3.3. Surface Energy and Water Cycles

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Introduction. The Surface Energy and Water Cycles (SEWC) are the two major cycles that largely defined the state of the environment in Northern Eurasia. A proper description of these processes in a Global Earth System model is a crucial prerequisite to successfully model the observed climate and its variations, including climate projections on the decadal to century time scales. To accurately simulate the complex interactions that define the Earth System, it is now necessary to correctly characterize these processes, and (a) *project/account for society's continued development and potential influence on future climate and environment dynamics* and (b) to *account for change in the rate of changes* (i.e., the acceleration in such processes as accumulation of CO_2 or degradation of land and sea ice) *that forces the slow-changing components of the Earth System (such as biosphere and cryosphere) to react and feed back to the contemporary and near future climate and the hydrological changes (3.1, 3.2, 3.4, and 3.5).* Now, with an increasing rate of current and projected global changes, Northern Eurasia is a "frontrunner" in these changes (Figures 2.1, 2.2, and 2.7[7] through 2.17). Box inserts A2.1 and A2.2 give vivid examples of large-scale regional changes in terrestrial hydrology that appear to be caused by both global climate changes and regional human impact. These examples (among many others) show that without a proper understanding of processes that control the contemporary climate and terrestrial hydrology and their drivers, society is helpless in addressing the future problems in a harsh and quickly changing environment. In Northern Eurasia, the scale of these problems is among the largest in the world. Thus, knowledge and ability to project the underlying processes that cause these problems is a necessity. In the diagnostic mode of weather modeling (the re-analysis mode) any erroneous parameterizations or misinterpretations of the processes that define the behavior of the system are corrected by the data. There is no such helping hand when we are trying to project future climate and state of environment or assess their vulnerability. All basic processes must be described as accurately and completely as possible within the model because the quality of this description becomes the only guiding light. This again leads us to the need to study processes. *At the land surface, these major processes together with the biogeochemical cycle are surface energy and water cycles.*

3.3.1. Major processes responsible for the maintenance and variability of the surface energy and water cycles in Northern Eurasia

The primary processes controlling the SEWC at the land surface are listed below with a short annotation.

[7] Figures 2.7 through 2.18 and Box Inserts A2.1 and A2.2 can be found in Scientific Background Appendix.

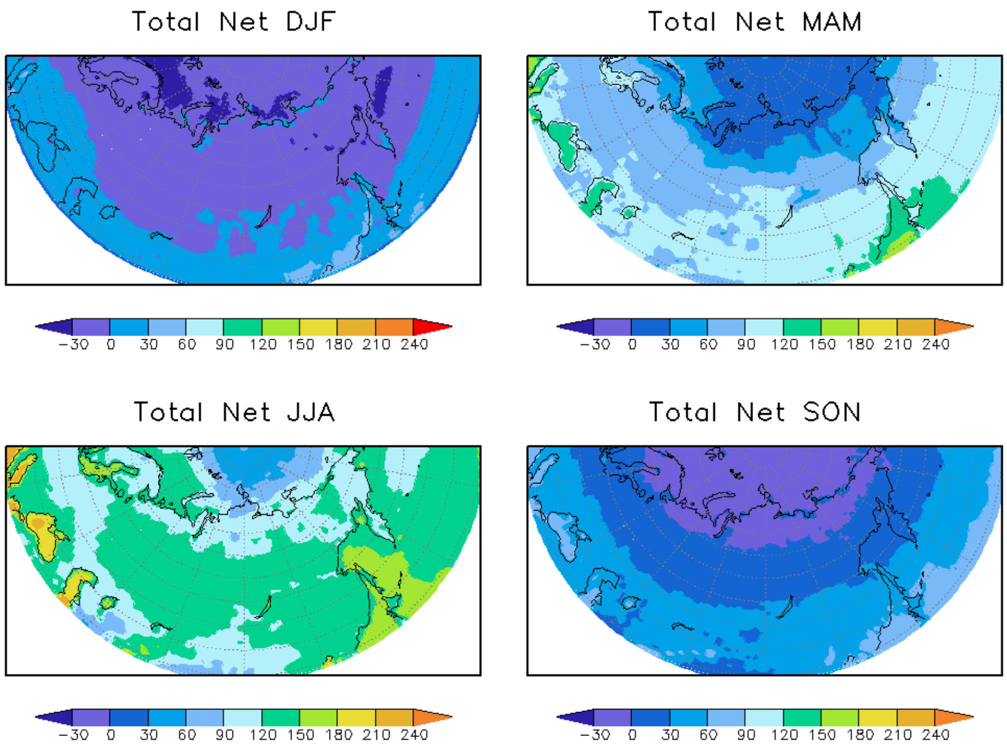

Figure 3.3.1. The mean total net surface radiation budget over Northern Eurasia on a seasonal basis from July 1983 through October 1995 as determined by the GEWEX SRB project (Stackhouse et al., 2004).

- ***Surface heat exchange.*** The surface is a focal area where (a) most of the solar energy absorption and a significant fraction of reflection occur, (b) a significant fraction of the outgoing long wave radiation forms, and (c) atmospheric warming by turbulent and long wave radiation fluxes is generated. The surface heat exchange defines temperatures at the surface and above and below ground, and changes the surface substance by snowmelt and evaporation as well as by providing the energy for the functioning of the biosphere. While at the top of the atmosphere above Northern Eurasia, the annual radiative budget is negative, the surface is a heat sink only in the winter season (Figure 3.3.1). The negative heat balance in Northern Eurasia is compensated by transport of latent heat from more temperate regions, a considerable part of which comes from Northern Atlantic region via the westerly atmospheric circulation.
- ***Atmospheric circulation.*** Advective processes (mostly westerlies, but Arctic and monsoon effects are also present) modify the climate of Northern Eurasia, reduce its continentality, and are the source of water for interiors of the continent. Weather conditions favorable for cloud formation and precipitation are highly variable in time and space. Thus, atmospheric circulation is a major source of the variability in land surface processes.
- ***Water exchange processes.*** Heat advection modifies regional climate while water vapor advection and precipitation *actually define it.* Most of the precipitable water that initially comes from outside the region may recycle several times in precipitation/evaporation processes (Drozdov and Grigorieva, 1963; Trenberth, 1999) until it leaves by runoff or via atmospheric flow. Generally, water resources are scarce over most of Northern Eurasia, but both the water deficit and the water abundance affect terrestrial ecosystem functioning and human activity and are a cause of numerous feedbacks associated with environmental and climate change (3.5).

- ***Role of land cover in the surface processes.*** Land cover (natural vegetation or disturbed conditions) modifies surface heat and water exchanges depending upon its physical (albedo, heat conductivity), mechanical (roughness, plant surface area density), and biological (leaf area index (LAI), stomatal conductance, photosynthesis, root system depth, etc.) properties. Some types of land cover (vegetation, snow, ice, frozen soil, and soil itself) are changing during surface heat and water exchanges, feed back to them and, therefore, have become integral components of the surface processes (3.5).
- ***Anthropogenic impact.*** Human activities cause direct (by land cover changes and water withdrawal and diversion) and indirect (by changing atmospheric composition and water quality) impacts on numerous processes in the biosphere, hydrosphere, cryosphere, and atmosphere. The impact of such disturbance on the land surface processes is the most direct and among the strongest (3.4).

