983, Ye (2000) reported a statistically significant trend of snow depth increase over much Russia [as a circumpolar response to increase mid-latitudinal precipitation over the northern hemisphere. About 10% of the Earth river water flows in the Arctic Ocean (of which ~2/3 is in Eurasia) influencing global ocean circulation patterns, hydrological dynamics, and causing sustained freshening of the deep ocean (Dickson *et al*., 2002)

(4) 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.

(5) Many studies of the hydrological regimes over Siberia and  discussions on a special international conference "Hydrological Impact of Climate Change" (Novosibirsk, 2007) and at the Workshop "Land Water Resources under Conditions of Changing Climate" (Pskov, 2007) led to the following conclusions: (i) the impacts of the present-day increase of temperature on the monthly mean river runoff is relatively small; (ii) there are no significant changes in  the winter runoff; (iii) the spring runoff decreases insignificantly due to diminished maximum of the snow water equivalent content; (iv) the time of the spring runoff peak is shifted towards the winter in several days due to earlier melting of snow;  (v)  the summer runoff decreases due to increase in evapotranspiration; (vi) the mean annual runoff decreased insignificantly.  As a whole, the results of hydrological simulations of the present-day climate change impact on water resources show that hydrologic response is not too strong to be a foundation for mitigating the effects of such changes by specific actions, such as reconstruction of reservoirs etc.

(6) In spite of substantial differences in modelling predictions of future changes of hydrological regimes, major tendencies with respect to the impacts on terrestrial ecosystems could be aggregated as following: (i) overall, global warming trends will increase productivity of terrestrial vegetation; (ii) summer aridity of climate very likely will increase in large continental regions what will provide diverse, but negative impacts on ecosystems; such impacts will be particularly dangerous in southern regions of Siberia; (iii) it is expected a substantial increase of stability of regional weather: increasing length of dry summer periods, increasing intensity of precipitation during wet days, thus, increasing risks of droughts and floods; (iv) thawing of permafrost would generate diverse but mostly negative impacts on ecosystems. These questions are considered in the following Sections.

(7) Many processes, which are responsible for hydrologic cycle, in particular, in regions of strong land surface hydrologic heterogeneity and high sensitivity to global warming are still poorly understood. Small lakes (and wetlands) significantly impact structure of the atmospheric surface layer and the surface fluxes of momentum, water and heat.  Wetlands are important source of the methane and their role in the atmosphere – land interaction is insufficiently studied. In many numerical models, developed for investigation of environment and climate, effects of lakes and wetlands are totally ignored or roughly parameterized. There are needed further studies on this problem caused, in particular, by improvement of the spatial resolution of climate models. On the other hand, anthropogenic factors play a crucial role in the dynamics of water ecosystems, strengthening negative consequences of global warming.

A number of Siberian projects considers impact of landscape structure, (mostly forest) vegetation and forest management activities on hydrological specifics of landscapes under changing environment and forests, particularly in the permafrost zone (e.g., Onuchin, 2007). One of findings of this project is understanding of the impacts of natural and anthropogenic disturbances on hydrological regimes of northern landscapes. The regularities received are region specific. It is shown that a combined impact of solifluction, fire, harvest, air pollution and soil contamination leads to substantial change of the structure and functioning of forest ecosystems.

## 3.1. Hydrological role of forest ecosystems

The hydrological role of forest ecosystems is many-facet. Forests regulate hydrological regimes at different scales and in different ramifications. It includes the forest effect on transformation and spatial distribution of precipitation and snow-cover, regulating of runoff, impacts on balance and quality of surface and ground water flows, soil evaporation and evapotranspiration. Climate change and anthropogenic activities may substantially impact these functions.

Many researches have been devoted to studying hydrological regime of forests in Northern Eurasia (Pobedinskiy, 1979; Lebedev, 1982; Rakhmanov, 1984; among many others). During the two recent decades, intensive studies have been conducted in forest ecosystems and watersheds in different regions of Siberia (western and eastern Sayan Mountains, southeastern Baikal region, Krasnoyarsk forest-steppe zone, northern Angara region and Putoran Plateau) (Onuchin and Burenina, 2008). The studies were provided over large geographical regions, and within a wide range of environmental conditions, landscape specifics, species composition, age, productivity. Annual precipitation varied from 250 to 1600 mm, background snow pack from 30 to 600 mm, and mean January temperature from –6 to –40ºC. The analyses covered important interrelated areas of forest hydrology, such as moisture cycling components (precipitation characteristics and interception, water used for transpiration, runoff development, and other issues) and forest hydrological functions including water protection, channel flow regulation, and soil erosion prevention, as well as the impacts of forest disturbances.

*Impacts of forest on precipitation.* Precipitation enhancement by forest is an actively discussed issue. There are two different opinions on the topic. On the one hand, there are evidences of a positive relationship of amount of precipitation with the size share of forest area, mostly due to increased roughness of areas. The general conclusion, reported for different areas is that forest contributes 40-60 mm (10-12%) to annual precipitation in most of the European Russia (Rakhmanov, 1962, 1975; Kalinin, 1950; Fedorov, 1977), Siberia (Lebedev, 1964) and Far East (Opritova, 1978), and 10% increase in forest area increased annual precipitation by 12-13 mm on average. On the other hand, a number of studies (Leyton and Rodda, 1970; Pozdnjakov, 1986; Voronkov, 1988) did not support such an opinion. However, interception of snow by forest canopy and its redistribution in the forest-gap system are the two well-studied aspects of forest influence on precipitation.

*Impacts of forest vegetation on snow cover.* Forest vegetation has a complex influence on snow cover development that depends on zonal and regional characteristics of snow cover as an environmental factor (Richter, 1984). Snow pack differences are induced by elevation, regional characteristics, and topographic conditions, which, in fact, determine precipitation amounts, are often much more pronounced and can smooth out or even completely obscure those induced by vegetation cover patterns (Protopopov, 1975).

Impacts of forest vegetation on snowfall is evident in snow pack differences between open sites and under forest canopy, as well as in changes of snow pack’s physical and mechanical properties (i.e., structure and solidity) and snow chemistry (Protopopov 1965; Sabo, 1956). Vegetation impacts snow cover distribution within individual forest stands (Protopopov, 1975). Snow cover depth usually increases from the stem of a tree toward its crown periphery, and under-canopy snow distribution depends on woody species and the prevalent wind. On upwind-forested slopes, blizzard-induced under-canopy snow transfer occurs, which process is known to be a key factor accounting for snow cover distribution and snow moisture balance changes (Grudinin, 1981). Wind blowing through the vegetation layer is also important. Forest ecosystems are known to transform wind profiles (Protopopov, 1975; Valendik, 1968). Several studies (Burenina and Onuchin, 1984; Gary, 1974) showed vertical wind profiles to be a mirror reflection of vertical tree crown biomass and LAI distribution. Therefore, the higher the forest canopy is raised, the stronger the under-canopy wind and, thus, the greater the amount of blizzard-driven snow.

Over the region, the deepest snow cover occurs in mountains, particularly in subalpine open woodlands and on downwind slopes, where it can be as deep as 180-240 cm due to blizzard-induced snow redistribution. Conversely, snow cover depth usually does not exceed 20-25 cm in southern Siberian forest-steppe regions and non-forested intermountain depressions. Apart from low winter precipitation, this can be attributable to snow removal by strong winds from vast areas, as well as increasing evaporation during blizzards.

Snow density also varies widely. While fresh snow density is about 0.08-0.12 g $cm^{-3}$, it increases up to 0.15-0.2 g $cm^{-3}$ just before snowmelt in areas with markedly shallow and short-term snow cover. Snow can be as dense as 0.3-0.5 g $cm^{-3}$ where snow cover is deep and lasts long, for example, in northern and high-mountain regions of Siberia. Snow depth, density, and moisture content were found to vary with elevation from 60 to 105 cm, 0.22 to 0.27 g $cm^{-3}$, 120 to 290 mm and respectively, in deciduous stands of chern-taiga altitudinal belt on the northern macroslope of Khamar-Daban mountain range. The respective values of 50-85 cm, 0.21-0.22 g $cm^{-3}$, and 105-190 mm were found for fir and Siberian pine stands at this elevation. Snowfalls are heavier and, thus, snow cover depth increases in Siberian pine and fir stands of the mountain taiga altitudinal belt. For example, the above three parameters were measured to be up to 140 cm, about 0.30 g $cm^{-3}$, and 350-430 mm, respectively, in birch and aspen stands, whereas they were found to range 85-150 cm, 0.27-0.33 g $cm^{-3}$, and 300-500 mm, respectively, in dark-needled stands of this belt. Closed single species Siberian pine stands growing on upwind slopes have shallower snow cover as compared to slopes protected from wind. Here, snow cover appeared to be 80-120 cm deep, 0.25-0.27 g $cm^{-3}$ dense, and contain 200-300 mm of water in these stands.

Snow regime of forests depends on landscape and forest specifics. For instance, open fir stands of Va site index along the tree line in Khamar-Daban mountains that accumulate part of wind-driven snow from adjacent non-forest areas showed the highest snow cover depth (160-180 cm), with snow water amount and density varying from 500 to 600 mm and 0.32 to 0.35 g $cm^{-3}$, respectively. Snowfalls appeared to be less heavy resulting in shallower and less dense snow cover in stands growing on the south-facing macro slope. Snow was recorded to be 40-80 cm deep, with its density and water amount ranging 0.16 to 0.20 g $cm^{-3}$ and 70 to 150 mm, respectively, in Siberian pine, Scots pine, and larch stands of the mountain taiga altitudinal vegetation belt. Here, elevation differences have a greater impact on snow depth than species composition. Snow was measured to be 8-12 and 18-22 cm deep and snow pack exhibited variations from 10 to 15 and 25-35 cm in the subtaiga forest-steppe altitudinal vegetation belt and birch stands, respectively.

Distribution of snow is mostly non-uniform - a snow depth variation coefficient was of 25-30% in mature, fully-stocked Scots pine stands growing on windward slopes and in riverhead valleys oriented northwest. This coefficient was calculated to be 15-17% in open subalpine fir stands on the southern macroslope, while it does not exceed 8-12% for dark-coniferous and deciduous stands found on sites sheltered from wind on the northern macro slope. Snow distribution showed similar trends in forest ecosystems of Yenisei Mountain Range. A characteristic feature of snow cover development on Putoran Plateau is that much more snow is accumulated in forest areas as compared to open sites. The reason of this is that open areas (tundra and stony deserts) account for a much greater area on Putoran Plateau than in mountain regions of Siberia and, as a result, strong winds drive snow from these vast areas to the forest during blizzards.

Research in boreal forests of Siberia (Sayn, Prybaikalje, Enisey *krjag*, plateau Putorana) showed that 1-5% of snow is caught by crown of deciduous stands and 10-45% - by crowns of coniferous. For summer, 8-27% of precipitation is caught by crown of deciduous stands and 15-40% - by crowns of coniferous.

*Impacts of forest on the total moisture evaporation*. The total moisture evaporation includes evaporation of precipitation intercepted by the forest canopy, moisture transpiration by vegetation, and evaporation from soil and snow surfaces. A number of studies conducted in Siberia revealed that evaporation of stand canopy-intercepted precipitation and transpiration dominate in the total evaporation, with their combined contribution ranging 80 to 90% in dark-needled mountain forests of southern Siberia (Lebedev, 1982; Lebedev *et al*., 1979) and 90-93% in forest-steppe regions (Protopopov *et al*., 1983).

*Liquid precipitation interception*. A new aggregated model, developed for quantifying *liquid precipitation interception*, is based on standard forest inventory parameters as predictors (Onuchin and Burenina, 2008):

$$I= -6.0-3.4\ln A+8.4\ln M+0.37S\ln M+0.32(F+P+SP)\ln M-0{,}015X,\ R^2 = 0.7, \qquad (1)$$

where $I$ is rain precipitation interception (%); $M$ is growing stock volume (m$^3$ ha$^{-1}$); $A$ is average stand age (years); $S$, $F$, $P$, and $SP$ are the amounts of spruce, fir, Scots pine, and Siberian pine, respectively, in a stand (expressed in species composition scale units); $X$ is annual liquid precipitation (mm); $R^2$ is multiple determination coefficient.

The individual rain interception model is:

$$I=35.3+6.1\cdot\ln M+0.13\cdot(S+F+P+SP)\cdot\ln M-146\cdot\ln X_i,\ R^2 = 0.81, \qquad (2)$$

where $Xi$ is individual rain precipitation amount (mm); the remaining characters denotes the same components as in equation (1).

These models show that the total liquid precipitation interception depends on stand age, species composition, growing stock volume, and precipitation amount. The total intercepted precipitation increased with increasing proportion of coniferous in forest stands, growing stock volume (especially between 20 and 150 m$^3$ ha$^{-1}$). Young stands intercept more rain than mature stands.

*Snow Interception*. Species composition is a key controller of precipitation interception by stand canopy. Deciduous species intercept less snow than conifers. This is particularly true with birch stands, where snow pack coefficients are close to 1.0 (Rakhmanov, 1984). Up to 20% of the total snow evaporates from tree crowns in larch stands (Tupikin, 1984). As it has been shown by Onuchin and Burenina (2008), precipitation interception in dark coniferous forests of mountain taiga of Khamar-Daban in south-eastern Baikal region correlates with age and biomass of stands

Snow interception is determined by various combinations of many factors. Many investigations on snow interception by various Siberian conifers show that Scots pine crowns have the greatest snow holding capability followed by Siberian pine, spruce, and fir (Geosystems…, 1979). While similar results were obtained in Baikal region (Onuchin, 1985), a number of studies (Kalinin, 1950; Molchanov, 1960; Rakhmanov, 1975) reported the greatest amount of snow to be held by spruce stand canopy in European Russia. Dry snow, frosty weather, and infrequent heavy snowfalls enhance snow penetration under forest canopy. Conversely, increasing air temperature that promotes sticking of snow to tree crowns combined with frequent light snowfalls enhances snow interception. Wind has a double role in this process. Even light wind makes snow fall down from tree crowns and accumulate under the forest canopy in dry frosty weather. Moist snow can keep on crowns long; however, it evaporates intensively under wind and thereby favours further snow interception and contributes to a decrease in under-canopy snow pack.

A combined effect of forest canopy closure and woody species composition on snow interception was recognized (Onuchin and Burenina, 2008). Increasing canopy closure usually reduce snow pack but only if the overstory was represented by tree species with a high snow holding capability. Otherwise increasing canopy closure did not increase the amount of intercepted snow. Decreasing snow pack with increasing canopy closure and stocking of stands of fairly similar age and productivity is common for all forests, except for deciduous stands, irrespective of climate and region (Alton and Frend, 1981; Matveev, 1984; Rukovskiy, 1956). A deviation from this general trend observed in some years is due to thaw spells (Rukovskiy and Kuznetsova, 1940).

Models developed for diversity of forests and growing conditions quantify interannual and regional differences in snow cover development using wintertime air temperature data (Onuchin and Burenina, 2008):

$$K=1150+0.026S_0-13\ln A/\ln T-15L\cdot D-2.3N\cdot D-6.6S_t\cdot D-1.9B,\ R^2 = 0.73, \qquad (3)$$

where $K$ is snow pack coefficient, %; $S_o$ is background snow pack, mm; $T$ is absolute mean January air temperature, $C^o$; $N$ is the units (the total proportion) of conifers, disregarding larch and spruce (*Picea shrenikiana*) in a stand; $L$ is the units (proportion) of larch in a stand; $S_t$ is the units (proportion) of spruce (*Picea shrenkiana*) in a stand; $D$ is stand canopy closure; $B$ is site index class (1, 2, 3 etc.); the remaining characters denote the same components as in equation (1).

*Snow redistribution in the forest-open site system.* There are a few studies that addresses the dependence of snow cover development in open sites on their sizes, shapes, and aspects. This area was investigated by Fedorov (1977), Golding and Swanson (1978), Onuchin (1984) and Sosedov (1962, 1967). A Canadian study in pine forests (*Pinus nigra*) revealed maximum snow pack to occur in glades with a diameter twice and three times the surrounding forest height, and snow accumulation showed a considerable decrease, where glade diameter either decreased lower, or increased beyond the above threshold values (Golding and Swanson, 1978).

Blizzards are also responsible for snow cover development on open sites as those make snow cover more compacted and increase evaporation and enhance snow transfer and redistribution. The study of snow cover development in northern Khamar-Daban macro slope of south-eastern Baikal region indicated that snow was transferred by blizzards in open sites of any size located in the upper parts of northwest-facing slopes, as well as in sites exceeding 15-20 ha, whatever their aspect. Blizzards were found to be much less active, if at all, on other sites located on the northern macro slope, as well as on those within the southern macro slope. Blizzard-driven snow was observed to be accumulated mostly along upwind forest edges. Blizzard is known to control snow accumulation to a great extent by transferring snow, enhancing its redistribution and moisture evaporation from its surface. Relatively small conifer forest glades well-sheltered from wind exhibited the highest snow accumulating capabilities. While about 95% of the total snow accumulated there during the winter remained up to snowmelt onset, the corresponding snow amounts were measured not to exceed 20-60% on vast open sites (Onuchin and Burenina, 2008).

An aggregated model has been developed based on data obtained on snow cover development on open sites in various landscapes of mountains of Southern Siberia (Onuchin, 1984a, 1984b):

$$\Delta X=X(0{,}11\ln L-0{,}0055L+0{,}00003X), \qquad (4)$$

where $\Delta X$ is snow pack increase, mm; $X$ is precipitation (snow) amount, mm; and $L$ is percentage of the forested area of a catchment.
The obtained results is of a substantial interest for estimating of human-induced changes of forested areas, e.g. after final harvest. Snow accumulating capabilities of forest ecosystems can be either reduced, or increase by different logging types. Although snow accumulation is determined by catchment-specific vegetation, climate, and weather, it exhibits a general trend to change depending on the amount of forested area and logging site pattern. Changes of snow moisture balance that are caused by forest structure and manifested in increasing snow pack can thus be interpreted as a forest

vegetation influence on hydrological regimes resulting, in fact, in increasing catchment water storage. This influence appeared to be particularly clear in catchments with a forested area of 20-40%. This effect was found to decrease with decreasing blizzard activity

This forest cover pattern-induced increase in snow accumulation, when considered in the context of the general hydrological cycle and structural water balance changes in catchments, depends on the location and rank of the considered area. For example, a forest pattern-induced increase in snow pack can be up to 80-100 mm in mountain taiga elementary (single-channel) catchments of 1 to 5 square km in area characterized by snow precipitation of 350-500 mm, while its absolute value does not exceed 20-30 mm for forest-steppe areas with less snow in precipatin.

*Transpiration.* Experimental studies for various Siberian regions show that moisture used for transpiration is in range of 224-320 mm. Of this amount, 55-70% comprises the total evaporation, while intercepted precipitation evaporation accounts for 20-35% of the total evaporation in forest ecosystems of Siberian forest-steppe zone. The respective values found for mountain dark-needled forests of southern Siberia are 39-55% and 35-55%. Studies carried out in mixed Siberian pine/fir stands of western Sayan mountains and Baikal basin revealed a narrow average variability range (171-233 mm) of absolute transpiration values, whereas its relative values appeared to vary considerably (19-33%) primarily depending on the amount of annual precipitation. Transpiration accounts for 50-65% and 25-30% of the total moisture evaporation in dry and wet year, respectively in these areas (Lebedev, 1982; Lebedev *et al*., 1979).

Using long-term ground truth data and estimates of intercepted precipitation, transpiration and evaporation based on aboveground vegetation biomass data, we calculated moisture evapotranspiration in forest ecoregions of central Siberia (Onuchin and Burenina, 2008). The total evaporation varies among geographical zones primarily due to radiation balance differences. However, in-zone transpiration amount depends on forest stand productivity. The total evaporation increases due to increases in moisture transpiration and forest canopy-intercepted precipitation evaporation with increasing above-ground vegetation biomass in Scots pine and mixed Siberian pine/fir stands (Kozlova, 1980, 1988; Protopopov, 1975). Overall, the total evaporation increases from north to south that can be attributable to north-southward increasing radiation balance and forest productivity, however the amounts and ratio between transpiration and intercepted precipitation evaporation vary even within individual vegetation zones (Onuchin and Burenina, 2008). This variability is less (from 184 to 216 mm) in the northernmost forest regions and increases between northern taiga forest regions. While intercepted precipitation evaporation amounts to 111 mm (40% of the total evaporation) in Turukhan region, it is as low as 34 mm (12%) in Lower Tunguska region. This can result from the fact that the former region is dominated by dark-needled woody species and the latter by larch. A similar trend is observed for central taiga forest regions. Intercepted precipitation evaporation is 125 and 116 mm (36-40% of the total) and 65-84 mm in dark conifer- and larch-dominated forest regions, respectively. Since highly productive forest stands dominate in southern taiga forest regions that are characterized by higher air temperatures, maximal moisture transpiration is observed here (Burenina *et al*., 2002).

*Influence of forest on runoff and water soil erosion*. Siberian rivers are of global importance as they impact on the fresh water budget of the Arctic Ocean. Formation of Siberian rivers runoff and its season dynamics depends on forest vegetation to a considerable extent. Many rivers of Southern taiga and mountain regions drain areas of land that experienced a dramatic land-cover change, with a decrease in overall forest area and a relative increase in deciduous trees. Land cover change in forest catchments (harvest, wild fires) impacts water balance and water-protective functions of forest.

The effectiveness of water protection and regulation functions is region- and forest stand-specific. Mountain forests have the greatest impacts on channel runoff. Maximal water protection effectiveness is observed in high and middle mountain forest belts of the boreal and temperate zones. The major part (76%) of the total runoff of rivers going down the northern Sayan macroslope and into Yenisei river is developed in the mountain taiga altitudinal forest belt (500-1 600 m a.s.l.), which accounts for about 60% of the total macro slope catchment area. About 20% of the total western Sayan mountain channel runoff occurs in the subalpine belt and mountain tundra (1800-2400 m a.s.l.) with an area not exceeding 15% of the total macros lope catchment. The forest-steppe vegetation belt (250-500 m a.s.l.) making up 15% of the total macro slope catchment area accounts for only 4% of the total channel runoff (Lebedev, 1982). Fairly similar channel runoff structure data were reported by Lebedev *et al.* (1975, 1979) for mountain rivers in south-eastern Baikal region. Mountain taiga forests of this region, where about the total local mountain river runoff is developed, provide extremely high quality and a perfect thermal regime of Baikal water (Lebedev *et al*., 1985).

Studies conducted in Baikal catchment show that final harvest accomplished during a high-precipitation cycle increases annual channel runoff by 20-30% depending on logging area and precipitation amounts. Forest harvesting has either no, or a reducing effect on annual channel runoff during a low-precipitation cycle (Protopopov *et al*., 1991). Changing catchment forest area is first of all reflected in water redistribution between runoff horizons. Wood extraction of 10-50% increases surface runoff by 10-20% and reduces ground (depth) runoff by the same percentage (Lebedev 1982, Lebedev *et al*., 1984). Ground runoff exhibits a decrease of 10-20% where 20-65% of catchment forest was harvested (Lebedev *et al*., 1984).

Large-scale logging induces changes of seasonal runoff structure increasing surface runoff and spring surface runoff proportion in annual runoff (Onuchin and Burenina, 2008; Lebedev *et al*., 1984). Post-logging recovery of forest water protection and erosion prevention functions occurs in different ways on slopes and in big river catchments. While erosion decreases several times during three to five years after logging on slopes, water silt load in big rivers can remain high for decades after forest logging.

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The following model describes soil erosion rates on individual (separate) slopes and in elementary catchments (Onuchin and Burenina, 2008):

$$\ln M=-9.3+0.95\ln X-0.064N\ln L+0.069\ln X\ln m/\ln L+5.03K+1.49\ln I+ \\ +0.0162\ln((X-W)/In)i-0.00026\ln((X-W)/In)i^2\,,\ R^2=0{,}86 \qquad (6)$$

where $M$ is sediment load module, t $km^2$; $N$ is time since the last disturbance (fire or logging), years; $X$ is precipitation amount, mm; $I$ is precipitation rate, mm/min; $m$ is soil mineralization level, %; $L$ is length of slope where surface runoff occurs, m; $W$ is forest floor moisture capacity, mm; $In$ is soil water permeability, mm/min; $i$ is slope, degrees; $K$ is a methodology indicator (it is assumed to equal 1 in the case of area sprinkling and 2 in erosion observations on permanent runoff sample sites and in catchments); and $R^2$ is multiple determination coefficient. All coefficients are 95% confident. Numerical experiments with this model showed the sediment load module increases with increasing precipitation rate and decreases with increasing slope length. Soil erosion decreases drastically after 1-2 years after logging.

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The time needed for a forest to recover its erosion prevention function depends on forest growing conditions (or environment) and human-induced disturbance type. This function was calculated to recover in five years on logging sites located on up to 5- degree slopes and characterized by 2% initial soil mineralization, whereas its recovery was found to take 17 years under 60% initial post-logging soil mineralization. The respective values appeared to be 15-25 and 22-35 years, depending on how much soil was mineralized by logging, for slopes of 10 and 20 degrees. Relatively rapid recovery of the forest erosion prevention function does not indicate that all forest water protection functions are successfully recovering. Post-disturbance recovery of surface and ground runoff regime and structure requires a much longer period of time as compared to that of the erosion protection function (Bizyukin, 1982).

Large-scale clear cuts result in changing runoff amount, seasonal dynamics, and redistribution by horizon, and enhance slope erosion, which adds to silt and sediment loads. The model of sediment load dynamics for a typical catchement (the Chadobets one) is based on strong correlation with channel runoff and burned or logging area (Onuchin and Burenina, 2008):

$$lnM=-0.937+3.188lnS_w+ 0.098lnS_g + 0.008Y,\ R^2= 0.43, \qquad (7)$$

where $M$ is sediment load, t km$^{-2}$; $Y$ is channel runoff, mm; $S_w$ is previous year logging area, %; and $S_g$ is previous year area burned, %. Dependently upon catchment specifica, models could have a different character, e.g., for the Irkineyva catchment:

$$lnM=-2.87+0.41ln(Y\cdot S_w)+0.2ln(Y\,S_g),\ R^2=0.47, \qquad (8)$$

where $S_w$ is total area of logging sites up to 15 years old; $S_g$ is total area of <=$5_{\text{year}}$-old burned sites. The remaining symbols are the same as in equation (7).

Fresh logging sites were found to have the major impact on sediment load. Fresh logging sites accounting for up to 5% of the total catchment area were calculated to increase sediment load 9-fold (from 2 to 18-20 t km$^{-2}$ yr$^{-1}$). However, no drastic soil erosion increase was observed where logging was timed properly. About 20% of a catchment forest area removal during 20 year lead to a sediment load increase twice to 2.5 times (i.e., sediment load module has increased from 2 to 4.5 t km$^{-2}$ yr$^{-1}$) as compared to its multiyear average. Burns influence sediment load less than logging.

*Conclusion*. Reviewed researches on the impacts of forests on hydrological regimes of territories are of a substantial interest for assessing the role of human-induced disturbances under climate change. Hydrological research across the region showed that restoration of water protective and, in particular, erosion- protective functions of forest after cuttings on separate slopes and in large catchments occur differently. The idea of ranging catchments according to hierarchical levels was used to make an analysis of erosion- protective and water- protective forest functions for the territorial units of different ranks. Data obtained by different methods were generalized and the elements of the system analysis and mathematical modelling of water- protective, water- regulating and soil-protective forest functions were used.

The identified numerical characteristics and regularities (dependence of canopy-intercepted precipitation evaporation and moisture transpiration by plants on forest inventory, total evaporation etc.) serve as basis for understanding the future trajectories of hydrological regimes. Human activities, particularly forest harvesting, could substantially impact hydrology of catchments. The new methodologies (Onuchin and Burenina, 2008) proposed allow substantially increase reliability of the results and quantifying general regularities.

## 3.2. Development of monitoring systems of water resources

Security threat for population in the basin of lower riches of Rivers Ob' and Irtysh is caused by intensive industrial transformation of the territory and accelerating frequency of extreme hydrological and meteorological phenomena that are tied with regional manifestation of global climate change. A large amount of different enterprises of oil and gas extraction and treatment, chemical, metallurgical, nuclear and agricultural functions in the basin of the Ob'-Irtysh river system, in territories of Sverdlovsk, Cheljabinsk, Tomsk, Omsk, and Tyumen regions. They are sources of contaminants and radioactive nuclides that are going in open waterways. It leads to decreasing quality of water downstream that is fixed in territories of Khanty-Mansi and Yamal-Nenetsk Autonomous *Okrugs* where water quality is estimated as “dirty” and “very dirty”.

Due to huge water resources of Khanty-Mansi Autonomous Okrug – Yugra (KMAO-Yugra), any full-scale hydrological and ecological study of all watershed territory is very complicated and resource consuming. It defines relevance of interdisciplinary experimental researches and mathematical modeling of dynamics of river ecosystems of basic water ways of the Okrug – Ob', Irtysh, Severnaja Sosva (Pushistov *et al*., 2007).

Topicality of the above problems defined motivation and thematic directions of participation of the research team of the Yugra State University in the Enviro-RISKS Project. The innovation methodology of development of high technological Expert Support System (ESS) (Water resources…, 2005) served as a conceptual and science background of the work that was realized in two directions: (1) as a management tool for use, restoration and protection of water resources of individual water bodies – River Severnaja Sosva and part of low riches of River Irtysh (Pushistov *et al*., 2005; 2006, Pushisyov, 2006; Pushistov and Vtorushin, 2006, 2007; Vtorushin, 2006; Pushistov and Vtorushin, 2007; Baklanov *et al*., 2008; Vtorushin *et al*. 2008), (2) for prevention of natural and technogenic extraordinary situation and management in crisis situation in territories of KHMAO-Yugra (Pushistov *et al*., 2007a,b,c, 2008).

*Development of information and modeling system of hydrodynamics and water quality of Severnaja Sosva River*. The relevance of development of information and modeling system (IMS) of hydrodynamics and water quality of Severnaja Sosva River (a large left tributary of the Ob' River in territory of KHMAO-Yugra) is defined by the following reasons:

- River Severnaja Sosva has a unique but vulnerable natural aquatic ecosystem; this ecosystem has a number of endemic species (including *tugun* – a famous Sosvin's herring) and is heavily contaminated (very high background concentrations of compounds of iron, copper, zinc and manganese which several times exceed maximum permissible concentrations (MPC) are observed here);
- in 2011-2020, the basin of upstream of the River will become a territory of large-scale industrial development of the unique deposits of solid minerals (indicated in the State Program “Ural industrial – Ural polar”) that makes the task of development of ESS for management of use and protection of water and biological resources of the river extremely important;

- in 2004-2006, Yugra Research Institute of Technologies and Yugra State University accumulated experience of development of background modeling complex (BMK) of hydrodynamics and water quality based on 2.5-D model CE-QUAL-W2 (available at http://www.cee.pdx.edu/w2/) destined for reproduction of hydrological, thermal and hydrochemical regimes of River S. Sosva and lower riches of River Irtysh using measurements of observation posts of Roshydrometeorological service and data of bathymetry from pilot charts (Pushistov *et al*., 2006).

A substantial problem of initial available data which are needed for development of the model of hydrodynamics and water quality was lack of satisfactory information for calibration and verification of the model (hydrometeorological data of entrance range and outlet, as well as hydrochemical data at the outlet were absent; amount of data about depths of the river-bed on pilot charts was not sufficient). It required a special experimental work.