Which Processes to study? Each of the above topics is important and should be investigated to achieve the NEESPI objectives. Priorities, however, should be set according to two criteria. *First, attention must be paid to the processes that directly feed back to the Global Earth System.* This justifies the interest of the International Community in the environmental changes in Northern Eurasia. These processes are also very important on the regional and larger scales. In most cases, the feedbacks to the global Earth System are only feeble manifestations of enormous changes within the subcontinent that “spill out” across the regional borders. Furthermore, by affecting the Global Earth System, they by definition affect Northern Eurasia. *Second, the processes of major societal importance must be addressed.* They may or may not affect the Global Earth System but for the region’s population they are of pivotal importance.

3.3.2. Processes that directly feed back to the Global Earth System

Processes in Northern Eurasia that have the capacity to feed back to the Global Earth System have been listed in 2.1. Below we provide a rationale for this listing.

Accelerated climatic changes across Northern Eurasia. y large perturbation of the global climate manifests itself most prominently in the cold and transition seasons in high latitudes over land areas and sea ice (Shnitnikov 1975; Vinnikov 1986; Figure 2.7). While the thermal inertia of the oceans is a major cause of its relative resilience to disturbance compared to the land areas, there are several reasons for a higher sensitivity of high latitudes to external forcing compared to low latitudes. First, if the external radiative forcing (ΔQ) is uniformly distributed along the longitude, its relative contribution to the surface radiation balance in the high latitudes will be more significant than in the tropics. Furthermore, several positive feedbacks (snow-ice and water vapor feedbacks being the most significant) are more prominent in high latitudes than in low latitudes. Finally, because the high latitudes are an energy sink, some proportion of tropical ΔQ from the tropics inevitably ends up in mid- and high latitudes. Thus, the pattern of the recent observed changes is a logical expectation of the progression of apparent impacts of a warming climate (Figure 2.2). These changes (if continued) may in turn further affect the global climate by:

- Changes in atmospheric blocking over the continents (Semiletov et al. 2000);
- An increase in the water holding capacity of the atmosphere[8];
- Systematic changes in the regional surface heat balance (Zolotokrylin 2002, 2003);
- Changes in meridional heat transfer in the atmosphere and thus the entire large-scale circulation pattern (Figure 3.3.2);

[8] Budyko and Drozdov 1976; Allen and Ingram 2002; Trenberth et al. 2003, Yang et al. 2003.

- Non-linear (and not well understood) changes in land surface hydrology and land cover (2.8, 3.1, 3.5, 3.6.1, and 3.6.2), and
- Interaction of all of the above that, combined, will yield non-zero feedbacks to the heat and water balance of the continent and, therefore, to the Global Climate System.

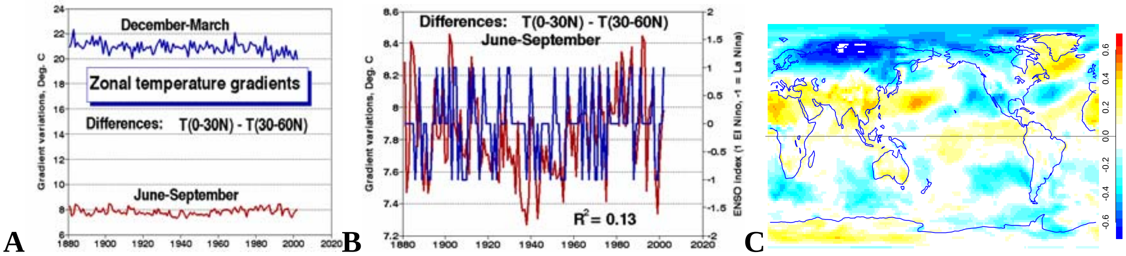

Figure 3.3.2. A. During the 20th century, systematic changes have occurred in the temperature gradient between the tropics and mid- and high latitudes affecting the meridional heat exchange. Changes in the warm season, while of a lesser magnitude, were (a) higher in relative terms and (b) of opposite sign to those in the cold season. (derived from data of Lugina et al. 2003, and Spirina 1970). B. A match of the ENSO occurrence (blue) and changes in the previous summer (June-September) temperature gradient. For the ENSO characteristic, the JMA ENSO index time series were used: (+1 for warm phase, 0 for neutral, -1 for cold). C. Correlations of the surface air temperature data with northern hemispheric meridional temperature gradient (zone 0-30ºN minus zone 60º-90ºN) for the winter season (Gershunov 2003). Note a significant reduction of Dec-Mar temperature gradients in the past three decades (A) due to a disproportional warming of Northern Eurasia (C).

Changes related to snow cover changes. Every year during the cold season, up to ~ 55% of the landmass of the Northern Hemisphere is covered by seasonal snow for a period of one week to 10 months. This is a major factor of the Northern Eurasian climate that affects (a) both shortwave and long wave components of the surface radiative balance (although cooling due to the high albedo of snow cover is the most prominent factor); (b) the shape of the hydrological cycle by accumulating the cold season precipitation and then releasing it during the snowmelt period into the soils and runoff; (c) the soil temperature profile by insulating the surface from cold winter air, (d) the energy losses associated with snowmelt, (e) the surface air temperature growth above the melting point, and (f) large-scale atmospheric circulation (including monsoon circulation) by controlling land-ocean temperature gradients. All of the above, in turn, feedback to the biosphere (cf., Jones et al. 2000) and shape many aspects of human activity (winter crops, reservoir management, transportation, construction industry, etc.). n all seasons when snow is present on the ground, it feeds back to ecology, weather, and society. But, its effect on the surface radiative balance is the highest in spring (Groisman et al. 1994). This is a season when most systematic changes in snow cover have been observed during the past century (Figure 2.12). For the former USSR territory, the snowmelt runoff is about 2600 km^3 and 70% of it returns annually to the Arctic Ocean (Krenke et al. 2004). The changes in this amount are critically important for the North Atlantic thermohaline circulation that maintains the global heat distribution (Broecker 1987).