*Field experimental works.* Complex experimental works at River S.Sosva have been provided by the team of the Yugra State University and the Territorial Center of Monitoring and Forecast of Extraordinary Situations of KHMAO-Yugra in fall of 2007. The goal of these works was to receive hydrological (levels, flow velocity and temperature of water), hydrographical (river-bad profile in ranges of measurements) and hydrochemical data of fine spatial resolution. The following equipment has been used:

- acoustic measuring device of flow velocity and depth “Mini” ADP RiverSurveyor system, SonTek/YSI, Inc, USA; double-frequency GPS-receiver Trimble 5700, Trimble Navigation Limited, USA; echo-sounder Garmin GPSMAP 178C, Garmin, Inc, USA; multi-parametric sonde YSI 6600 Sonde Environmental monitoring system, YSI, Inc, USA; computer Notebook DELL Latitude C640, DELL, Inc, USA. All this equipment allows automated processing of data in real-time mode.

Experimental works at River S.Sosva were provided between the mouth of River Mania and settlement Igrym. Thirty one fathom ranges have been provided between hydrological stations Sosva (328 km from the estuary) to the station Sartynia (258 km). At these ranges, measurements of depths’ cross-sections (Fig. 9), levels of water (Fig. 10) and flow velocity were provided.

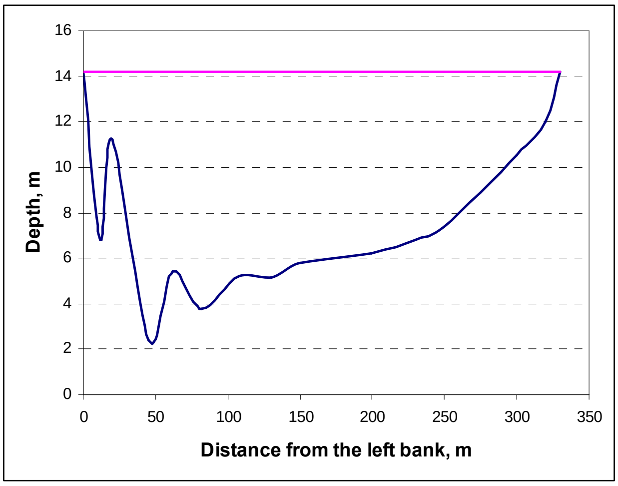

**Fig. 9.** *Cross-section of depths at the range Sos'va (range 1).*

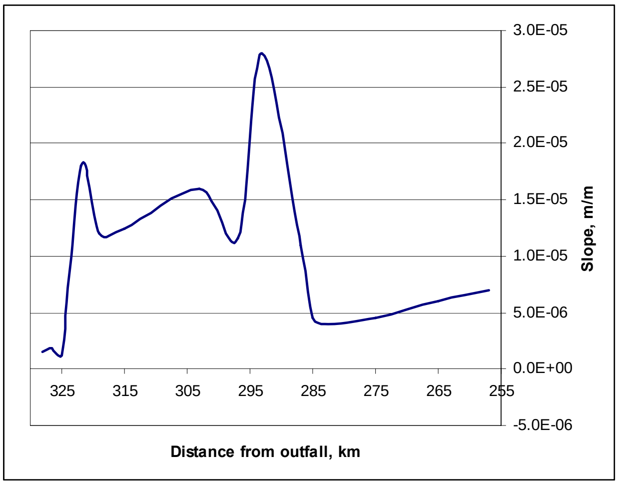

**Fig. 10.** *Slope of water surface between stations Sos'va and Sartynia.*

During the above field works, water withdrawal was provided aiming at following analyses on the content of oil products and heavy metals. The express-analyses of water quality (temperature, electroconductivity, salinity, specific resistance, mineralization, dissolved oxygen, hydrogen ion exponent, redox potential, turbidity) was provided using a hydrochemical multuparameter sonde.

*Results of modeling of hydrological variables and comparison with results of observations.* For assessment, the specified input parameters were used in a previously developed model of hydrodynamics of the reach of river S. Sos'va between ranges Sos'va and Sartynia (Pushistov *et al*., 2006). The model of bathymetry of flood-land reach of the river was formed based on a topographic map at scale of 1:25000. The network model has the following parameters: number of segments – 177, length of segment – 400 m, number of vertical layers – 103, thickness of the layer – 0,2 m; roughness' parameters by Manning and Shazy were assumed at 0,03 and 70, respectively. The period of modeling coincides with the period of the field work at the mentioned above part of the river – from 20-21 September 2007. Boundary conditions at the entrance range (segment 1) for level (H) and temperature (T) of water were set using data of station Sos'va, and H at the outlet – using data of station Sartynia (segment 177). One can conclude that the model is rather accurate and adequate (the absolute error of H of the measurements in 11 points comprises at 1.4 cm for the formulation by Manning and 1.2 cm – by Shazy). Table 4 contains the values of cross-averaged horizontal flow velocities (U) in ranges by "Mini" ADP and corresponding modeling values U (the parametrizing of near-bottom flow was done by Manning).

***Table 4.*** *Comparison of results of cross-averaged flow velocity ($U_H$ – measurements, $U_n$ – modeling results) in surface water level*

| **Number of segment** | 2 | 4 | 11 | 15 | 24 | 51 | 65 | 78 | 91 | 105 | 117 | $U_{av}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **$U_H$ (m/sec)** | 0,33 | 0,36 | 0,31 | 0,42 | 0,38 | 0,41 | 0,51 | 0,42 | 0,51 | 0,38 | 0,55 | 0,42 |
| **$U_n$ (m/sec)** | 0,45 | 0,37 | 0,51 | 0,38 | 0,38 | 0,42 | 0,58 | 0,49 | 0,51 | 0,41 | 0,43 | 0,45 |

The above results were presented at the international conference ENVIROMISS-2008. Owing to the participation in the project Enviro-RISKS, the Yugra State University together with institutions and partners Public Corporation «SPC Monitoring», Tomsk State University, Department of Hydrology of Land, SPE «Polet» (Nizny-Novgorod) has prepared and submitted to the Department of Investments, Science and Technology of the KHMAO-Yugra a new Project - «Development of scientific and technical measures on creation of high technological system of automatized monitoring and management of use and protection of water resources in zones of step-by-step industrial developing of Polar Ural in the basin of Severanaja Sos'va River ».

*Basic principles and some results on creation of the monitoring and warning system of natural and man-made emergency situations of the Khanty-Mansiysk Autonomous Okrug-Yugra.* Territorial System of Monitoring, Laboratory Control and Prediction of Natural and Man-Made Emergency Situations (further – TSMP ES) is designed for emergency situations timely detection and forecast, development of recommendations on prevention of natural and man-made emergency situations and mitigation of damage. TSMP ES includes the Territorial Centre of Monitoring, Laboratory Control and Prediction of Natural and Man-Made Emergency Situations, territorial branches and institutions of federal executive authorities, organizations and institutions of executive authorities of entities of the Russian Federation, other structures located on the territory of the RF entity authorized to solve problems of monitoring, laboratory control and prediction of emergency situations sources. TSMP ES also comprises the territorial level of the network for monitoring and laboratory control of RF civil defence (further – NMLC).

The territorial NMLC tasks involve monitoring and control of radiation, chemical and microbiological environmental components, at wartime and at peace, on the territory of RF entity. Under the threat or in case of a large-scale natural, man-made or biological-social emergency situation, the direct guidance of works on ES prevention and suppression is performed by the executive authorities, and also by the corresponding coordinating control bodies of the Unified State System for Emergency Situations Prevention and Liquidation (RSES) – the Commission on Emergency Situations Prevention and Suppression and Securing Fire Protection, as well as by permanently operating RSES control bodies. In accordance with the «Regulations on the Unified State System for Emergency Situations Prevention and Liquidation» (approved by the RF Government Decree №335 of May 27th 2005), the RSES routine control bodies, at the level of RF entities, are:

- Control Centers in Emergency Situations (CCES) of the Central Administrative Boards of RF Ministry on Emergency Situations in RF entities, unified on-duty control services (UODCS) of the territorial structures of federal and local executive authorities;
- Unified On-duty Control Services of municipal bodies;
- On-duty Control Services of organizations (objects).

At the interregional level, there functions are fulfilled by the Regional System of Monitoring, Laboratory Control and Prediction of Natural and Man-Made emergency situations (further – RSMP ES) whose activity is coordinated by the Privolzhsko-Uralskiy Regional Centre of Monitoring, Laboratory Control and Prediction of Natural and Man-Made Emergency Situations (further RCMP ES). At the federal level, the RSMP ES activity is coordinated by the All-Russian Centre of Natural and Man-Made Emergency Situations Monitoring and Prediction (Zalokhov, 2007, Methodological…, 2005).

*Modern Instrumental-Communication and Information-Modelling Methods and Technologies of Prevention and Prediction of ES and Security Threats.* Preparation of ES urgent monitoring forces and means should be based on the modern approaches to the creation of a system instrument of ES monitoring, prevention and prediction. The basic element of such a system instrument is the information-modelling system (IMS) with hierarchical on-line information processing on the following levels:

- sources of initial information (observation and measurement data),
- data management (BD and GIS),
- mathematical modeling and prediction,
- preparation of information for decision making support and bringing this information to the users.

It seems expedient to use positive experience of the developed countries in applying high information technologies to solving specific tasks of ES eco-system monitoring, prediction and prevention on the territory of the Khanty-Mansiysk Autonomous Okrug-Yugra. There are many world-companies leaders in elaboration of various IMS for decision making support in case of ES; among them, for instance:

- ESS company (Austria) specializes in receiving and processing of information on the conditions and decision making support systems in ES cases,
- SYRECO consulting group (Italy) specializes in assessment of risks in the chemical and the processing industries,
- an expert organization in information technologies LNEC Informatica (Portugal) specializes in data transmission and distributed applications for risks assessment and ES prevention,
- GMD company (Germany), a large national research institute with great experience in high-performance parallel computations and applications related to nature management and ES prevention technologies,
- ASIT consulting group (Switzerland) specializes in cargo transportation safety and has a great experience in the field of integrated information processing and transmission means for cargo transit,
- German consortium of 4 companies implements EUROPEAID 121 579/C/SV/RU “Monitoring and Warning System for the Ob/Irtysh river Basin”,
- International consortium implements “ARGOS CBRN Decision Support for Emergency Management”.

This list can be enlarged by adding a number of universities and institutes working in the sphere of modeling both separate natural/ man-made ES and complete systems. Let us mention some of such elaborations: Portland State University (USA) – the CE-QUAL-W2 model – two-dimensional, cross-averaged model of hydrodynamics and water quality [20]; Danish Meteorological Institute (Denmark) – meteorological safety on motor roads [21]; Swedish Institute of Environmental Research (IVL), in the framework of the Unified Water Directive, is working on WATSHMAN project «A Water Basin Management System» [22]. Experience of and collaboration with these companies were used in this study.

*The Concept of creation and operation of the KhMAO-Yugra TSMP ES.* In 2007, the Concept of KhMAO-Yugra TSMP ES creation and functioning was elaborated by ICC «Promtechbezopasnost» Moscow (A.A. Malyi, project manager) and KhMAO-Yugra TCMPR ES (P.Yu. Pushistov, head of the Project). It included the main provisions and opinions of creation and functioning of the Khanty-Mansiysk Autonomous Okrug-Yugra Territorial System for monitoring, laboratory control and prediction of emergency situations.

The Draft Concept structure: (1)prerequisites of the territorial system creation; (2) functions and tasks of the territorial system; (3) composition of the territorial system; (4) Territorial System Foundation Order; (5) requirements to legal and metrological base of the territorial system; (6) Territorial System Operation Order; (7) territorial system dataware; and (8) realization of the Concept.

*Prerequisites of the Territorial System creation.* The Khanty-Mansiysk Autonomous Okrug-Yugra is characterized by high natural, man-made and biological-social risks. In 2006, 43 man-made emergency situations were registered on the territory on the Khanty-Mansiysk Autonomous Okrug-Yugra, in accordance with criteria confirmed by the RF Ministry of Emergency Situations Order № 329 of July the 8th, 2004. As a result of these emergency situations, 91 people died and 13 people suffered.

<u>Explosions and fires</u>. In 2006, 32 emergency situations accompanied by fires, explosions and the cost of damage was estimated at 3.65 million rubles. The number of fires in residential, social and cultural constructions is particularly alarming. For the 10 months of 2006, the State Statistics registered 2535 fires on the territory of the Khanty-Mansiysk Autonomous Okrug-Yugra with direct material damage of 107.3 million rubles. 127 people died and 195 people suffered in fires. In the course of fire extinguishing, 946 people were saved and evacuated by firemen. In comparison with the analogous period of the last year (APLY), the number of fires reduced by 4.6% (2659 fires in 2005), the damage was increased by 18.7% (90.4 million rubles in 2005), the number of the deceased in fires increased by 4.9% (121 people in 2005), the number of suffered remained the same (195 people in 2005).
<u>Automobile accidents and crashes.</u> According to ES criteria, 3 traffic accidents with 16 deceased were registered.
<u>Accidents at trunk pipelines.</u> In 2006, there were 4 accidents at trunk and field pipelines. 2 people died, none suffered. Material damage is estimated at 1.5 million rubles.
<u>Accidents at electrical power systems - 1</u>. Due to unfavorable weather conditions, high-voltage lines between 5 transmission towers were broken. As a result, 4 settlements of the Surgut region (Sytomino, Peschaniy, Lyamino, Gorniy) were deprived of electric power.
<u>Heat networks accidents (in the heating season) - 1</u>. Because of heat pipe breakdown, a boiler plant in Raduzhniy failed. As a result, 16 dwelling houses were deprived of heating, vital activity conditions of 6000 people were impaired. None was died or suffered. Costs of ES consequences' liquidation made up 534 thousand rubles.

The Autonomous Okrug territory is also characterized by hazardous natural phenomena, such as extremely low temperatures, strong snowstorms, glaze-clear ice, intense precipitation, floods, forest fires, etc. Mass epidemic infection of people and animals is also possible. A great number of potentially hazardous objects function on the territory of the Khanty-Mansiysk Autonomous Okrug-Yugra. It results from the above that the problem of KhMAO-Yugra population and territory defense from natural, man-made, biological-social emergency situations and significant security threats is of vital importance.

*Structure of the territorial system.* In accordance with the RF GOST (State Standard) 22.1-5-95 «Monitoring and Prediction. The main regulations», the territorial system should consist of the following main elements: organizational structure; overall system model, including monitoring objects; hardware complex; situation development models; methods of observation, data processing, situation analysis and forecast; and information-communication systems.

TSMP ES of KhMAO - Yugra as a vertically integrated system of support in decision-making at crisis situations management includes the following levels:
Level 1: The Territorial center (TCMP ES) with a situation management hall for the crisis situations management, providing information and technical support of work Commission on ES and fire safety of the Autonomous Okrug as well as the Centre for Crisis Situation Management.
Level 2. Zonal departments (offices) of TSMP ES in Nizhnevartovsk, Surgut and Nyagan.
Level 3: Services (subjects - the organizations) of TSMP ES, supervision and laboratory control networks of the Khanty-Mansiysk Autonomous Okrug - Yugra, including Monitoring and Laboratory Control System. According to the data from December, 1st, 2007 the tripartite agreements between the Ministry of ES of Khanty-Mansiysk Autonomous Okrug, Department of Civil Defense of Population and subjects of TSMP ES have been signed with 14 organizations, and with 7 organizations are under study.
Level 4: Network of Unified Emergency On-Duty Control Services (UEOCS) of the municipalities of the Autonomous Okrug.
Level 5: The level of ES information sources and threats to potentially dangerous and crucially important objects, an additional network of natural ES prevention posts, mobile forces and means of operative information-practical monitoring of places ES and threats to safety of living.

According to the Concept, principle of modularity lies in the basis of TSMP ES activities. The following thematic modules (information-management subsystems) are gradually worked out and put into operation: (1) «Civil defense», (2) «Technotronic security» - is operated since 2007, (3) «Nature Security» - has been developed since 2007, (4) «Biosocial ES», (5) «Radiation Security»,(5) «Civil Defense», (6) «Fire Safety», (7) «Safety in the waters», (8) «Critical Objects», (9) «Search and rescue service», and (10) «Subsystem of operative reaction to threats of the population's life».

*Structure of TCMP ES.* The organizational structure of the territorial system comprises the control body – the Territorial Centre of Monitoring, Laboratory Control and Prediction of Emergency Situations, which is, at the same time, the scientific-methodical and information-technological centre of TSMP ES.
1. The Unified Emergency On-duty Control Service (UEOCS) consists of:
1.1. Emergency Situation Service (ESS);
1.2. Command-and-Control Service (CCS);
1.3. Fire Extinguishing and Rescue On-Duty Service (FERODS);
1.4. Data Analysis and Telecommunication Means Support Service.
2. The Board on Monitoring, Laboratory Control of Emergency Situations and Realization of the Engineering-Communicational and Material-Technical parts of TSMP ES design:
2.1. Department of field instrumental-information monitoring and laboratory control of emergency situations and security threats;
2.2. Department of communication facilities, communication networks and computer engineering;

2.3. Department on informing population and authorities of emergency situations and security threats.
3. The Board of Emergency Situations Analysis, Prediction and Realization of the Information-Technological Part of TSMP ES Project:
3.1. Department of Development and Implementation of New Information Technologies and TCMP ES Databases Maintenance;
3.2. Department of Natural and Biological-Social Emergency Situations Analysis and Prediction;
3.3. Department of Man-Made Emergency Situations Analysis and Prevention.

*Proprieties and prospects.* The system approach has been consistently used during the preparation and implementation of the ideas on expansion of the territorial system of monitoring and forecasting of natural and technogenic ES in the territory of the Khanty-Mansiysk Autonomous Okrug. In fact the efficiency of creation, development and functioning of the territorially-distributed and vertically integrated system of monitoring, the laboratory control and forecasting of ES in the territory of the Autonomous Okrug depends on the results of the decision making of the following primary goals:

- creation of the normative-legislative base that would provide all levels of functioning of TSMP ES;
- technical equipment for processes of collection, processing, representation and storage of the monitoring and forecasting information;
- use of modern technologies of information flows processing and working out of ES forecasts and threats to safety of living; and
- staff training.

The guarantee of the mentioned tasks successful solving is the consolidation of all types of resources (administrative, intellectual, information-technological and financial) and the structural interaction of all bodies (services) of the local RSES subsystem, as well as active drawing of the regional, national and international experience. The further high technologies development of TSMP ES in KhMAO – Yugra will require the successful problems solution of staff training and a high level in decision of scientific-applied problems.

*Conclusion.* Yugra State University was founded in 2002. This is the youngest but successfully developing university over the West-Siberian region of Russia. Participation in the project Enviro-RISKS helped scientists, professors, teachers, and students to get access to international researches that have been providing by the project’s partners (EU, Russia, Kazakhstan), to information resources of other projects were fulfilled in different countries in field of environment monitoring, nature use management and restoration of ecosystems. YuSU’s team, within the prpject Enviro-RISKS, have been prepared 15 science papers and made at 20 presentations at international, Russian, and regional conferences and workshops. YuSU included above 20 post-graduates and students. Results of the Enviro-RISKS project were used for preparation of tutorials for students of the YuSU as well for employees of institution of monitoring, prevention and liquidation of emergency situation.

# 4. Anthropogenic Impacts on Natural Landscapes and Terrestrial Ecosystems

## 4.1. Negative impacts on environment, atmosphere and water

Man-made impacts and changes are widespread in Siberia. They are mostly connected to extraction and exploration of fossil fuel (oil and gas) and use of other natural resources (wood, metals etc.). Some regions of Siberia were and are impacted by different types of industrial pollution and contamination (including radioactive contamination, e.g., after previous nuclear explosions on Novaya Zemlja). It impacts the environment, genofond and health of population, particularly of indigenous Northern populations. There are significant statistical trends of increasing sickness rate – chronic, allergic and oncological ones.

Current peculiarities of social and economic development of Siberia which are accompanied by the destructive anthropogenic impacts on the environment and natural landscapes may substantially accelerate the negative consequences of climatic change. Existing today methods of industrial exploitation of northern territories do not provide for any optimistic estimate of future interactions of the industry and environment in Siberia. The level of atmospheric pollution and soil contamination in major regions of intensive oil and gas extraction has exceeded all acceptable limits. The rate of contamination has been increasing. The quality of river water, specifically in southern regions with maximal density of population does not correspond to the norms of water use for drinking and fisheries. The governance of natural resources (in particular, forests) and the control of the use of natural resources are below a critical level. The impacts of toxic anthropogenic water contamination, the decline of the human immune system, increasing stresses, impacts of many negative social phenomena connected, among others, to intensification of migration processes, with a high probability will accelerate the negative impacts of climatic change on standards of life and health of the population, as well as enforce undesirable feedbacks.

Two following regional examples present some details. In West Siberia (data from "Russian Federation", 2006)

- annually up to 35 000 breaks of oil pipe lines occur in northern regions of intensive oil and gas extraction;
- from the above total number, ~ 300 are officially registered with oil spills >10 000 t of each;
- tundra surface is destroyed more than at 15%; and
- physical destruction of natural landscapes exceeded >30% of total areas of the territories of middle and southern taiga.

In territories of Yamalo-Nenetsk autonomous okrug (data from the official report on state of environment (2004))

- rivers of the Ob'-Irtish basin belong to 5th and 6th classes of water quality that means "dirty" and "very dirty"; concentration of combination of *Fe, Mn*, oil products, etc. exceeds maximal concentration of pollutants by several ten-fold;
- ecological state of environment is a driver of 80% of sickness;
- parasitic contamination of water and fish substantially increased during the last decades;
- there is a clear destructive impact of industrial intervention on life of indigenous nations.

Data on unsatisfactory ecological situation in large industrial cities, flood-lands of large Siberian regions and quality of water reported in many publications and assessments (e.g., in Proceedings of

Conferences ENVIROMIA and CITES, “Ecology of flood-lands of large Siberian rivers and the Arctic” (Tomsk, 1997, 2008) etc.).

## 4.2. Changes of land use – land cover

Land use-land cover changes in the region are mostly defined by increasing anthropogenic pressure and unsustainable use of natural resources. The latter impacts areas of forests and agricultural lands. As a typical example we present data of dynamic of forest resources in East Siberia.

*Dynamics of forests of East Siberia*. Data of the State Forest Account for 1961-2007 of Krasnoyarsk kray, Republic Khakassia, Taimir and Evenkia Autonomous okrug and has been used for analysis of dynamics of forests in East Siberia (Table 5 and 6). Data of Tables 6 and 7 show that during 45 years the following major changes took place in forests of East Siberia:

- forested areas decreased at 5108.2 thousand ha;
- area of mature and overmature coniferous and deciduous forests decreased at 17210.4 thousand ha (25%) and 1670.5 thousand ha (17%), respectively;
- total growing stock decreased at 3175 million m3’
- exploitable growing stock decreased in coniferous at 3725 million m3 (35%) and increased in deciduous forests at 1%.

Thus, decreasing of quality of forests in East Siberia has been observing during the last 46 years. Major reasons of that are in the practice of harvest of most productive coniferous forests in form of concentrated clear cuts; large forest fires and outbreaks of dangerous insects which damage coniferous forests.

***Table 5.*** *Dynamics of total forest fund and forested area in East Siberia (thousand ha).*

| Year of SFA | Total FF area | Including forested area | | | | |
|---|---|---|---|---|---|---|
| | | total | coniferous | incl. mature and overmature | deciduous | incl. mature and overmature |
| 1961 | 145360.9 | 107154.8 | 87609.1 | 69613.2 | 18506.6 | 9981.8 |
| 1973 | 144940.6 | 108271.2 | 89615.9 | 70421.2 | 17648.1 | 9318.2 |
| 1988 | 161760.5 | 112355.4 | 93951.7 | 72552.7 | 17310.6 | 7876.8 |
| 1993 | 159759.5 | 103624.2 | 80929.6 | 54766.1 | 15778.0 | 7804.9 |
| 1998 | 159781.8 | 104639.9 | 81324.7 | 54179.2 | 16324.2 | 8003.5 |
| 2003 | 164636.6 | 106421.5 | 82353.0 | 53608.7 | 17025.1 | 8454.2 |
| 2007 | 155684.2 | 102046.6 | 79081.7 | 52402.8 | 15973.7 | 8311.3 |
| change | +10323.3 | –5108.2 | –8527.4 | –17210.4 | –2532.9 | –1670.5 |

***Table 6.*** *Dynamics of growing stock of forests of East Siberia (million $m^3$).*

| Year of SFA | Total growing stock | coniferous | | deciduous | |
|---|---|---|---|---|---|
| | | total | incl. mature and overmature | total | incl. mature and overmature |
| 1961 | 14352.53 | 12705.70 | 10612.29 | 1627.61 | 1088.98 |
| 1973 | 13511.13 | 11903.36 | 9946.96 | 1590.69 | 1117.59 |
| 1988 | 13824.22 | 12281.85 | 10051.58 | 1524.19 | 971.32 |
| 1993 | 11740.30 | 10175.19 | 7417.26 | 1542.12 | 1026.47 |
| 1998 | 11734.22 | 10114.29 | 7327.16 | 1596.34 | 1074.39 |
| 2003 | 11906.95 | 10222.13 | 7150.2 | 1661.06 | 1126.29 |
| 2007 | 11177.54 | 9595.70 | 6887.23 | 1558.58 | 1099.12 |
| Change | –3174.99 | –3110.00 | –3725.06 | +69.03 | +10.14 |

Air pollution of large industrial centers provides negative impacts on surrounding ecosystems. Emissions of sulphur dioxide of the Norilsk metallurgical plant, probable the biggest emitters over the globe, exceed 2 million t annually. This resulted in development of about 2 million ha of technogenic desert, of which about 500 thousand of forests.

# 5. Impacts on Ecosystem State, Dynamics and Productivity

The current and future impacts of global change on ecosystem state, dynamics and productivity are heterogeneous and depend upon complicated interaction of different drivers. They include both positive and negative consequences and features.
The major positive expectations include:

- potential increase of productivity due to climatic trends; and
- potential expansion of agricultural lands,

and the negative consequences include:

- loss of soil fertility;
- increase of frequency of years with crop failure;
- increase of outbreaks of pests and diseases; and
- acceleration of natural disturbances.

## 5.1. Impact on productivity

It is expected that the warming trend will support productivity of agriculture and forests, at least in some regions (particularly, in West Siberia). Climatic models predict that bioclimatic potential for agriculture will increase by 20% in the Russian Far East and up to 50% in West Siberia. Application of Dynamic Global Vegetation Models (DGVM) to regional forests provided by the EU-funded project SIBERIA-II (Multi-Sensor Concept for Greenhouse Gas Accounting in Northern Eurasia, 2002-2005) shows that warming will impact major indicators of productivity (Fig. 11).

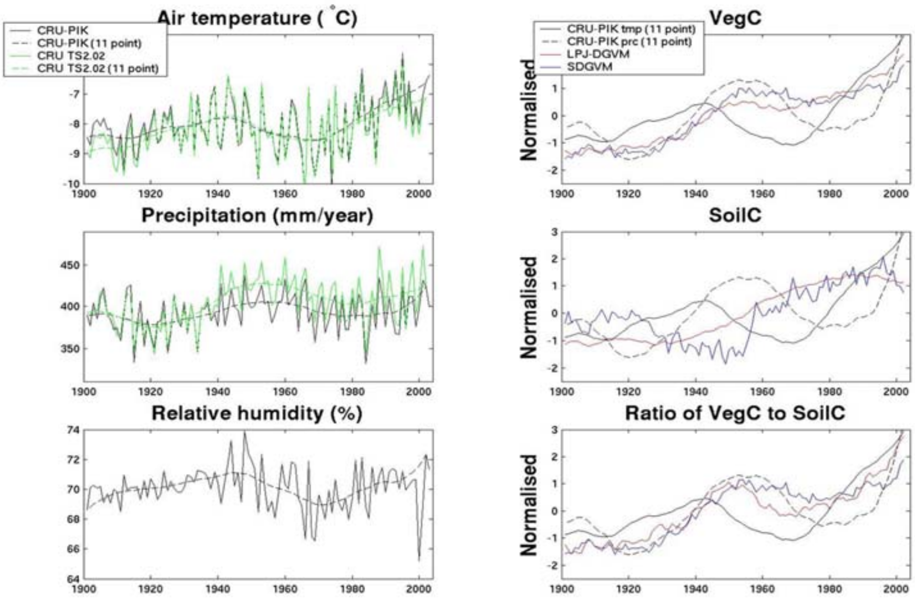

***Fig. 11**. Impacts of climatic indicators on ecological parameters of ecosystems. Climatic data are calculated based on CRU-PIK and CRU TS.02 databases. Estimates were done using the LPJ and Sheffield Dynamic Global Vegetation Models.*

However, it is very likely that increasing variability of climate will provide for agriculture more negative problems than the overall positive impacts of warming trends. A number of modelling forecasts report that the number of years with crop failure (more than 50% of the many year average) will increase 2-fold by 2020 and 3-fold by 2070.

Modeling of responses and feedbacks of terrestrial biota to climate change requires diverse empirical data. Important results on productivity of terrestrial ecosystems, particularly for forests, have been received during the last decade. Detailed estimates of gross and net growth, mortality, live biomass, and NPP of the terrestrial vegetation at the regional and country scale attempting at estimating of uncertainties of the results were done by IIASA together with Siberian institutions. All indicators were estimated in a consistent way using information of the State Forest Account (SFA) - 2003 by each forest enterprises of the region by a definite date based on a specially developed modeling system. The system includes: (1) regionally distributed models of growth of stands of major forest forming species; (2) multi-dimensional models of live biomass (phytomass) and (3) models of biological production of forest ecosystems. Uncertainties of the results were analyzed with an approach developed by the International Institute for Applied Systems Analysis for large-scale complicated ecological tasks which do not allow direct formal verification. Table 7 and 8 contain estimate of live biomass and Net Primary Production of East Siberian forests by beginning of the 3rd Millennium. Spatial distribution of NPP of all vegetation classes is presented in Figure 12.