The fresh water transport through the Arctic Ocean. Thermohaline circulation is a global-scale overturning in the ocean that transports significant heat via a poleward flow of warm surface water and an equator-ward return of cold, less saline water at depth. The overturning, crucial to this transport in the Northern Hemisphere, occurs in the Greenland, Irminger and Labrador Seas (Broecker 1997, 2000). The overturning also moderates anthropogenic impact on climate because it removes atmospheric CO_2 to the deep ocean. The occurrence and intensity of overturning is sensitive to the density of water at the surface in these convective gyres, which, in turn, is sensitive to the outflow of low-salinity water from the Arctic Ocean. This outflow from the Arctic basin is subject to significant interannual oscillations. About 10% of the global river runoff is discharged to the Arctic Ocean, which is only 5% of the global ocean area and 1.5% of its volume (WCRP-72 1992). About three-quarters of the inflow come from the six largest rivers, the Yenisey, the Lena, the Ob, the Mackenzie, the Pechora and the Kolyma (Vuglinsky, 1997; Forman et al. 2000). Five of them are in Northern Eurasia. The effect of global change on hydrology in Northern Eurasia has been estimated for various future projections[9]. These results showed a possibility of extremely serious changes in hydrological regime of the North Eurasian rivers in the 21st century. In particular, *an increase in Arctic outflow (if the current trends will continue, e.g., Peterson et al. 2002, Figures 2.14 and 2.15) could reduce the overturning and, therefore, the oceanic flux of heat to northern high latitudes*.

Changes in surface albedo related to vegetation changes, shift of ecological zones, and land use changes. These changes directly affect the surface heat and water balance and are discussed in 3.4 and 3.5 in detail. While it is possible to reconstruct some of these changes over time[10], large-scale environmental monitoring became a reality only in the era of remote sensing. During the last two decades, the area of forested land, green vegetation (NDVI), forest fire scares, agricultural fields, and their changes with time are objectively monitored and documented from satellites (4.1). The period of this monitoring is still too short to permit confident conclusions about a shift of ecological zones, but pilot estimates (e.g., Figure 2.1) have already indicated large-scale changes in the biogeochemical cycle over Northern Eurasia with global implications (3.2). There is substantial spatial variability in winter albedo within the boreal forest due to the spatial mosaic of coniferous forests, deciduous forests, and non-forested wetlands and burn scars. The latter have a higher albedo of ~ 0.6 in the cold season when the short-statured vegetation is snow covered. Thus, it is important to know the proportion of the landscape occupied by short-statured ecosystems within boreal forest. During summer, the albedo of deciduous stands and boreal non-forested wetlands is higher than the albedo of coniferous forests (Rauner 1972; Chapin et al. 2000a). Therefore, changes in the land cover composition directly affect surface heat balance.

Thawing of permafrost. Degradation of permafrost and changes in the soil carbon cycle in Northern Eurasia have the potential to noticeably affect the atmospheric CO_2 and CH_4 concentrations and, therefore, global climate, ecosystems, infrastructure, and hydrology. Section 3.6.1 specifically addresses all issues related to this process.

Changes in the boreal forest ecosystem. A description of the interaction of Surface Energy and Water Cycles with the forest ecosystems and feedbacks to the regional climate is provided in Section 3.5.1. Additionally, changes in energy and water balances in this zone may directly affect sinks and sources of carbon (3.1, 3.2) and runoff of major rivers of Northern Eurasia. Considering the large area occupied by this ecosystem in Northern Eurasia (~50%), these changes feed back to the global climate.

Ongoing aridization of the continental interior and dust storms. Temperature rise without appreciable changes in precipitation (or even its decrease) can lead to aridization in steppe, semi-arid and arid climatic zones of Northern and Central Eurasia. Additional causes for aridization could be of anthropogenic origin (water withdrawal and/or intense agricultural use) and glaciers and permafrost degradation. Whatever the causes may be, an increase of the dust load in the troposphere may be a result. With an average transport time of up to

[9] Georgievsky, et. al., 1996; Shiklomanov and Georgievsky, 2001; Shiklomanov and Shiklomanov 2001, Georgiadi and Milyukova, 2002, Mokhov et al. 2003.

[10] e.g., the lake levels, changes in the area of agricultural land (3.4; Golubev et al. 2003), and reports of the forest harvest and inventories (Shvidenko and Nilsson 2002).

several weeks, mineral particles can be transported great distances downwind from the source, causing diverse effects on health, environment, and climate (Figure 3.3.3). *Once lifted into the atmosphere, both anthropogenic and natural components of mineral aerosols play an important role in air quality, atmospheric chemistry, ecology, biogeochemical cycles, cloud formation, rainfall, agriculture, Earth's radiation budget, and, hence, climate change.* Since Central and East Asia is the second largest source of atmospheric dust in the world, a quantitative understanding of Eurasian dust sources, transport routes, and effects on the climate system on regional and global scales is urgently needed. Section 3.6.3 addresses these issues in detail.

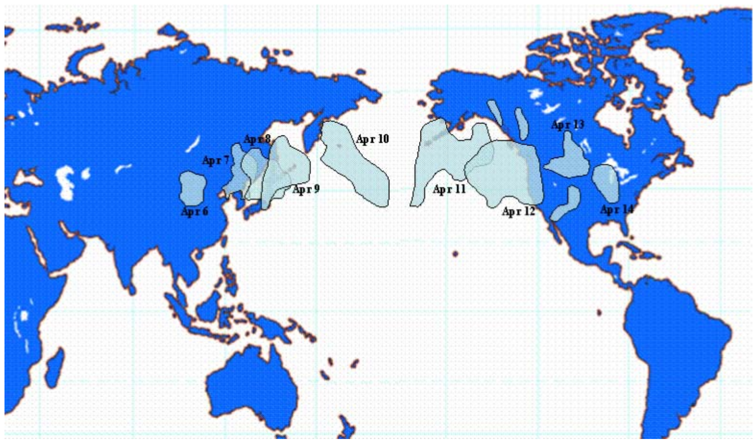

Figure 3.3.3. Long-range transport of the dust storm originated over the Gobi desert on April 6th, 2001 (based on TOMS aerosol index; Darmenova and Sokolik, 2002).

Deglaciation in the mountain systems of Central Asia and Caucasus, increasing water withdrawal, and increasing dryness of steppe and semi-arid zones. Climate variations at high altitudes (similarly to high latitudes) may have larger amplitudes compared to lowlands[11]. Thus, the changes over the greatest highlands in the world, a group of mountainous systems and plateau of Central Asia that are spread from the Himalayas in the south to Tien Shan, Junggar, and Altai-Sayani, in the North, have been historically and are anticipated to be large. In Northern Eurasia, the Tien Shan, Junggar, and Altai-Sayani mountains hold one of the greatest concentrations of perennial snow and ice in the mid latitudes and constitute a vital source of water for Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan, and Xinziang (West China), where the total population reached 100 million by the end of the 1990s. In Central Asia, there are approximately 30,000 glaciers with a total area of about 25,000 km^2. Eighty percent of these glaciers have been retreating since the 1950s (Haeberli, 1990) with a recent acceleration (Khromova et al. 2003). Managing water resources in these hugely populated areas is a complex problem because changes in the hydrological regime (in addition to natural forcing) have strong anthropogenic components. It makes a difference for global climate, biosphere, and human society if (a) cold snow/ice covered mountains and plateaus in the center of Eurasia feed surrounding areas with water via lengthy rivers or (b) the same areas become heat islands of dry deserts that duly evaporate atmospheric precipitation and provide an ample source for dust storms over the hemisphere (Middleton et al., 1986). Observations indicate that the Caucasus Mountains and some regions in the Central Asian Mountains are in transition from the former to the latter types of landscape (Aizen et al. 2003, Figures 2.13 and 3.6.5; Table 3.6.1[12]).