***Table 7.*** *Live biomass of forests of East Siberia. Data are expressed in Tg = $10^6$ t of dry matter.*

| Species and groups of species | Live biomass by components, Tg dry matter | | | | | | | Total | incl. GP |
|---|---|---|---|---|---|---|---|---|---|
| | Stem | incl. bark | Branches | Foliage | Roots | US | GFL | | |
| Krasnoyarsk kray | | | | | | | | | |
| Coniferous | 2792.4 | 360.1 | 441.0 | 184.0 | 980.4 | 105.1 | 190.0 | 4693.0 | 291.5 |
| Pine | 754.2 | 73.0 | 118.5 | 46.5 | 270.4 | 16.6 | 80.4 | 1286.6 | 83.6 |
| Spruce | 337.1 | 49.9 | 56.4 | 29.9 | 195.4 | 24.6 | 29.2 | 672.5 | 49.0 |
| Fir | 405.3 | 51.6 | 79.1 | 44.6 | 92.3 | 13.2 | 15.6 | 650.1 | 54.8 |
| Larch | 553.0 | 93.7 | 66.2 | 13.6 | 218.3 | 16.8 | 26.3 | 894.3 | 29.2 |
| Cedar | 742.9 | 91.9 | 120.8 | 49.5 | 204.0 | 34.0 | 38.5 | 1189.6 | 75.1 |
| SWD | 777.4 | 130.4 | 165.8 | 32.8 | 271.5 | 36.4 | 57.5 | 1341.4 | 66.7 |
| Incl. birch | 605.0 | 103.2 | 129.2 | 27.1 | 211.3 | 30.6 | 47.9 | 1050.9 | 55.4 |
| Aspen | 171.8 | 27.0 | 36.5 | 5.6 | 59.9 | 5.8 | 9.5 | 289.2 | 11.1 |
| Others | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 |
| Shrubs | 0.0 | 0.0 | 5.2 | 2.3 | 4.1 | 0.0 | 3.1 | 14.7 | 3.5 |
| **Total** | **3569.8** | **490.5** | **612.1** | **219.2** | **1256.0** | **141.6** | **250.6** | **6049.2** | **361.9** |
| Taimir AO | | | | | | | | | |
| Coniferous | 46.6 | 8.9 | 7.5 | 1.8 | 25.3 | 5.2 | 12.8 | 99.2 | 8.5 |
| Spruce | 5.5 | 0.9 | 1.1 | 0.6 | 3.7 | 1.0 | 1.4 | 13.2 | 1.5 |
| Larch | 41.1 | 8.0 | 6.4 | 1.2 | 21.6 | 4.2 | 11.4 | 86.0 | 7.0 |
| SWD | 0.8 | 0.1 | 0.2 | 0.0 | 0.4 | 0.2 | 0.3 | 1.8 | 0.2 |
| Birch | 0.8 | 0.1 | 0.2 | 0.0 | 0.4 | 0.2 | 0.3 | 1.8 | 0.2 |
| Shrubs | 0.0 | 0.0 | 4.1 | 1.8 | 3.2 | 0.0 | 7.4 | 16.5 | 4.8 |
| **Total** | **47.4** | **9.1** | **11.8** | **3.7** | **28.9** | **5.4** | **20.5** | **117.6** | **13.5** |
| Evenkia AO | | | | | | | | | |
| Coniferous | 1878.5 | 315.9 | 249.1 | 68.4 | 745.2 | 85.7 | 187.0 | 3214.0 | 168.9 |
| Pine | 202.2 | 23.5 | 24.0 | 15.5 | 43.6 | 5.5 | 29.3 | 320.1 | 28.9 |
| Spruce | 43.8 | 6.5 | 7.4 | 3.8 | 25.4 | 5.1 | 5.8 | 91.4 | 7.7 |
| Fir | 1.1 | 0.1 | 0.2 | 0.1 | 0.3 | 0.1 | 0.1 | 1.9 | 0.2 |
| Larch | 1505.0 | 269.5 | 197.5 | 41.2 | 640.7 | 67.6 | 143.6 | 2595.6 | 118.9 |
| Cedar | 126.4 | 16.2 | 20.0 | 7.8 | 35.3 | 7.4 | 8.2 | 205.1 | 13.3 |
| SWD | 88.4 | 16.5 | 19.6 | 4.2 | 38.8 | 8.3 | 12.9 | 172.3 | 11.9 |
| Incl. birch | 84.9 | 15.8 | 18.7 | 4.1 | 37.6 | 8.1 | 12.6 | 165.9 | 11.6 |
| Aspen | 3.6 | 0.6 | 0.9 | 0.1 | 1.3 | 0.2 | 0.4 | 6.4 | 0.3 |
| Shrubs | 0.0 | 0.0 | 10.7 | 4.7 | 8.3 | 0.0 | 24.8 | 48.5 | 14.6 |
| **Total** | **1966.9** | **332.3** | **279.4** | **77.4** | **792.4** | **94.0** | **224.7** | **3434.8** | **195.5** |

Comprehensive analysis of uncertainties gave the following results. Inventory based growing stock volume for the country as a whole had a bias that changed over the period of the study, from about +7% in the 1960s to 0 around the 1980s. During the last two decades, the data of the SFA underestimate the total growing stock over the country on average approximately 3-4% with a larger bias (4-6%) in the European part and at +2-3% in Asian Russia. Currently available information does not allow us to make any more accurate conclusions. Regional data are more uncertain due to diversity of local impacts which cannot be properly quantified. An overall conclusion is that the total live biomass of forests of large regions is defined with uncertainty ±4-6% (here and below CI=0.9), NPP ±7-12%, net and gross growth ±5-7%, mortality ±10-15%, and the last three indicators, defined in this study, likely contain a small (of about 1-3 percent) bias.

***Table 8.*** *Net Primary Production of forests of East Siberia (Tg C year$^{-1}$)*

| Species and groups of species | NPP by components of live biomass, Tg C/year | | | | | | | NPP, total | Incl. GP |
|---|---|---|---|---|---|---|---|---|---|
| | Stem | incl. bark | Branches | Foliage | Roots | US | GFL | | |
| Krasnoyarsk kray | | | | | | | | | |
| Coniferous | 10.7 | 4.1 | 31.3 | 36.8 | 11.9 | 23.9 | 118.7 | 316 | 44.4 |
| Pine | 4.4 | 0.9 | 6.5 | 6.2 | 1.6 | 9.3 | 28.9 | 286 | 10.7 |
| Spruce | 1.0 | 0.6 | 4.3 | 7.9 | 2.6 | 3.5 | 19.9 | 323 | 6.5 |
| Fir | 2.0 | 0.9 | 4.5 | 4.4 | 1.8 | 2.4 | 16.0 | 267 | 6.0 |
| Larch | 1.1 | 0.5 | 7.4 | 6.8 | 1.3 | 2.7 | 19.9 | 302 | 8.9 |
| Cedar | 2.3 | 1.2 | 8.5 | 11.4 | 4.6 | 5.9 | 34.0 | 389 | 12.2 |
| SWD | 8.6 | 2.3 | 13.2 | 12.4 | 5.0 | 9.1 | 50.6 | 362 | 18.3 |
| Incl. birch | 7.0 | 1.9 | 11.3 | 9.9 | 4.2 | 7.6 | 41.9 | 366 | 15.6 |
| Aspen | 1.5 | 0.4 | 1.9 | 2.5 | 0.8 | 1.5 | 8.6 | 346 | 2.7 |
| Others | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 457 | 0.0 |
| Shrubs | 0.0 | 0.3 | 0.4 | 0.2 | 0.0 | 0.2 | 1.1 | 183 | 0.5 |
| **Total** | **19.3** | **6.8** | **44.9** | **49.4** | **17.0** | **33.2** | **170.5** | **327** | **63.3** |
| Taimir AO | | | | | | | | | |
| Coniferous | 0.1 | 0.0 | 0.5 | 0.6 | 0.4 | 0.9 | 2.6 | 144 | 1.0 |
| Spruce | 0.0 | 0.0 | 0.1 | 0.2 | 0.1 | 0.2 | 0.6 | 321 | 0.2 |
| Larch | 0.1 | 0.0 | 0.4 | 0.4 | 0.3 | 0.7 | 2.0 | 124 | 0.8 |
| SWD | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 290 | 0.0 |
| Birch | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 290 | 0.0 |
| Shrubs | 0.0 | 0.9 | 1.1 | 0.4 | 0.0 | 0.5 | 2.8 | 189 | 1.3 |
| **Total** | **0.1** | **0.9** | **1.6** | **1.1** | **0.5** | **1.4** | **5.5** | **166** | **2.3** |
| Evenkia AO | | | | | | | | | |
| Coniferous | 11.4 | 4.4 | 44.3 | 39.2 | 7.8 | 20.5 | 127.8 | 298 | 54.8 |
| Pine | 1.1 | 0.2 | 1.5 | 1.6 | 0.3 | 2.9 | 7.7 | 201 | 2.8 |
| Spruce | 0.1 | 0.1 | 0.9 | 1.5 | 0.7 | 0.9 | 4.2 | 331 | 1.5 |
| Fir | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 211 | 0.0 |
| Larch | 10.0 | 4.0 | 40.7 | 34.5 | 5.8 | 15.6 | 110.5 | 307 | 48.7 |
| Cedar | 0.2 | 0.1 | 1.2 | 1.7 | 1.0 | 1.2 | 5.3 | 321 | 2.0 |
| SWD | 0.9 | 0.2 | 1.5 | 1.6 | 1.2 | 2.1 | 7.5 | 255 | 2.7 |
| Incl. birch | 0.8 | 0.2 | 1.4 | 1.6 | 1.1 | 2.1 | 7.3 | 253 | 2.6 |
| Aspen | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.1 | 0.2 | 304 | 0.0 |
| Shrubs | 0.0 | 2.9 | 3.5 | 1.3 | 0.0 | 1.6 | 9.4 | 189 | 4.1 |
| **Total** | **12.3** | **7.6** | **49.4** | **42.2** | **9.0** | **24.2** | **144.7** | **285** | **61.8** |
| **Grand total** | **31.7** | **15.3** | **94.9** | **92.7** | **26.5** | **58.8** | **320.7** | **302** | **127.4** |

Major findings of this study lead to a conclusion that major indicators of bioproductivity of terrestrial ecosystems for large regions can be obtained with uncertainties acceptable for assessing dynamic changes in ecosystems due to changing environment. (1) In spite of many substantial gaps of different nature, forest inventory data can be used as a background for assessing major indicators of productivity of Russian forests at regional and country levels. Remotely sensed data are very useful for cognition of the processes driving productivity of forests but still are not accurate enough to be used in practical implementation at the country level. (2) Currently both available scientific basis and models are satisfactory for reliable estimation of basic indicators of productivity of the country's forests. (3) System harmonizing of the results is possible due to (a) use of both unified information basis and consistent modeling system, and (b) multiple constraints based on available independent results.

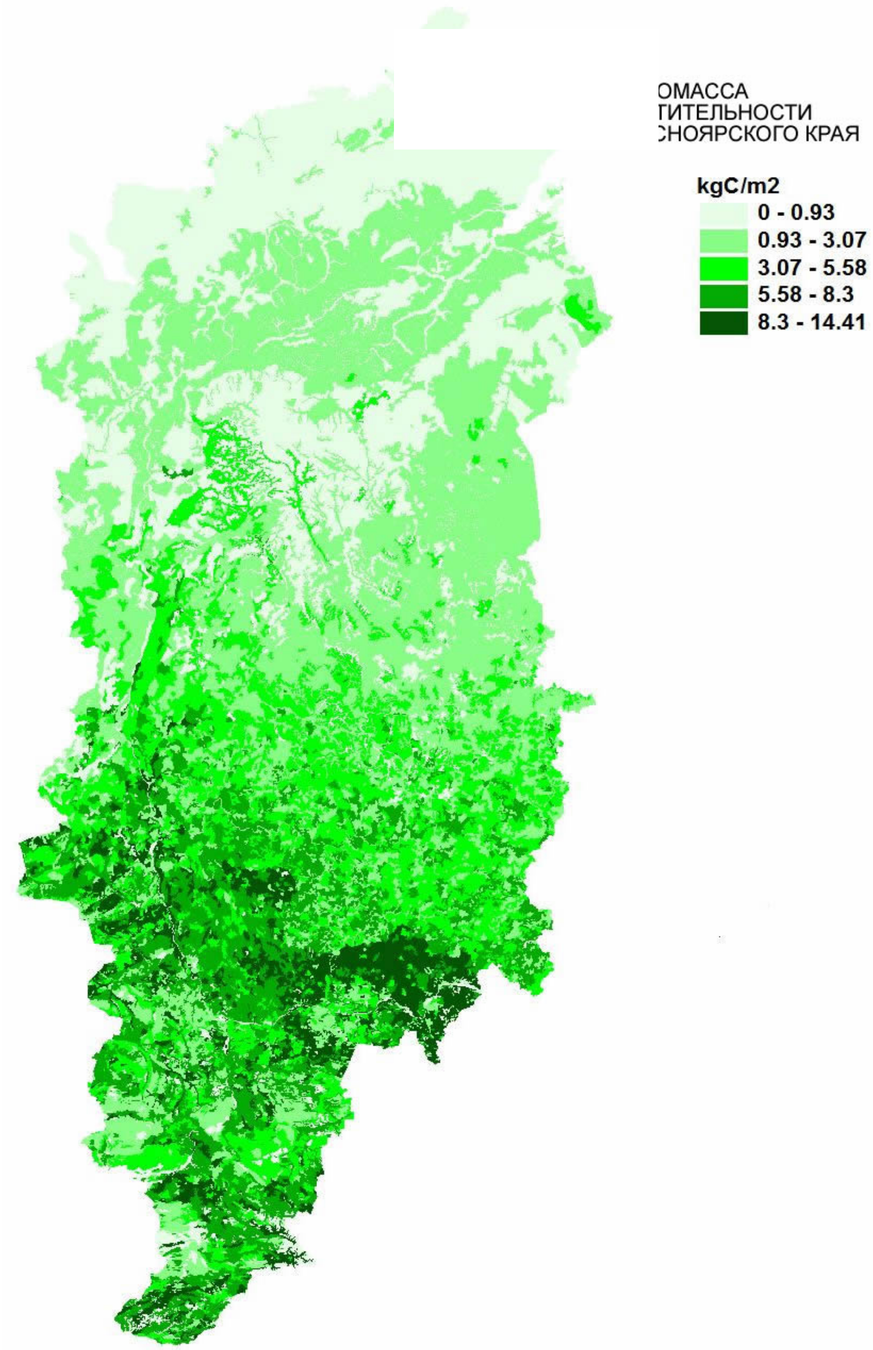

***Fig. 12.*** *Density of live biomass (kg C/m2) of vegetation of Krasnoyarsk kray*

(4) Because all empirical models are based on averaging of measurements for a long period of time, further improving of the results requires either accounting for temporal trends or – preferable - combining “empirical” and “modeling” approaches in order to properly estimate biological productivity of Russian forests in a changing world.

## 5.2. Change of allometric regularities in forest stands

During most of the 20th century, the Northern Hemisphere was subjected to industrial pollution, and changes in regional and global climate. Climatic trends and the atmospheric load of nitrogen and other chemicals were especially significant in Western Europe, Central and North-Eastern US, and North-Western Russia. Live biomass structure depends on ecological condition. Recent studies showed that, over the past four decades, the allometric relationships among various plant parts have changed in the Russian forests. Live biomass structure is important precondition for remote sensing and numerous models.

Analysis of satellite data has revealed an increase in the Normalized Difference Vegetation Index (NDVI) in Eurasia and North America since such observations began in the early 1980s (Myneni *et al.*, 2001; Slayback *et al.*, 2003). Russian forests, which account for more than 70% of all circumpolar boreal forests (FAO, 2001), have undergone substantial greening from the taiga to the forest steppe on the west side of the Ural Mountains and along the zone of the southern taiga in Siberia. To the east of the Ural Mountains, in northern Siberia, the NDVI shows a slight downward trend. Despite negative trends over some regions, averaged over Eurasia as a whole, the seasonally accumulated NDVI shows an increase of ~12% during the 1982–1998 period (Myneni *et al.*, 2001). It has been suggested that this increase in NDVI reflects a large carbon sink in the living woody biomass of Russian forests of ~284 Tg C $yr^{-1}$ over the period 1995–1999 (Myneni *et al.*, 2001). For Russian forest conditions, this figure corresponds to ~560 Tg of dry matter or a net increment of about $1{\cdot}10^9$ $m^3$ of growing stock per year (Shvidenko and Nilsson, 2003). Thus, in line with this estimate, the forests should have increased in growing stock by ~$5{\cdot}10^9$ $m^3$ over this five-year period. However, n a 1998 report, the national forest inventory shows a net increase of only $1.19{\cdot}10^9$ $m^3$ of growing stock as compared with the 1993 inventory (FFSR, 1999). It has been shown that the large discrepancy between forest inventories and satellite-based estimates arises, not from random errors, but from the changes in tree structure and some other changes in the Russian forests. NDVI were calibrated on ground-based estimates of total living biomass (Myneni *et al.*, 2001) to estimate of a carbon sink. This calibration holds true only if the percentage of foliage in the living biomass remains constant. At the same time, in a changing environment (e.g., changes in temperature, nutrient supply, luminosity, water regime), plants are capable of maximizing their productivity by rapidly adjusting the carbon allocation (Bazzaz, 1997).