[11] Vygodskaya 1982; Polikarpov et al. 1986; Barry 1992; Oerlemans 2001.
[12] Figures 3.6.1 through 3.6.5, and Table 3.6.1 can be found in Scientific Background Appendix.

3.3.3. Processes of major societal importance

- ***Extremes.*** Normal functioning of society assumes "average" climate/weather conditions. Extremes usually negatively affect this functioning (droughts and low levels in rivers, lakes, and ponds, fires, floods [in particular catastrophic ice-jam floods on large Siberian rivers or floods in densely populated areas], landslides, and soil erosion after heavy rains and/or unusually intensive snowmelt, cold and hot spells) and affect various aspects of societal activities, health, and even human lives. Numerous changes in frequencies of extreme events in Northern Eurasia have been reported[13] and and projected (Mokhov et al. 2003; Shmakin and Popova 2003; Hegerl et al. 2004).
- ***Terrestrial hydrology and water supply.*** Industry, agriculture, human sustenance and health, recreation fisheries, and environmental health depend upon sufficient and timely fresh water supply. Water quality is an issue for many of these needs. According to forecasts by the WorldWatch Institute, two-thirds of the world's people will be suffering water shortages by 2025, including those in the southern half of Northern Eurasia (ICCP, II, 2001). Probable runoff decrease of the rivers of southern slope (Don, Dnieper) and subsequent deficit of water resources in the steppe regions of Russia and Ukraine, the ongoing and worsening water deficit in Central Asia, and changes in the hydrological regime of the Arctic are the major areas of concern (Vörösmarty et al. 2000; Peterson et al. 2002).
- ***Soil / freeze/ refreeze/ thaw of permafrost interaction with hydrological processes.*** Thawing of permafrost causes numerous structural damages to the infrastructure, shifts and/or replacement of the ecosystems, and changes in the coastal zone of the Arctic Ocean and hydrograph of Siberian rivers. With projected increases in surface temperature and decreases in surface moisture levels, the active layer thickness will probably increase, permafrost area extent will decrease and permafrost will become thinner, leading to subtle but predictable ecosystem responses such as vegetation changes. Permafrost in arctic regions exerts a significant influence upon hydrologic and ecosystem dynamics through controls on vegetation and drainage. In relatively flat areas where the frozen layer is near the surface, the soil moisture contents are usually quite high. These areas have relatively high evapotranspiration and sensible heat transfer, and a low conductive heat transfer due to the insulative properties of thick organic soils. The climax vegetative species and soil forming processes are dominantly controlled by the closely coupled permafrost and hydrologic conditions. As permafrost degrades, the soil moisture holding capacity increases, soil drainage improves and moisture is no longer held near the surface but percolates to deeper reservoirs. Thermokarst lakes are formed on flat terrain. As permafrost becomes thinner or absent, groundwater contributions from springs become more important (Vörösmarti et al. 2001a).
- ***Snow cover (impact on flooding, interaction with ecosystems and agriculture).*** Snowmelt is a major cause of flooding in most of Northern Eurasia. Projected intensification of winter precipitation, shortening of snow cover season, changes in spring freshet, and dependence of agriculture (winter crops) and wild life on snow are focal points of concern.
- ***Glaciers (changes, impact on hydrology).*** The current retreat of mountainous glaciers, while initially considered as a factor that was increasing the streamflow, will eventually yield decreasing river discharge. There are indications that in the Caucasus and mountains of Central Asia, the degradation of glaciers has already advanced to the state of decreasing rates of runoff from melting ice. Currently, glacier melting is increasing

[13] Mestcherskaya and Blazhevich 1997; Georgievsky et al., 1999; Heino et al. 1999; Groisman et al. 1999, 2003, 2004; Georgiadi 1993; Milly 2002; Zolotokrylin 2003.

only in the heads of river basins with large-scale glaciation. In the river basins with relatively small-glacierized areas, the increase of the glaciers' melt has already led to a decline in the glaciers' area and has thus reduced their contribution to river runoff (Aizen et al., 1997, 2003). This can explain, at least partly, the wastage of large Central Asian lakes, such as Balkhash, Lobnor, and Aral (Figures 2.8, 2.9a, and 2.16).

- ***Surface-atmosphere interactions in changing climate and land use.*** Some of these interactions along with certain changes can be dangerous (e.g., dust storms and landslides). Others may gradually lead to harmful (and sometimes irreversible) negative changes in soil (salinization, inundation, and desertification) and biosphere (replacement of species with others "less useful" for society) (3.1, 3.4).

3.3.4. Surface Energy and Water Balance: Quantifying the Components and their Interactions

3.3.4.1. Climatology

Surface radiation balance. A climatology of the Surface Energy Balance was first constructed in the early 1960s from the data of a relatively sparse network of in-situ observations by Budyko (1963). In the maps that comprise the Atlas of the Earth Heat Balance (Budyko 1963), smooth and sparse isolines are justified by the accuracy of the information available at that time for monthly and annual time scales (Figure 3.3.4a). After

A.

B.

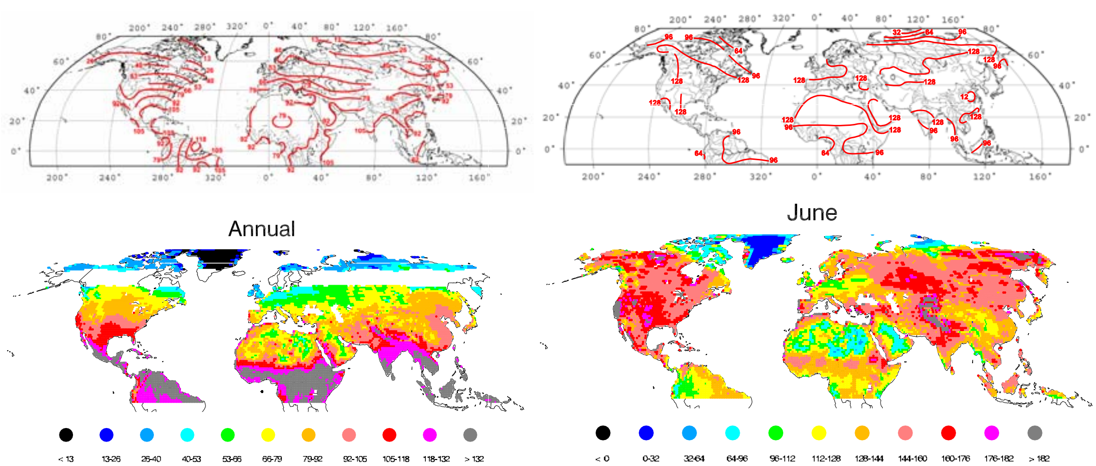

Figure 3.3.4. Mean annual and June surface radiation budget (W m^{-2}) of northern hemispheric land areas (a) according to Budyko (1963) and (b) Stackhouse et al (2004). The authors of Atlas of Heat Balance (Budyko 1963) skipped mountainous regions in their analyses due to insufficient information available at that time. Their maps were originally prepared in different units, which explains the unusual choice of isolines presented in this figure after conversion to Wm^{-2}. In the "twilight" zone (57°N-65°N) in winter months, calculations of shortwave surface radiation fluxes are not provided by the NASA satellite product.