Live biomass measures are a very labour consumed process and for Russian forests were available 3332 sample plots. The data were collected different researchers in 1953-2002. On those plots, the measurements of live biomass by fractions (made by destructive methods) and measurements of relevant biometric characteristics of forest stands were provided.
Because these measurements were designed for estimating the characteristics of various forest ecosystems and not for detecting temporal trends, the distribution of measurements in time occurred randomly. To obtain representative temporal statistics, these data were aggregated within regions with sufficient numbers of measurements for each age group of tree species with similar plant physiology and for a wide range of forest conditions.

Over the past few decades, all regions of the Russian forests have been subjected to an increase in mean annual temperature (Gruza *et al.*, 2000). Although, in the 20th century, average winter temperatures in the Northern Hemisphere increased at a faster rate than summer temperatures (Folland *et al.*, 2001), during the period 1960 to 2000, the Northern hemispheric summer temperatures became warmer by at least ~1°C. Furthermore, the region of the northern and central taiga and the tree line zone (latitudes >60°N) exhibit a stronger summertime temperature increase than the Northern Hemisphere as a whole or only the lower latitudes (Lugina *et al.*, 2003).
In fact, during the last 40 years, the maximum increase in average summer temperatures of ~2°C was reached in Eastern Siberia (Jones and Moberg, 2003). On the west side of the Ural Mountains, the increase in summer temperature was accompanied by frequent wet spells, resulting in 10–20% increases in mean annual precipitation (Sun and Groisman, 2000), as well as significant increases in summer soil moisture (Robock *et al.*, 2000), river runoff, and groundwater level (Georgievsky *et al.*, 1996). A smaller increase in mean annual precipitation has occurred in forest ecosystems in the watershed regions of the large Siberian rivers in the southern taiga. A substantial decrease in the number of summer days with precipitation and a weak trend of decreasing annual precipitation was observed in the northern taiga of Siberia (Sun and Groisman, 2000; Gruza *et al.*, 2000). Overall, we

can conclude that the surface temperature has increased over all areas of Russian forests, while the precipitation has increased in the southern taiga zone of European Russia and parts of West Siberia, and has decreased in the northern and central taiga in Siberia.

One of the integral climatic indicators often used to detect possible water stress (or its absence) in plants is the Palmer Drought Severity Index (PDSI (Palmer, 1965). The negative PDSI values reflect prolonged drought, while values greater than zero reflect normal or wet spell conditions. Analysis of empirical orthogonal functions of this index reveals that, since 1950 most changes in PDSI in Siberia can be explained by linear trends towards drier conditions. Within European Russia and the southern taiga of Siberia, the index has remained constant or increased slightly towards wetter conditions (Dai *et al.*, 2004). The PDSI is positively correlated with changes in vapour pressure deficit, soil moisture, and runoff (Dai *et al.*, 2004). Therefore, we can use temporal changes in this index as a potential indicator of resulting changes in the water regime of trees. Here, we have employed the Global Data Set of the PSDI for 1870–2002 (Dai *et al.*, 2004), and calculated linear trends of PDSI (Table 9) within practically the same geographic regions where we estimated trends in the allocation of carbon among tree parts. Our analysis indicates that regional trends in PDSI are closely correlated with changes in green parts of living forest biomass.

***Table 9.*** *Estimates of the area-averaged, 1950–2000 mean annual PDSI, their standard deviations and trends.*

| Region | Mean annual (1950–2000) | Standard deviation (1950–2000) | Trend/50 years |
|---|---|---|---|
| 1. West North and Central Taiga | 0.04 | 1.46 | -0.50 |
| 2. West South Taiga | 0.10 | 1.26 | 0.60 |
| 3. West Forest Steppe | 0.09 | 1.25 | 0.53 |
| 4. East North and Central Taiga | -0.63 | 0.98 | -2.08 |
| 5. East South Taiga | -0.41 | 1.13 | -1.74 |
| 6. East Forest Steppe | -0.13 | 1.60 | -0.70 |
| Area-average for all regions | -0.27 | 0.74 | -1.01 |

In order to separate the possible effect of *Time* from the effect of other variables, *Age* and *RS* of tree stands have been included into the analysis. Because the dominating part of trends in surface temperature and PDSI can be explained by linear trends (Dai *et al.*, 2004), it makes sense to look for a possible response of green parts (as the fraction most sensitive to changes in temperature and hydrologic balance) in the same functional form.

Therefore, a simple multiple linear regression model with intercept could be used:

$$R_i = a \times Age + b \times RS + c \times Time + d \quad , \qquad (1)$$

where $R_i$ is an aggregated *i* biomass fraction expressed in metric tons per cubic metre of growing stock of the green parts ($R_1$), aboveground wood ($R_2$), and roots ($R_3$); *Age* and *RS* are age (20–200 years) and relative stocking of stands (0.3–1.0), respectively; *Time* is the year of measurement from 1953 to 2002; and *a, b, c, d* are regression coefficients, where *c* is the estimate of temporal trend of tree fraction $R_i$.

Overall, within the whole forest (average of all regions and species), we detect a significant increase in the fraction of green parts (Fig. 13).

A more detailed statistical analysis revealed a strong increase in the fraction of green parts in European Russia among the dark coniferous species of the northern and central taiga, the light coniferous species of the southern taiga, and the deciduous species of the forest steppe. A smaller but statistically significant increase in the fraction of green parts among light coniferous species was found in the Siberian southern taiga. A decline in the fraction of green parts and an increase in the fractions of aboveground wood and roots were detected in the predominantly larch forests of the northern and central taiga in Siberia. The area-averaged trends in PDSI show direct proportionality to regional trends in green parts (Fig. 14).

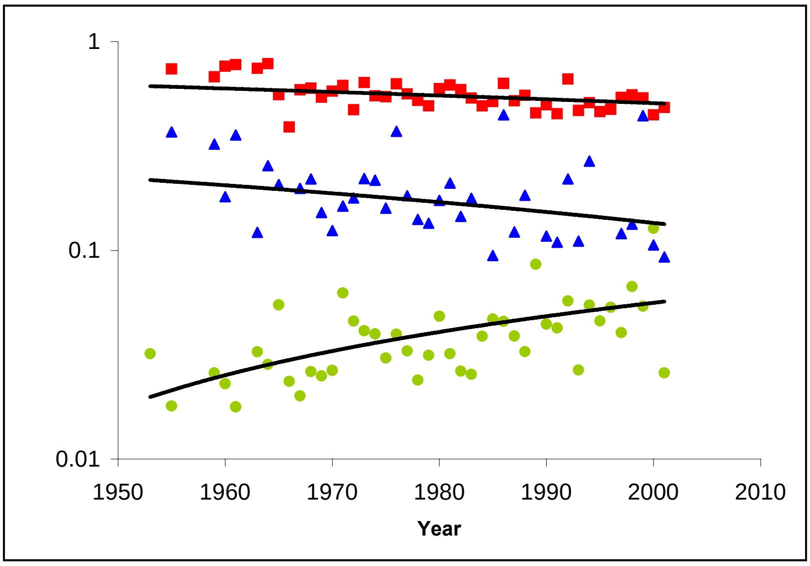

***Fig. 13.*** *Apparent changes in phytomass fractions at sample plots in the Russian forests [tons per m$^3$ of growing stock]. Green circles represent the fraction of green parts; red squares, the fraction of aboveground wood (stem and branches); and blue triangles, the fraction of roots.*

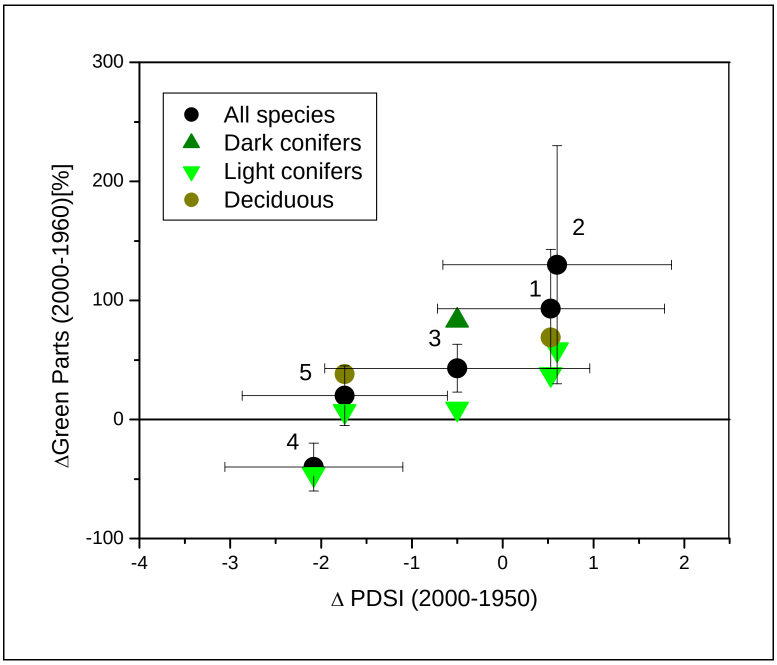

***Fig. 14.*** *The area-averaged trends in green parts versus PDSI trends as estimated over regions (region 4 and 5 – northern and southern parts of Siberia, respectively). Significant trends were found in each of the five regions for the majority of species (all species combined) and for the dominant groups of species in a given region. Horizontal and vertical error bars represent the 0.9 confidence interval of estimates for PSDI and the green parts, respectively.*

These results are in agreement with the current theory of resource allocation in plants (Reekie and Bazzaz, 1987). According to this theory, a non-structural carbon (e.g., sugars) is considered the appropriate currency of allocation and cost, and is used to “purchase” other resources essential for plant functions (Grifford and Evans, 1981). Analysis of a large quantity of data demonstrates that trees increase their investment in photosynthetic tissue relative to the water-conducting tissue in the stem (sapwood) as the environment becomes wetter (Mencuccini and Grace, 1995; DeLucia *et al.*, 2000; Mencuccini, 2003). Earlier works have shown that the leaf area index is driven mostly by the local water balance (Grier and Running, 1977; Gholz, 1982). The overall conclusion of all these studies is that a given species of tree can afford a larger crown in moist regions than in arid regions where it must invest more carbon in roots and sapwood.

However, in three of the five regions of the Russian forests that we analyzed, the PDSI demonstrates a trend towards aridity even though regions 1 and 3 showed increased greenness for negative PDSI values. Therefore, if the water regime was the only factor influencing changes in the allocation of carbon to green parts, the relationship shown in Figure 14 would cross the center of the coordinates and we would see a decline in the average fraction of green parts in the Russian forests. Because this relationship passes above the center of the coordinates at zero PDSI (a result that is statistically significant for the average among species — black circles in Figure 14), on can conclude that a small increase in aridity over the northern taiga and over the forest steppe region of western Russia was compensated by some other environmental change, which caused an increase in carbon allocation to green parts. As stated above, analysis of the geographic distribution of allometric ratios demonstrate that coniferous species has a tendency to increase the allocation to foliage as the annual mean temperature increases (Palmroth *et al.*, 1999; Gregg, 1994; Bongarten and Teskey, 1987). This fact can be explained by the temperature-induced decline in the hydraulic resistance of stems and roots (Mencuccini, 2003). Thus, it might be “cost efficient” for trees to support a larger crown as the temperature increases. As some modelling studies have shown, depending on the soil moisture and structure, an increase in the mean annual temperature of ~2$^o$C might cause 10–100% increase in the leaf-to-sapwood ratio (Magnani *et al.*, 2002). Therefore, the increase in surface temperatures could be the main factor that caused the overall increase in the fraction of green parts in living biomass. Some other factors, such as atmospheric depositions of nitrogen (particularly in European Russia) or an increase in the atmospheric concentration of $CO_2$, might contribute to the increase in the fraction of green parts. Meta-analysis of long-term experiments on the fertilization of boreal forests with nitrogen demonstrates a decline in the hydraulic efficiency of trees, which allows for the development of a larger photosynthetic apparatus and increases the resistance of trees to drought (Mencuccini, 2003). An increase in atmospheric $CO_2$ effects stomata opening and improves the drought resistance of plants as well (Mencuccini, 2003). A significant increase in atmospheric $CO_2$ (doubling the pre-industrial concentration) might lead to early maturation of plants and an increase in their fecundity. For example, in four-year $CO_2$ fertilization experiments (Duke Forest, NC USA), the average stem diameter of loblolly pine trees reaching maturity declined, while the allocation of carbon to cones increased by ~30–100% (LaDeau and Clark, 2001). However, since 1960, the atmospheric $CO_2$ concentration has increased by only 18% (Keeling and Whorf, 2004).

Because increased temperature, atmospheric $CO_2$, and nitrogen deposition are all favourable to the allocation to leaves and needles, any of these factors could contribute to the observed changes in biomass fractions in the Russian forest. At the same time, taking into account the magnitude of these changes, the increase in the annual mean temperature and variations in the aridity are the two most probable explanations of the strong linear proportionality between the area-averaged PDSI trends and regional trends in green parts (Fig. 14). Therefore, we conclude that over the last four decades, the Russian forests have demonstrated an acclimation to recent climate change through the increase in the share of foliage (leaves and needles) and some decrease in the shares of stem wood and roots. According to these estimates of changes in the carbon density of various tree parts, however, the rates of increase in carbon density of stem wood and roots are 3–5 times smaller than the rate of increase in the carbon density of green parts and the rate of increase in the seasonally accumulated Eurasian NDVI (Fig. 15).

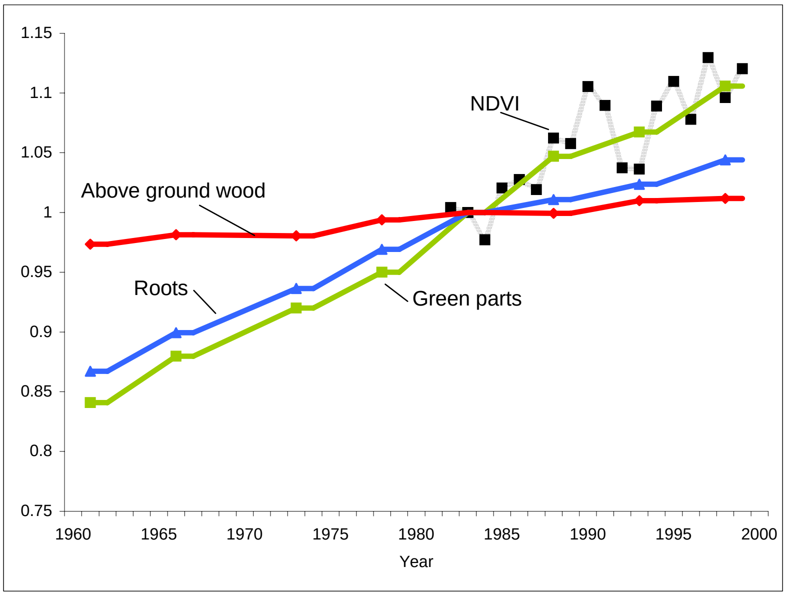

***Fig. 15.*** *Estimates of area-averaged carbon densities of green parts (leaves, needles as well as understory and green forest floor), aboveground wood, and roots in the Russian forests based on data of national forest. These results reflect on changes in the allometric ratios as well as all documented changes of Russian forests, which explain some differences of the relationships comparatively to Figure 1. All data, including the area-averaged seasonally accumulated NDVI over Eurasia (Myneni et al., 2001), were normalized to their 1983 values.*

The difference in the geographic area of carbon density and NDVI estimates (the Russian forest versus the whole of Eurasia) is unlikely to be a reason for such a large difference since the Russian forest represents most of Eurasian forests. At the same time, the normalized trend in carbon density of green parts practically coincides with the area-averaged normalized NDVI trend. Therefore, these data provide the only known independent line of evidence in support of the Eurasian NDVI trend to date. In other words, these data point to the fact that ~12% increase in the Eurasian NDVI coincided in time with a similar (~10%) increase in the biomass of green parts of the whole Russian forest. Because the green parts are responsible almost all Net Primary Production (NPP) of forest ecosystems, these results suggest that the recently observed significant increase in the apparent NPP of Russian forests (Nemani *et al.*, 2003; Slayback *et al.*, 2003) has been mostly caused by the shift of carbon allocation towards the leaf tissues. As an overall conclusion, use of recognized regularities is important for organizing reliable monitoring of Siberian forests by remote sensing methods.