launching a sequence of the Earth-observing satellites by NOAA and NASA, a new epoch of the Earth Energy Budget studies started (Barkstrom 1984; Barkstrom et al. 1989; Kyle et al. 1993). In particular, in the framework of the International Satellite Cloud Climatology Project (ISCCP, Rossow and Schiffer 1999), time series of major components of the surface radiation budget have been constructed from July 1983 to October 1995 (and will be updated to present) with a 3-hourly time- and 1-degree spatial resolutions. All observations for this budget are made from space and thus a special system of radiation-transfer models is used to calculate fluxes at the surface[14]. A comparison of climatology based on ISCCP and Budyko

[14] Gupta et al 1992, 2001; Darnell et al. 1988, 1992; Wilber et al. 1999; Stackhouse et al. 2004.

(1963) is shown in Figure 3.3.4. There are many reasons for these estimates to be different, including different definitions of “surface” in forested areas (cf., Figure 3.5.2) and a 40-year-long advance in understanding of radiation processes that came with remote sensing. But, discrepancies in high latitudes (that emerge only when all radiation fluxes are low and disappear in the summer time) may also be a manifestation of an accuracy problem in the remote sensing product (4.4). *The need of a higher accuracy in quantification of surface radiation components in high latitudes is especially acute, particularly in the cold season, and must be addressed in the NEESPI studies.*

Other components of the surface heat balance. The positive surface radiation balance is partitioned into heat flux into the ground and turbulent heat fluxes back into the atmosphere through sensible and latent heat flux. If snow and/or ice are on the ground, energy is also utilized in snow/ice melt. Qualitative evidence that all four of these processes took place everywhere is overwhelming, but the information on how they are interacting and what quantitatively is going on at a given point and at a given time is sparse. The most critical situation arises from the lack of information on turbulent heat fluxes. When partitioning of the surface radiation balance is made by various land surface schemes, it is usually assumed that (a) heat flux into the surface is relatively small[15] and (b) that melting and evaporation are dominant if snow and/or soil moisture are available. But, there are constraints on these assumptions: (a) Snow may be shaded by vegetation and thus melt may be delayed by several weeks; (b) Even in the cases of bare soil, the uppermost soil level can create a crust that prevents/reduces further evaporation; (c) Various types of vegetation have developed different adaptations to control the transpiration process, regulating their stomatal conductance; (d) In dense forest stands, surface energy storage (which is spent on changes of biomass temperature and photosynthesis carbon gain) can account for 10-12% of daily net radiation; and (e) Mosaic composition of vegetation species and terrain elements, make it difficult to quantify the turbulent heat processes theoretically while tower observations over forested land show very different partitioning of turbulent heat fluxes depending upon the forest type[16]. A reliable and representative observational base to test the performance of the currently available land surface schemes over the entire variety of typical landscapes in Northern Eurasia is virtually absent. Use of the modern generation of tower flux observations is quite rare over the region. Moreover, it is difficult to extrapolate the results of these observations over the regions beyond the point of measurement (e.g., Sogachev et al. 2002). Therefore, *a new modern observational base for surface flux measurements in the NEESPI region and new scaling-up schemes are desperately needed.* ring comprehensive field experiments in the past ten years[17] when all components of the surface energy balance were directly measured, the observed surface energy balance often did not close (R_n - G > LE+H; where R_n is the net radiation flux, G is the heat flux into ground, and LE+H is the sum of the surface vertical turbulent fluxes). The main cause of this systematic imbalance is not the experimental methodology but a conceptual deficiency. It is related to the fact that the

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[15] This is generally true for most soils and wetting conditions. However, there are indications that in some areas of Northern Eurasia the terrestrial endogenic energy discharge by the convection in the Earth’s crust is much higher than the background level thus contributing to biodiversity (Gorny 1998; Gorny and Teplyakova 2001). Beyond obvious evidence (areas around hot springs), observations of this effect are virtually absent.

[16] E.g., Rauner 1972; Chapin et al. 2000a; Tchebakova et al. 2002; Chapin and Chambers 2003.

[17] Bernhofer, 1992; Foken et al. 1993; Lee and Black, 1993; Fitzjarrald and Moore, 1994; Barr et al. 1994; Panin and Nasonov, 1995; Baldocchi et al. 1997; Blanken et al. 1997; Goulden et al. 1997; Lafleur et al. 1997; McCaughey et al., 1997; Pattey et. al. 1997; Panin et al. 1998; Laubach and Teichmann, 1999; Polonio and Soler, 2000; Kim et al. 2001 ; Wang, 2001; Huizhi et al. 2001; Sakai et al. 2001 ; Turnipseed et al. 2002; Beyrich et al. 2002; Wilson et al. 2002; Gustafsson et al. 2003; http://www.ihas.nagoya-u.ac.jp/game/GAME-Siberia.html).

energy-mass exchange between the land surface and the atmosphere is determined by applying theories that are based on the hypothesis of stationarity and horizontal homogeneity (SHH) neglecting the advection terms. In SHH conditions the cospectral form derived by Kaimal et al (1972), Kaimal and Finnigan (1994) have been taken as the archetype of surface-layer turbulence spectra. It works over flat homogeneous surface but fails over complex horizontally inhomogeneous terrain. *Currently, better estimations of surface sensible and latent heat fluxes over Northern Eurasia are needed to fill the large gaps in measurements over this area. Theoretical basis for new approaches*[18] *does exist but it still has to be implemented.*