## 5.3. Shifting of vegetation zones

The discussed above substantial climate change will inevitably impact zonal distribution of vegetation. It is necessary to point out that shifting climatic conditions (which would be favourable for forests) to the north, does not mean the shift of actual forest vegetation due to limitations of spatial distribution of trees: many studies support the fact that rates of distribution of tree species are in limits of tens, rarely one-two hundred meter per year.

Due to a number of modelling results (Tchebakova *et al.*, 2003; Pleshikov *et al.*, 2002), the process of shifting of climatic zones will result in a substantial (in some assessments – two-fold by the end of the century) decrease of forested area, increase of steppes and, specifically, a substantial increase in the area of desertified steppes. This will negatively impact biodiversity, standard of life of local population and conditions for wild animals.

## 5.4. Increase of extent, severity and frequency of disturbances

One of the most dramatic expected impacts of global change is substantial increase of extent, severity and frequency of disturbances such as wild fire and outbreaks of dangerous insects and impacts. Historically, disturbances were a major driver of development and dynamics of boreal forests. Already now post fire successions comprise in the taiga zone from 20 to 50% of forest land in middle and southern taiga zones of Central Siberia (Vashchuk and Shvidenko, 2006).

The warming during the last decade presented impressive examples of possible acceleration of disturbances in Siberia. Due to satellite assessments, the annual area of vegetation fires exceeded 10 million ha in 1997-2005. The areas of wild fire on forest land in 1998 comprised about 12 million ha and in 2003 – 17 million ha (Fig. 16). The amount of consumed fuel and severity of fire were very high. Estimates of carbon emissions were estimated at 160-210 Tg C in 1998 and about 230 Tg C in 2003.

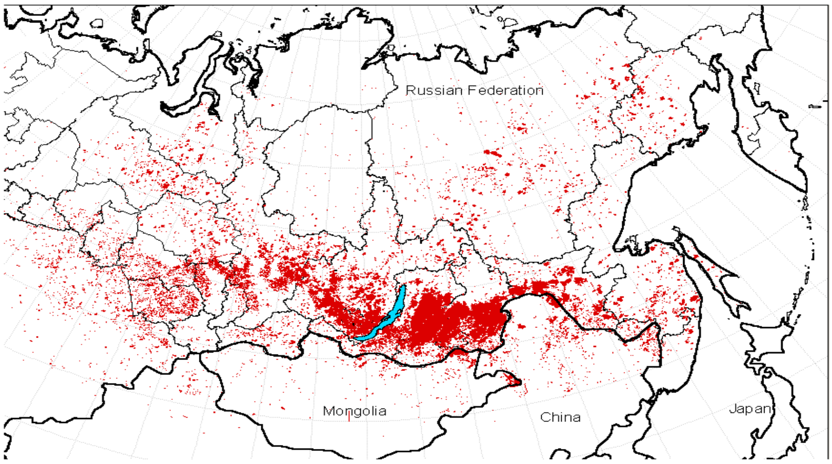
April - November of 2003 year. The total hot spots distribution in Siberia and Far East . NOAA/AVHRR 12,15,16
Center of Remote Sensing. Institute of solar-terrestrial physics SB RAS.

***Fig. 16.** Areas of vegetation fire in Asian Russia in 2003*

Assessing the negative consequences of disturbances, particularly forest fires, researchers usually limit the consideration of the problem to the relatively short period of time that is presumably needed for restoration of the destroyed biotope. The impacts and consequences considered include direct fire-related loss of biological resources and commercial products, the rate and capacity of biological resources restoration, emissions of carbon and other pyrogenic products, specific features of the destruction of existing phytocenosis and formation of initial post fire stands, etc.

It is commonly believed that post-fire rehabilitation leads to the formation of a new stand whose structure and composition would be very close to those of the pre-fire stand, and where the negative consequences of fire are extinguished and graded in a relatively short period of time. The philosophical background of this approach stems from the reversible nature of pyrogenic disturbances of forest ecosystems. However, recent studies have indicated that post-pyrogenic consequences of forest fires are cumulative in nature. Based on the fire's duration and severity, the level of the fire's concentration over territories, landscapes' and ecosystems' specifics, etc., the transformation of historically stabilized ecological processes is observed in all ramifications, including both biotic and abiotic components.

The above transformation and irreversible character of changes in forest ecosystems particularly becomes evident after so-called *catastrophic fires* (Yefremov and Shvidenko, 2004). Catastrophic forest fires mean fires covering an area of more than 10,000 ha, resulting in the total destruction of vegetation and organgenic horizons of soils, or the simultaneous occurrence of several fires of the same total area and intensity over a total area of 1,000 km$^2$ (Sheshukov, 1971). The term *catastrophic* is sometimes used in a different but close context. The classification of post fire catastrophic "traumatism" by A.Sapozhnikov (1984) includes the highest level of a fire's impacts on forest ecosystems and the following destruction of the soil cover, intensive soil erosion, and development of stone fields in mountains. After such fires, the forests are destroyed completely, and are not restored before new soils are generated. For this class, the loss of potential productive forest land is estimated at more than 80% and lasts for a period of over 20 years (Sapozhnikov, 1984). Shvidenko and Nilsson (2003) used the term *catastrophic fire year* as a year for which the extent of fire is more than three-fold to the multi-year average and where the severity of fire is extremely high. Such fires provide irreversible (for the period more than 100 years) change of the ecotope as well as provide the long-term environmental impacts on natural landscapes as a whole; impact of major biogeochemical cycles; and often cause "green desertification" over large territories.

Long-term pyrogenic consequences are the irreversible transformation of the forest environment, which is obvious beyond the restoration period of an indigenous forest ecosystem, i.e. exceeds the lifetime of major forest forming species (i.e., ranging from 150-400 years for major forest forming species of the Asian part of Russia).

Asian Russia has a clearly expressed geographical distribution of forests and specific nature of forest growing conditions that causes the high burning ability of forests. It makes this region an ideal model for studying the patterns and roles of forest fires in the evolution of forest vegetation and their input into global processes.

For boreal forests, fires have always been the main factor determining forest-forming and forest-producing processes and specifics of succession regularities. Based on the retrospective analysis of the vegetation cover structure, taking into account the presence of charcoal in soil horizons and native bed rock depositions, one can conclude that catastrophic forest fires have occurred over the entire quaternary period. Peaks of the highest forest fire occurrence coincided with droughts and peaks of solar activity, as their frequency was between 40 to 80 years. In recent years, there has been a trend toward an increased magnitude and frequency of catastrophic fire occurrence. In particular, over the last 40 years, catastrophic forest fire occurrence was observed in different regions of the taiga zone in 1976, 1988, 1998, 2003, i.e. every 10–12 years with the evident increase during the two recent decades.

Climate is a major driver of increasing frequency and severity of forest fire. However, there appear to be a clear link between the increased magnitude of catastrophic fires and enhanced anthropogenic impacts on forests. The history of linear trends prior and after the 1980s clearly shows an increased level of natural fire incidence, which might be viewed as an increase in the share of forest fire caused by anthropogenic factors. If we assume the indicators of burning given in Table 10 as the rate of natural forest fire regimes, we observe a dramatic prevalence in the rate of actual fire occurrence during recent decades over the rate of (mostly) natural fire occurrence of the previous periods, as well as an extensive destructive effect of forest fires regarding to the total forest fund area and, in particular, to local forest areas affected by repeated forest fires.

For example, in Khabarovsk Kray alone, due to official statistics, 1,314 forest fires, which occurred there in 1998, affected 2.7 million ha or 3% of the total forest fund area. The fires were concentrated on an area of some 15 million ha. The severity of fire was extremely high and significant areas (estimated at 0.4 million ha) have lost organogenic horizons of soils almost completely (Kulikov, 1998). It is worth to mention that the data of official forest fire statistics are substantially underestimated (Shvidenko and Goldammer, 2001), and the real area enveloped by fire in 2003 is about 10 times higher (Vashchuk and Shvidenko, 2006). However, under any estimates, it is evident, that fires of that magnitude should be viewed as a pyrogenic disaster beyond a regional context, with century-long biotic, environmental, and socio-economic consequences.

***Table 10.*** *The actual and ecologically acceptable norm of fire occurrence rates (in percent) by forest formations of taiga zone.*

| **Indicators** | **Rate of burning**[a] |
|---|---|
| Actual overall average annual fire occurrence rate | 0.35 (1.0-1.3 during catastrophic years) |
| Maximum | 4.0 |
| Minimum | 0.02 |
| Evolutionary acceptable rate of burning for main forest formations | |
| Dwarf pine forest | 0.01 |
| Spruce - fir forest | 0.1 |
| Cedar - broadleaf forest | 0.07 |
| Hardwood deciduous forest | 0.2 |
| Larch forest | 0.3 |
| Forests of river valley | 0.5 |
| Softwood deciduous forest | 0.3 |
| Grass-meadow communities | 0.6 |

[a] Rate of burning is calculated as a ratio (in %) of the total fire-affected forested area to total forest land of individual forest formation.

Generally, the long-term environmental consequences of catastrophic forest fires became apparent in the following aspects (Yefremov and Shvidenko, 2004):

- a significant (up to several times) decrease of the biological productivity of forest lands due to the destruction of the indigenous ecotope and replacement of indigenous vegetation formations;
- irreversible changes in the cryogenic regime of soils and rocks;
- change of long-term amplitude of hydrothermal indicators beyond natural fluctuation;
- changes of multi-year average hydrothermal and bio-chemical indicators of aquatic and sediment runoff, as well as of hydrological regimes and channel processes of water streams;
- accumulative impacts on atmospheric processes resulting in global climate change;
- acceleration of large scale outbreaks of insects and disease;
- irreversible loss of biodiversity including rare and threatened flora and fauna species;
- transboundary water and air transfer of pyrogenic products; and
- change of historical migration routes for migratory birds, ground and water animals.

Losing forest-producing lands is the most pronounced negative post-fire consequence of catastrophic forest fires. It leads to a dramatic degradation of the indigenous ecotopes up to the irreversible and complete loss of forest-producing potential. There is a pronounced statistical link between deforestation of lands and a forest fire occurrence rate (Yefremov and Shvidenko, 2004). In particular, the correlation coefficient between the share of unforested areas and a forest fire occurrence rate is estimated to be 0.49 (0.05 level of statistical significance) (Sheingauz, 2001). At the level of forest enterprises, a 1% increase in a forest fire occurrence rate will cause an 8.4% increase in the percentage of forest cover.

By estimates, over the last 50 years, forest fires increased the total area of deforested lands in the Asian part by up to 20 million ha. Generally, single or repeated catastrophic forest fires transform about 30% of highly productive forest land (with a total stock of live biomass of up to 200-300 Mg dry matter per ha) to barren land areas for which forest regeneration is postponed for an indefinitely long period of time. Such lands comprise up to 70% of bogs, 15% of grass-small shrub and shrub lands, 10% of open woodlands, and up to 5% of stone fields and stone outcrops. These territories can only be rehabilitated through targeted and labor consuming meliorations. The natural restoration of forests in these areas requires several hundreds.

The post-fire mechanism of indigenous ecotope transformation is closely linked to the changes of the multi-year average hydrothermal regime of soils. For the southern part of the taiga zone, the average temperature of surface and near-surface subsoils of burned out forested areas is twice as high as the surface's temperature of soils under the forest canopy of areas that have not been affected by fire. Maximum soil temperatures could reach as high as 65°C resulting in a thawing of the near-surface layer of permafrost. The future succession trajectories of such territories depend on climatic peculiarities, properties of landscapes and severity of fire. As usual, given the lack of the forest stands' main drainage capability leads to changes in the water regime of habitats, irreversible swamping or meadow formation or, eventually, to the formation of post-fire stands with a lower productivity. On permafrost of continental territories with an insufficient amount of precipitation, it leads to the development process of northern steppization and replacement of forests by dry steppe and shrub vegetation. Catastrophic fires eventually increase albedo and substantially impact all components of heat balance over large territories.

These changes have been the focus of many studies and are well quantified. Mechanisms and levels of the impacts of forest fire on the hydrological regime and water flow of rivers and, consequently, on spawning conditions for salmon and other valuable fish are less understood. The latter is of major importance for the Russian Far East, e.g., for the Amur River basin. A number of studies identified a linkage between the forest cover percentage in a watershed and annual runoff. Thus, a 10% change in the forest cover percentage in a watershed results in a 1.5-2% change in annual runoff. More importantly, deforestation of watersheds results in a dramatic fluctuation of water levels and flood performance. In addition, large fires impact temperature and contaminate water with ash and products of soil erosion that can lead to the mass mortality of fish.

There are specific features of the impacts of catastrophic fires on major biogeochemical cycles. Many years ratios between ground, peat (sod) and crown fires shift to increasing crown and peat fires. The consumption of fuel is about 1.5 times higher compared to multi-year averages. The total amount of consumed carbon reaches 5–10 folds during catastrophic years. In 1998 the area of fire for entire Russia was estimated to be about 10 million hectares and consumed carbon – about 165 Tg C (Kaji *et al.*, 2002). The increase of peat and sod fires changed the gas composition of emissions increasing the share of methane (up to 2–3%) and carbon monoxide (up to 10–12%). It substantially increased the global warming potential of emissions. The post-fire mortality on areas affected by non-stand replacing fires is on average twice as big as under "normal" fire conditions. Eventually, large previously forested areas can be completely destroyed due to the post fire die-back accelerated by following windfalls. Taking into account the increasing probability of recurrent fires, this situation usually initiates digressive succession developments, which lead to the impoverishment and degradation of forest landscapes.

Another specific feature of catastrophic fires is their impacts on large-scale atmospheric processes, because such impacts appear to be obvious if vast areas are enveloped by hot spots of high concentration. For example, the 1998 summer and autumn fires generated smoke that affected an area of over 500,000 km$^2$. In the southern part of Khabarovsk Kray, the smoke generated by the 1976 autumn forest fires spread over an area that was five to seven times larger than the burning area. The NOAA-5 weather satellite infrared images showed that the haze covered the north-east of China, the southern part of Khabarovsk Kray, the northern Japanese Sea including the Tatar Strait and Sakhalin. This is quite comparable with the scale of impacts of baric systems. For nearly four months during the 1998 summer and autumn catastrophic forest fires, the solar-flux levels at a height of 2 m in the smoke affected area was between 10 to 20 percent under completely fair weather due to light-scattering effects. This reduced the maximum air temperature by 10–15°C and produced a pronounced “nuclear winter” phenomenon.

Observations of atmosphere patterns over the burning and smoking forests in Eastern Siberia and the Far East recognized the presence of anticyclones above huge chunks of Asian territory, from the Yenisei River to the Okhotsk Sea (Sokolova and Teteryatnikova, 2002). These territories where enormous amounts of forest fuels is accumulated and which are characterized by a special atmospheric state, had a large-scale smoke blanket, the size of which was comparable to the extent of baric systems (i.e. over an area of 350–400,000 km$^2$) and which have a long period of high atmospheric pressure. It forces the cyclones to take a southern bypass. The latter is the cause of intensified drought episodes over the fire-affected areas that extenuate the forest fire situation. The presence of anticyclones in temperate latitudes of Eastern Asia both in winter (this is common) and summer time (which is unusual) is due to the increased air density (through the cooling down of near-surface layers caused by the smoke aerosol), and summer anticyclones are duplicating the mechanism of winter ones. Alternatively, such a meteorological situation can generate long periods of rainfall and catastrophic floods like the basin of Yangtze River in summer of 1998.