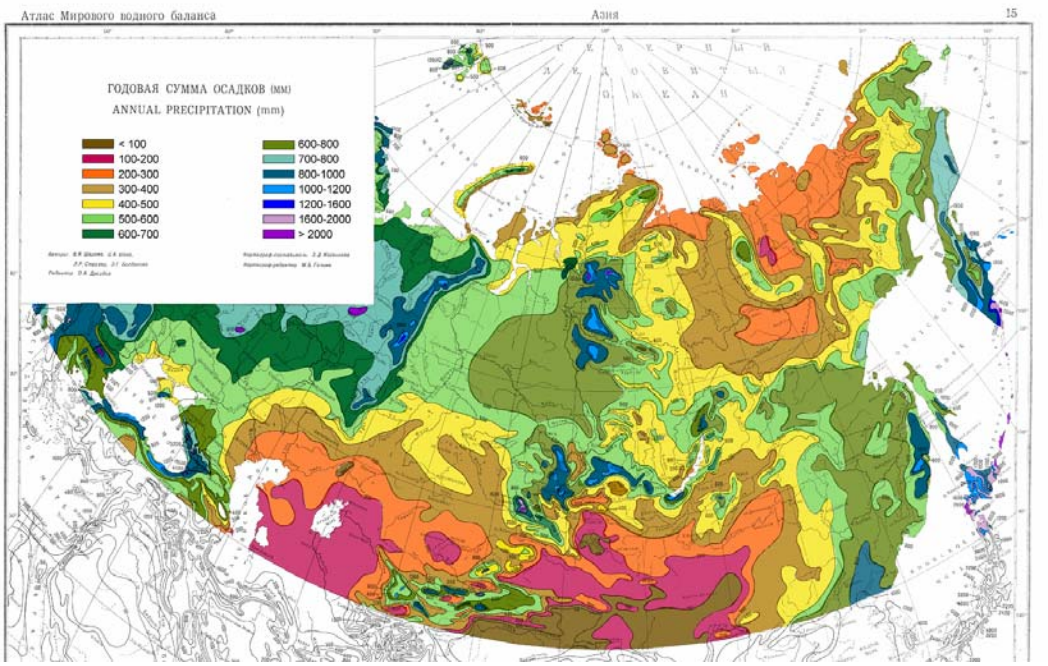

Figure 3.3.5. Annual precipitation (in mm) over Northern Eurasia (adapted from Korzun et al. 1974).

Surface water balance. Among the five major components that define the surface water budget, precipitation, snow accumulation and melt, runoff, evaporation and soil moisture, only the first three components are observed at relatively dense meteorological and hydrological networks (at about 10^5 sites throughout Northern Eurasia; although in northern sparsely populated parts of the continent the density of this network is insufficient; Chapter 6). The meteorological network delivers information for the controlled environment of standardized meteorological sites, while natural ecosystems (e.g., forest) and agricultural fields are covered by a fewer number of stations. Evaporation has been observed at about 100 sites in the former Soviet Union (Golubev and Kuznetsov 1980) and soil moisture measurements are made at agrometeorological stations along the narrow belt, mostly in forest-steppe and steppe climatic zones at about 10^4 sites (Vinnikov and Eserkepova 1991; Robock et al. 2000). Therefore, when rigorous water balance studies were conducted in the former Soviet Union in the 1960s and 1970s (Korzun et al. 1974), however, evaporation was a calculated variable. Quantitative maps of the precipitation pattern for Northern Eurasia utilizing this thirty-year-old research (Figure 3.3.5) have been recently improved for mountainous (Kotlyakov et al 1997) and Polar Regions (Bogdanova et al. 2002) but, nevertheless, to date, they represent the most comprehensive precipitation climatology in

[18] E.g.,Kazanskiy and Zolotokrylin, 1994; Panin et al. 1998; Finnigan et al. 2003; Avissar et al. 2004.

Northern Eurasia for the mid-20th century. Measurements of each component of the surface water balance have deficiencies. Some of them are due to the extreme paucity of observations (evaporation, soil moisture, all components north of 60°N). There is a major deficiency (bias) in precipitation measurements, especially for solid and mixed precipitation (Groisman et al. 1991; Goodison et al. 1998; Bogdanova et al. 2002). Peak runoff measurements are hampered by the over-bank flow that is difficult to account on level terrain. Failure to close surface heat balance (cf., previous sub-section) creates further difficulties in use of the MODIS-E (evapotranspiration) algorithm (Running et al. 1994). Low intensity of the water cycle in Northern Eurasia increases the relative errors of its estimation by remote sensing and makes useless some of the methods of its evaluation, e.g., microwave soundings of precipitation (4.4; Huffman 1997). All the above severely constrain water cycle studies in Northern Eurasia, particularly those when the goals of the study are the cycle changes and their interpretation. The *projected Global Precipitation Mission (GPM) may be of a major help in this regard. Therefore, preparations for a best possible calibration of the GPM instrumentation to account for specific conditions in Northern Eurasia are among the NEESPI objectives.* ***Soil moisture*** is the most critical element in the surface processes analyses. Soil moisture has a spatial mosaic distribution that is difficult to model and monitor and is poorly observed[19]. But, it controls evaporation, runoff, and vegetation and is a focal point of essential process studies at the land surface[20]. Furthermore, soil moisture measurements are virtually absent in the forest and it is impossible to estimate it there using the observations at the neaby agriculture field sites. The underground zone especially in the boreal forest is a strong regulator that smoothes seasonal and long-term variability of river runoff (Wood, 1999; Oltchev et al. 2002). Processes that define the base flow in the permafrost zone (about 30% of annual runoff) are insufficiently investigated. Terrestrial hydrological changes are now a focal application point of several processes that feed back to environment, society (3.3.3, 3.4, 3.5, 3.6.2), and even to global climate (3.3.2). *Their study should be based on a reliable observational data base and description of the major processes that are, at least, inadequate.*

Atmospheric transport of water vapor. A relatively dense spatially distributed network of aerological stations has allowed for early estimation of major characteristics of the water vapor distribution in the atmosphere and its transport over most of Northern Eurasia within the former Soviet Union boundaries (Kuznetsova 1978, 1983; IWP 1984). It appears, that while the atmosphere over the western half of Northern Eurasia is more humid, most of the water vapor (~88%) passes over it (or recirculates) and the "utilization" of the water vapor in Siberia is more effective. About half of the water vapor is converted to soil moisture and eventually streamflow. One of the semi-closed branches of the water cycle originates in the Northern Atlantic: evaporation from the ocean, atmospheric moisture transfer to Eurasia by westerlies, precipitation, runoff into the Arctic Ocean, and return to the Northern Atlantic via oceanic currents. *At present, there is no clear understanding of the characteristics of these highly variable processes that control the energy and water budgets of Northern Eurasia. This problem can be addressed with a focused regional modeling effort and a multi-facet observational program.* Modern estimates based on satellite observations (Randel et al. 1996) show similar results for total water content of the atmosphere (Figure 3.3.6). Assessment of the results of Figure 3.3.6 indicates the total water content of the atmosphere

[19] Actually, the same spatial heterogeneity problem, which makes it difficult to evaluate turbulent heat fluxes over complex horizontally inhomogeneous terrain, affects hydrological and land surface – atmosphere interaction studies in the region and requires a thorough study (Avissar et al. 2004).
[20] Shukla and Mintz, 1982; Georgiadi et al. 1998; Rodrigues-Iturbe, 1999; Hinzman et al. 2004; Vygodskaya et al. 2004.

has significantly increased since the 1960s, especially over Kazakhstan. To date, the aerological network remains the single source of information about the water vapor transport over Northern Eurasia because the radar network does not yet cover the entire continent. Interannual variability of this transport is poorly known. *Modern satellite measurements of the water vapor in the atmosphere of Northern Eurasia (including microwave and spectrally-resolved infrared water vapor sounders would improve quantitative assessment of temporal variations in climatic and hydrological processes on regional scales***.**