Analysis of the meteorological processes that is based on pressure charts identified one specific feature. In all the years, when in early summer the usual tropospheric ridges at a baric height of AT-500 came into being in the smoke affected atmosphere, rather than in a clear one, the anticyclones (associated with a drought) persisted in this area over the entire summer. This smoke-affected anticyclone is not destroyed over the entire warm period. Similar spatio-temporal sustainability for the continental ridges that are not affected by smoke aerosol does not exist in contrast to the smoke affected ones. During the summer, the continental tropospheric ridge is being supported by powerful heat fluxes from fire and hot smoke. Only the decreased solar radiation in late summer eliminates the influence of smoke atmospheric aerosol that leads to the gradual destruction of the continental tropospheric ridge.

During catastrophic forest fires, such meteorological conditions occurred in 1954, 1968, 1976, 1988, and 1998 in the Amur River Region, in 1979, 1985, 1998 and 2003 – in the Eastern Siberia (from Krasnoyarsk Kray to Burjatia and Chita regions), in 1996 – in Amur Oblast and in the Republic of Sakha, and in 2002 – in the Republic of Sakha (Sokolova and Teteryatnikova, 2002). Despite an incomplete understanding of the mechanism of the above-mentioned regularities, we could assume that catastrophic forest fires have a substantial influence on the formation and alteration of surrounding parameters of the regional climate, with an apparent effect on global climate through a hierarchy of linkages.

Climate change is linked to the profound transformations of biotic processes. In particular, in recent years, for the first time in its history, Khabarovsk Kray faced an intensive outbreak of gypsy moss (*Limantria dispar*) on an area of some 8 million ha. There is evidence that this phenomenon is an aftereffect of the pyrogenic disaster of 1998. It is worth to note that the synergism of fire and biotic disturbances is typical for whole Northern Eurasia. Hence, the outbreak of Siberian eggar (*Dendrolimus superans sibiricus*) impacted from 8 to 10 million hectares in Saha Republic in 2001-2002 under similar conditions.

Negative impacts of catastrophic fires on biodiversity is evident (Kulikov, 1998), in particular, at ecotones’ boundaries and boundaries of natural habitats of animal and plants. They decrease the amount of fodder, lead to fragmentation of habitats and eventually substantially decrease populations of animals, reptiles and birds. Also migrating birds and ungulates now use routes that differ from their traditional ones.

Quantitative data of the impacts of catastrophic forest fires on erosion processes and substantial increase of amount of washed away soils are limited. However, many examples of such impacts are observed in mountain areas and such a redistribution of soil changes both the productivity of ecotopes and aqueous runoff quality, transform river flows and bring about the irreversible loss of spawning sites. There could be other dramatic consequences as well. It is necessary to note, that all these transformations are of a transboundary nature and their significance is beyond the regional context.

It is readily apparent that the international community should recognize the importance of catastrophic forest fires in the context of global climate change. It should identify criteria for the assessment of global threshold indicators regarding regional-level pyrogenic disasters and international responses for the management of catastrophic forest fires around the world.

# 6. Expected Risks for Terrestrial Ecosystems

Risks for terrestrial ecosystems, for agriculture and forestry initiated by climate change and anthropogenic activities could be categorized as following:

- negative processes connected to permafrost destruction including physical destruction of sites, thermokarst, solifluction;
- loss of soil fertility due to water erosion, soil compaction, desertification, lack of nutrients, solinization, increasing water table and other changes of water regime, soil contamination;
- impoverishment of soil biota, decline of productivity of lands;
- lack of water resources in arid regions;
- damage of agriculture lands in river valleys due to increase of inundation;
- outbreaks of traditional pests and microorganisms;
- alteration of forest fire regime
- anomalous outbreaks and spatial distribution of traditional and new insects;
- loss of biodiversity;
- “green” desertification;
- impacts of air pollution, soil and water contamination

*Permafrost degradation*. Modelling studies on permafrost behaviour in 21st century predict decreasing the total area of permafrost by 10-18%; 15-30% and 25-35% by 2030, 2050 and 2080, respectively; the area of continuous permafrost will likely decrease by 25-50% by 2080 (Anisimov *et al.*, 2003). Intensive development of thermokarst, gully formation, landslides, solifluction, floods, paludification (or aridity depending on geographical distribution and landscape peculiarities, with following processes of northern steppization and “green desertification”) is expected for large areas, especially for continuing ice-rich soils (which cover about 35% of Yakutia and 35-40% of north-eastern Russia). Due to predictions made by the Permafrost Institute in Yakutsk, lake and swamps cover may increase (at 1.3-3 times for a future moderate warming by +3 $^{o}$C), non uniformly in different regions of Asian Russia. If the observed warming trend $\Delta t_0 \geq 0.06^{o}C\ yr^{-1}$ sustains, the unprecedented changes in geocryological, landscape and ecological conditions are very likely in high latitudes of Siberia

Permafrost and wetlands contains a huge amount of carbon: available estimates are in the range from 400 to 900 Pg C. Another estimates indicated that the methane in Holocene permafrost deposits of the Lena Delta originated from modern methanogenesis by cold-adapted methanogenic archaea. Microbial generated methane in permafrost sediments is so far an underestimated factor for the future climate development. The organic carbon of the permafrost sediments varied between 0.6% and 4.9% and was characterized by an increasing humification index with permafrost depth, and a high $CH_4$ concentration was found in the top 4 m layer (Wagner *et al.*, 2007). Warming may provide dangerous acceleration of major biogeochemical cycles, basically at the expense of a thermal increase of carbon emissions (as $CO_2$, CO and $CH_4$). Hydrates of northern seas are a second potential large source of greenhouse gases.

*Impoverishment of fragile (pseudo-equilibrium) ecosystems of high latitudes.* A number of ecosystems, particularly of northern latitudinal and altitudinal ecotones are under a particular threat due to global change. Degradation of cryoxerogenic landscapes of high latitude in Asian Russia could serve as an example. These landscapes suffer from solinization, increase of alkalinity, water, wind and thermokarst erosion. The arable lands in Saha Republic are constantly decreasing: 1990 - ~140x$10^3$ha, 1996 - 132x$10^3$ha, 1998 - 120x$10^3$ha. Today 40% of hay fields in Yakutia suffer from surplus salinity and 50% of pasture undergone digression of different extent. Very likely, the specifics of on-going and expected climate change will accelerate these processes.

*Acceleration of natural disturbances.* It is very likely that predicted climate change will provoke a dramatic increase of extent, severity and frequency of such disturbances as vegetation fire and insect outbreaks. A combined impact of fire and other anthropogenic and natural disturbances will accelerate the process of green desertification (current estimates give 1 to 2 million ha per year during the last decades). There is a threat of catastrophic fire seasons (defined as those during which a total burnt area exceeds the many year average more than 3 fold); during the last decade such seasons occurred in 1998 and 2003. The world experience shows that even very advanced in forest fire protection countries are not able provide any satisfactory extinguishing of forest fire during the catastrophic years.

*Risks for coastal areas and marine ecosystems*. Increasing sea level and flooding coastal areas, change of salinity regime of low reaches of rivers, change of ecological processes in deltas, substantial intensification of processes of coastal erosion will negatively impact coastal and delta ecosystems. Acceleration of rates of decreasing sea ice, shrinking ice cover of Arctic seas already impacts of population of northern animals.

*Changing the hydrological regime.* Risks initiated by the change of hydrological regime are region specific. Transformation of the hydrological cycle including a change of runoff of large Siberian rivers will impact the condition and dynamics of vast wetland territories of West Siberia and north of the entire region. Decrease of water table in permafrost area in combination with the acceleration of the fire regimes will provoke processes of northern steppization and green desertification. Steady deficit of water resources will cause losses of yield of agricultural crops and pastures in southern regions.

*Acceleration of emissions of greenhouse gases.* Warming and direct and indirect anthropogenic impacts on natural landscape could provide substantial increase of emissions of greenhouse gases (mostly $CO_2$ and $CH_4$). Currently, even taken into account the substantial increase of disturbances, terrestrial ecosystems of Siberia still serve as a net carbon sink at the level of 30-40 g C $m^{-2}$ $year^{-1}$. However, it remain unclear how much warming of permafrost areas impacts the budgets of greenhouse gases during the last decade.

*Ecosystems and human health.* It is very likely that climatic changes will impact human health and living conditions in a clearly negative ways both directly and indirectly through changes of ecosystems. The direct impact includes increasing severity and frequency of extreme climatic phenomena, such as flooding, increasing wind, and – in southern parts of the region – increased number of hot days, heat waves, and longer and more intensive dry periods. Additionally, warming increases the danger of infectious diseases, particularly those which are distributed by insect-carriers or by water. Sharp intensification of epidemic processes caused by intestinal infection in the south (sometimes –

up to unprecedented levels), increasing parasitic and non-infection pathology, and evident northward shifting of the areas of carriers of infection, are already observed in different regions of Siberia. From another side, negative impacts of global change on the region's ecosystems (particularly, agriculture and forest) will impact well-being and standards of life of local population.

# 7. Conclusion

A list of the most substantial ecological and landscape-ecosystem consequences of expected climatic change includes, *inter alia*:
(1) permafrost degradation (decreasing the total area of permafrost is predicted to be 10-18%; 15-30% and 25-35% by 2030, 2050 and 2080, respectively; the area of continuous permafrost will likely decrease by 25-50% by 2080; intensive development of thermokarst, paludification (or aridity depending on geographical distribution and landscape peculiarities, with following processes of northern steppization and "green desertification" there);
(2) increasing sea level and flooding coastal areas, change of salinity regime of low reaches of rivers, change of ecological processes in deltas, substantial intensification of processes of coastal erosion;
(3) acceleration of rates of decreasing sea ice, shrinking ice cover of Arctic seas, and – in future – change to the global cycle of fresh water;
(4) shifting of all types of vegetation to the north; this process will result in a substantial (in some assessments – two-fold by the end of the century) decrease of forested area, increase of steppes and, specifically, a substantial increase in the area of desertified steppes; this will impact biodiversity, standard of life of local population and conditions for wild animals;
(5) acceleration of natural disturbances, such as fire and insects' outbreaks; wild fires in Asian Russia in 2003 (the satellite estimate of areas enveloped by vegetation fires comprised about 23 million ha) and the outbreak of Siberian moth in Larch forests of middle taiga in 2001-2002 (an area more than 10 million ha) clearly demonstrated the scale of expected natural disturbances in the "catastrophic" weather conditions years;
(6) transformation of the hydrological cycle including a change of runoff of large Siberian rivers, the condition and dynamics of vast wetland territories of West Siberia and north of the region;
(7) dangerous acceleration of major biogeochemical cycles, basically at the expense of a thermal increase of carbon emissions (as $CO_2$, CO and $CH_4$) because the majority of carbon is accumulated in organogenic soils, permafrost and hydrates of northern seas; and
(8) steady deficit of water resources and losses of yield of agricultural crops and pastures in southern regions.

It is very likely that climatic changes will directly impact human health and living conditions in a clearly negative way due to increasing severity and frequency of extreme climatic phenomena, such as flooding, increasing wind, and – in southern parts of the region – increased number of hot days, heat waves, and longer and more intensive dry periods. Additionally, warming increases the danger of infectious diseases, particularly those which are distributed by insect-carriers or by water. Sharp intensification of epidemic processes caused by intestinal infection in the south (sometimes – up to an unprecedented level), increasing parasitic and non-infection pathology, and evident northward shifting of the areas of carriers of infection, are already observed in different regions of Siberia.

Current peculiarities of social and economic development of Siberia which are accompanied by the destructive anthropogenic impacts on the environment and natural landscapes may substantially accelerate the negative consequences of climatic change. Methods existing today of industrial exploitation of northern territories do not provide for any optimistic estimate of future interactions of the industry and environment in Siberia. The level of atmospheric pollution and soil contamination in major regions of intensive oil and gas extraction has exceeded all acceptable limits. The rate of contamination has been increasing. The quality of river water, specifically in southern regions with maximal density of population does not correspond to the norms of water use for drinking and fisheries. The governance of natural resources (in particular, forests) and the control of the use of natural resources is below a critical level. The impacts of toxic anthropogenic water contamination, the decline of the human immune system, increasing stresses, impacts of many negative social phenomena connected, among others, to intensification of migration processes, with a high probability will accelerate the negative impacts of climatic change on standards of life and health of the population, as well as enforce undesirable feedbacks.

Land use – land cover change (LULCC) in the region during the last decades was mostly driven by economic processes and inherited specifics of wrecking systems of natural resources used. It revealed in impoverishment of forests and decreasing their quality over large areas (decreasing areas of valuable coniferous forests; restoration of forests through change of species; increasing areas of burnt areas and dead stands etc.), particularly in densely populated areas. From other side, the restoration potential of boreal forests remains very high that results in restoration of disturbed areas and encroachment of forests and shrubs in previously non-forest areas. The second typical feature of LUCC is abandonment of agricultural land in the forest steppe and steppe zones of the region. Such lands are out of any management activities now that transforms these territories in weed- and disease-breeder. These lands require a special program of reforestation taking into account expected climatic conditions in the ecotone forest-steppe.

During the last decade, there were substantial findings of research on the topic received by a number of institutes of Siberian Branch of RAS; regional and central universities; such Western and international institutions like Max Plank Institute of Biogeochemistry (Jena, Germany); Friedrich-Shiller University (Jena, Germany); National Institute of Environmental Studies (Tsukuba, Japan); International Institute for Applied Systems Analysis (Laxenburg, Austria); some others. Results of these studies help much in development of information base, methodologies and models of integrated approach.

At the same time, current knowledge of specifics and consequences of global change is limited; levels of uncertainties of estimates and predictions are high and often unknown. Many questions that are vital for future generations require in-depth consideration and analysis. These questions include such fundamental problems as thresholds of acceptable (not destructing) impacts on ecosystems taking into account non-linear and multi-variant responses of ecosystems to long-term accumulation of stresses; system (holistic) analysis of complicated systems which contain components of different nature – biophysical, ecological, social and economic; theory and practice of decision making under uncertainties; development of integrated observing systems; and many others.

In spite of numerous projects in the region on the topic, there are many gaps and weaknesses in information background, organizing and coordinating research of changing environment, ecosystems and use of natural resources. These gaps are mostly dealt with needs of empirical data which would be complete with respect to major parameters of ecosystem functioning, spatial and temporal coverage of data. The Siberian Branch of the Russian Academy of Sciences which is main coordinator and driver of science in the region does not have enough resources to cover all scientific needs of huge, fragile and dynamic territories. Under such conditions, existing science Programs are not able to completely carry out their coordinated role. International efforts implemented in the region are fragmented and – by definition – cannot serve as an overall organizing base, although such integrated activities as Global Carbon Project of IGBP and NEESPI (Northern Eurasia Earth System Partnership Initiative) play an evident important role.

System combination and coordination of research of the abovementioned type require a new systems approach, which would be able to provide a real interdisciplinary integration of different problems and methods; would involve all relevant scientific institutions of the region; accumulates available resources; involves all major stakeholders, local authorities and business; and finally would bridge of science –policy – implementation. Such an approach could be realized within the ***Siberian Integrated Regional Study***. The Enviro-RISKS project substantially contributed to understanding of science plan and institutional decisions of SIRS.

Problems connected to global change still are not considered as a basis for important social, economic and management decisions in many countries of the world including Russia. The country as a whole, and Siberia particularly, require urgent development of a long-term strategic program of adaptation of natural landscapes and all parts of the regional economy to climatic change, and the mitigation of negative consequences of climatic change. The Siberian program should have a clear regional character in all ramifications – in assessment of predictions, by priorities and objectives, and by ways of practical implementation. The program should have a solid legislative, economic and social basis. Without such a program, all speculations on the transition to sustainable development of Siberia would remain only words and far from reality.

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