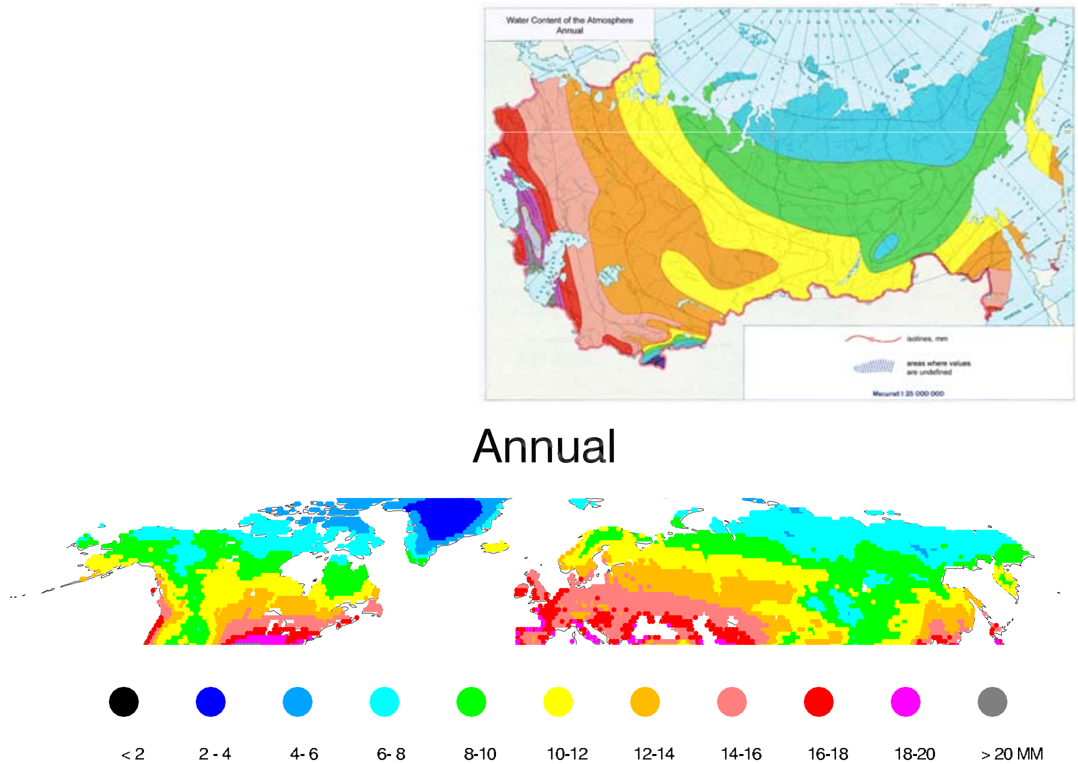

Figure 3.3.6. (a) Annual water vapor distribution in the atmosphere over the former USSR in the [surface to 300 hPa] atmospheric layer based on rawinsonde network for the 1961-1970 period (IWP 1984) and (b) the same quantity over the land areas north of 40º N constructed from satellite (TOVS) and rawinsonde data for the 1988-1999 period (Randel et al. 1996).

3.3.4.2. Changes

To trace the changes in surface energy and water cycles during the past century, we must rely upon the most frequently observed climatic and hydrological variables that directly or indirectly characterize these changes[21]. The time series for surface air temperature, precipitation, snow cover extent, and streamflow are the most commonly available. Figures 2.2, 2.7 through 2.17 show several major features of these changes.

> *The surface air temperature is a function of both short- and long-wave radiation budgets, heat advection, and turbulent heat flux and has significantly increased during the past century (IPCC 2001; Razuvaev 2003; Lugina et al. 2001; Figure 2.2). Snow cover has retreated throughout the century in the spring season (Brown 2000; Figure 2.12). The volume and areal extent of mountain glaciers has decreased markedly (Khromova et al.,*

[21] Radiation measurements are sparse (in situ network) or short (remote sensing) to make reliable conclusions about these changes in Northern Eurasia. Although attempts to make such conclusions on a global and continental spatial scales have been made (Pivovarova 1977, Bryson and Goodman 1980; Vinnikov and Groisman 1982).

2003; 3.6.1). Precipitation and streamflow along the arctic slope of Northern Eurasia have increased[22] *while in internal regions of Central Eurasia dryer conditions have been gradually established during the past several decades*[23]*. In Northern Eurasia, the pattern of runoff changes became much more complicated during the past 50 years due to large-scale direct human intervention (reservoirs' construction, water withdrawal and diversion) and natural and man-induced landscape changes (Figures 2.9, 2.15; and Box insert A3.6.1). In some regions, the natural component (that itself may be a manifestation of global change) prevails while in others, anthropogenic factors dominate.*

3.3.4.3. Major unresolved issues

Critical research tasks include:

- develop, corroborate, and establish modern tools of comprehensive monitoring of the contemporary state of the climate, landscape, and terrestrial hydrology of Northern Eurasia, especially in high latitude and mountain regions.
- integrate results from historical data sets and present observational systems and process studies into a unified knowledge base (a) to better understand the contemporary changes and (b) to capitalize on the past knowledge of the major processes that control surface energy and water cycles in Northern Eurasia[24]. *A concise effort to deliver these results to the research community will ascertain the role of Northern Eurasia in the global SEWC and facilitate all ongoing experiments and studies.*
- create, test, and apply an interactive suite of the land surface models that can account for major land surface process dynamics in Northern Eurasia and interactively feed back to regional and global climate, environmental, and economic models thus closing an

[22] Vinnikov et al. 1990; Groisman, 1991; Groisman et al. 1991, 2003; Georgievsky et al. 1996; Groisman and Rankova 2001; Peterson et al. 2002; Shiklomanov et al. 2002; Yang et al. 2002; Figures 2.14 and 2.15.

[23] Kira 1995; Vaganov 1997;Aizen et al. 1997; Glantz, 1999, Figures 2.11 and 2.12.

[24] An enormous amount of effort has been made during the past decades to allow reliable description of the processes of the heat and water exchange at the surface and to parameterize them for the typical landscapes around the world, including Northern Eurasia (Budyko 1963; Rauner 1972; Korzun et al. 1974; Fedorov 1977; The Study…, 1984; Krenke et al. 1990; KUREX-91, 1998; ISLCSP, Sellers et al. 1995; Global Energy and Water Cycle Experiment and its sub-projects in North America (GCIP, MACS) and Northern Eurasia (BALTEX, GAME) [Lawford 1999; Stewart et al. 1998; Raschke et al. 1998, Kotlyakov and Georgiadi, 1998]; Project for Intercomparison of Landsurface Parameterization Schemes (PILPS; Luo et al. 2003; Bowling et al. 2003); and many others). A network of heat-balance stations deployed since the mid-20th century over the former USSR covers fallow and bare soil types of landscape, but not the forested land. There were ~100 of these stations in the peak of their deployment in the 1970s. A network of research stations (including water balance stations that represent a set of 22 experimental watersheds filled with meteorological and hydrological instrumentation) up to recent time covered all major biomes of the former USSR. Methodology to estimate the surface sensible heat flux from routine in-situ synoptic observations is representative only for bare soil and snow covered landscapes (Groisman and Genikhovich 1997). This methodology can be used at approximately 4,000 locations in Northern Eurasia in the former USSR, Mongolia, China and Romania. The "complex" method of relating surface energy and water balance (Budyko 1971) provides an approximation for climatology of sensible and latent heat fluxes. Long-term field studies of heat energy balance within vegetation cover in European forests were summarized by Rauner (1972). In this study, adjustments have been developed to account for radiation and turbulent flux enhancements over various types of forest compared to the forest-free sites where most of meteorological and all heat balance and actinometrical networks are located. A network of flux measurements (FLUXNET), similar to those that cover some regions of North America, Asia, and Europe (Wofsy and Hollinger 1997), Schulze, 2000; Valentini 2003) is not yet fully deployed across Northern Eurasia. Several international projects have recently been launched to mitigate the lack of vital information on these fluxes. They include field studies in Eastern Siberia (Holllinger et al. 1995; Kelliher et al. 1997, including those in the framework of the GAME (http://www.ihas.nagoya-u.ac.jp/game/GAME-Siberia.html), the Euro-Siberian CARBONFLUX, and TCOS-Siberia projects (set of publications in *Tellus* **54B**, 2002) and the joint Japanese-Russian effort to monitor heat, water vapor, methane, and CO_2 fluxes at a 500 km spatial resolution over Western Siberia (Inoue, 2003).

important loop critical for future climate and environmental change projections and enhancing the society wellbeing.

- address the following issues critical for understanding of surface and energy cycles in the region;

  (a) process studies:

  - Surface heat fluxes should be parameterized within scalable land surface models. These parameterizations should account for landscape heterogeneity.
  - Precipitation (especially convective precipitation) should be realistically described at the storm event level.
  - Hydrological flow-formation models should be enhanced to incorporate anthropogenic impact, glaciers and permafrost dynamics on the background of global warming.
  - Land surface water cycle closely interacts with land cover. It includes the pathways and fluxes of water among snow, glaciers, rivers, lakes, permafrost, ground aquifer, and flow within soils. Contemporary land surface models should reproduce (estimate and project) the variability of the land surface water cycle (including the water composition) and provide a summarized feed back to the atmospheric and riverine branches of the water cycle and to the major biogeochemical cycles. Anthropogenic impact on runoff and its interactions with climatic changes and natural variability should be thoroughly studied and incorporated into the land surface models.
  - A network of research field stations, including Water Balance Stations (WBS), within major biomes of Northern Eurasia has to be re-vitalized and re-equipped with modern instrumentation. Direct measurements of all components of surface energy and water balance should be conducted at most of these the sites. Keeping in mind a significant uncertainty of our understanding the hydrological processes in the permafrost zone, continuity and enhancement of the observational program at the research stations in this zone is a high priority.
  - Permafrost thawing processes should be properly described including interactions with vegetation and soil moisture.
  - The role of blowing snow and sublimation in the distribution of snow cover and seasonal snowpack (SWE) needs to be determined.
  - Advance extreme events modeling (floods, droughts, heat, cold, wet, and dry spells, fire weather, early/late frost, damaging thunderstorms, glacier lake outburst floods, etc.) should lead to an early warning system of natural hazards (cf., (c)); In particular, techniques of forecasting the ice-jam flooding on the Siberian rivers and recommendations on reduction of their catastrophic consequences should be developed.
  - New scaling techniques should be developed to transfer changes and feedbacks among processes of different spatial and time scales (e.g., Randall et al. 2004; Sogachev et al. 2002, 2004). Sub-grid heterogeneities and their impact on heat and moisture fluxes as well as on hydrological processes should be assessed.
  - Controls on the water chemistry processes associated with changes in cryosphere (glacier, snow, and permafrost), biosphere (bogs, soil, vegetation), as well as anthropogenic impacts (pollution, land use, water withdrawal) should be quantified.
  - Understanding ongoing aridization of continental interior, the chemical composition and volumes of primary and secondary aerosols in Northern Eurasian deserts and semi-deserts is important for projecting the global radiative forcing.
  - Estimation of geocryological consequences of global warming should be assessed.

  (b) climate modeling studies:

- How can we improve parameterization of convective precipitation?
- Snow under a canopy is poorly represented in GCMs, how can we improve this situation with physically-correct parameterization (e.g., Onuchin 2001)?
- How can we include the proper representation of permafrost and seasonally frozen ground dynamics into GCMs?
- How can we organize an interactive feedback of impact models to GCMs?
- Do we need river routing to properly force the terrestrial hydrological cycle (or is instant integrated discharge with sharpened seasonality, as in current GCMs, sufficient)?
- It now becoming clear that biogeochemical and land biospheric (dynamic vegetation) components should be an indispensable part of global projections based on GCMs. How can we effectively incorporate them in these GCMs?
- Future projections require estimates of probability distributions changes rather than changes in means; thus a chain of consequences evolves
    - ⇨ massive ensembles rather than single deterministic simulations are needed
    - ⇨ how many members in projection ensembles will be sufficient?

(c) from the point of view of observers and users:

- A representative network of major environmental and hydrometeorological fields should be established (selected) and a homogeneous time series at this network should be collected, maintained, and disseminated to the broader scientific community. Each major biome must be well covered by this network. Furthermore, the observations at this network should be linked with modern remote sensing observation systems (Alsdorf et al. 2003; Wagner et al. 2003), complement them, and provide a much needed third-dimension (time) to assessments of contemporary changes of the Global Earth System.
- Reliable water demand projections should be conducted. These include development of new irrigation practices and new water consumption standards.
- A system of natural hazards' early warning should be developed.
- Historical geochemistry records on major, minor, and trace elements should be collected and assessed. This will allow establishment of a long-term monitoring of the biogeochemical cycle dynamics over the continent. In particular, the measurements of insoluble mineral material deposited on glacier surfaces in Northern Eurasia should be organized and assessed. They may provide a better understanding of aerosol production and transport in the Northern Hemisphere.
- The most recent hybrid observational system of the surface energy and water cycles is a real-time, distributed, uncoupled land surface simulation system (Land Data Assimilation System, LDAS) is a combination of fine resolution (1 km and less) land surface vegetation information, in-situ and satellite observations of precipitation, radiation, and snow cover, and land surface and regional circulation models[25]. *We propose that a system similar to LDAS for North America (NLDAS) would greatly advance scientific analyses in the NEESPI region.*

[25] Developed by NASA in cooperation with NOAA and several U.S. universities, LDAS delivers a spatial resolution of 0.125º for North America and 0.25º for the globe and its performance is now extensively tested for North America (Meng et al. 2003; Rodell et al. 2003; Cosgrove et al. 2003; Pinker et al. 2003; Lohmann et al. 2003; Robock et al. 2003). While LDAS includes sophisticated models to describe the processes at the surface, they all are diagnostic models that work well when quality input information is supplied to them.