5. MODELING

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5.1. Introduction

The triad of major aspects of modeling as such (studying processes, filling gaps in observations, and projecting the future) will be represented in full measure in NEESPI. The overarching, complementary scientific questions for the NEESPI modeling component are:

- What processes control energy, water, and carbon fluxes over Northern Eurasia (NEA) and how do the fluxes vary in space and time?
- What are the direct and feedback effects of environmental changes in NEA on the global Earth System (in particular, how do global climate changes impact NEA ecosystems and society)?
- How have these feedbacks evolved during the instrumentally recorded period and in the geological past?
- Are our models capable of simulating observed environmental changes?
- Can we correlate data obtained from different fields (e.g., parameters of biological turnover of carbon between forest and soil and their dependencies on climate changes) for initialization of model runs?
- Can our models provide an operational interface between on-ground and remote sensing data for data assimilation?

If the answers to the above questions are uncertain, then how our models must be improved to address them? And especially, how do we enhance the capability of our models to simulate the past and to estimate the spectrum of possible future environmental (and societal) changes both in NEA and globally? And, finally, can we assess the vulnerability of NEA to future environmental conditions, even if skilful projections are not possible? These questions are of vital importance to assist policymakers to formulate robust decisions about future human perturbations to the regional and global environment, including atmospheric composition changes (emissions of greenhouse gases (GHG) and aerosols) and land-use changes.

5.2. Background

A key feature of NEA climate projected for the 21st century by state-of-the-art global coupled Atmosphere-Ocean General Circulation Models (AOGCM) is a strong surface air temperature increase (compared to most of the Earth), especially in the second half of the century (e.g. Meleshko et al., 2004). Most of the AOGCMs also project an overall precipitation increase in the north and northeast, but a decrease of soil water content in the interior regions of NEA (already arid) during the summer. The high-latitude (including northern NEA) amplification of global warming due to atmospheric GHG increase is a well-known feature of AOGCM projections (IPCC, 2001). The amplification is attributed to positive feedbacks in the climate system. An important feature of those simulations is a large across-model scatter.

To what extent the projected changes are a result of real processes and feedbacks, rather than to model imperfections? Some presumably crucial processes (e.g. possible changes in vegetation, soil, and permafrost and the effects that these changes will have on future climate) are not adequately taken into account in the state-of-the-art climate change projections. The role of the biosphere, specifically the role of the terrestrial ecosystems dynamics, in the contemporary and projected climatic changes is not yet well understood (3.1, 3.2, 3.5) and was not accounted for on a full extent during the past cycle of the IPCC Assessments (IPCC, 2001). There are indications, including the palaeo-evidence, that, over NEA, this role has been (and very likely will be) especially pronounced (3.5). Clearly, all important processes operating in the NEA environmental systems must be properly represented and successfully simulated by AOGCMs as a necessary condition to provide credible projections of future changes. Our insufficient understanding of the processes and associated feedbacks seriously hampers model skill. The inherent nonlinearity of the climate system also limits the projection skill of the models (Rial et al., 2004).

5.3. Research approach

The NEESPI modeling component will consist of developing and validating models of different systems and scales, scaling model descriptions of different processes, reproducing NEA natural system states and evolution observed in past and present, and, finally, assessing the predictability and projecting future changes. The main foci are processes and feedbacks within the NEA socio-environmental system, and between the NEA system and the global Earth system.

The proposed modeling efforts are to be organized on three scales: local, regional, and global. Such structuring in particular determines clear links between observational and modeling components of NEESPI. Local studies will be mostly process-oriented and connected with *in situ* observational data sets and the most advanced fine-resolution remote sensing information. Regional studies (most naturally – river-basins, administrative regions, major forest tracts, etc.) heavily depend on fine- and moderate-resolution remote sensing information. The global scale studies presume employment of existing global reanalyses and objective analyses of observational data.

The approach implies using (developing) a wide range of models, including atmospheric boundary layer models, soil-vegetation-atmosphere transfer (SVAT) models of different levels of complexity, permafrost models, air pollution models, models of coastal zone evolution, data assimilation schemes, regional 3D atmospheric models coupled to comprehensive land surface components, regional high-resolution hydrologic models (including river routing), dynamic general vegetation models (DGVM), global models, particularly, GCMs, comprehensive Global Earth system Models (GEM, based on AOGCMs with advanced biospheric components), Earth system Models of Intermediate Complexity (EMIC), and Integrated Assessment Models (IAM).

The modeling activity will be supplemented with developing model diagnosis and intercomparison tools, data assimilation, as well as down- and up-scaling techniques.

5.3.1 Local scale modeling

A local scale signifies a scale finer than 10 km^2. It is the scale of single experimental point sites at which individual fluxes or cycle components can be measured directly and individual processes can be modeled explicitly. In forested areas it corresponds to elementary inventory unit (stand). Such studies are crucial before integrating the processes at regional or global scales.

5.3.1.1 Energy and water cycles

For parameterization of the vertical energy/water fluxes at the land surface, so-called SVAT (Soil-Vegetation-Atmosphere Transfer) models of different levels of complexity (single-layer and vertically/spatially structured models) have been developed (reviewed by e.g. Sellers et al., 1997). SVATs reproduce the entire cycles of energy and water transformations at the land surface and within the soil, snow, and vegetation cover. The processes are regulated by both physical and biological mechanisms and their interaction, so the models have to parameterize all of them. To do this, SVATs evaluate the state variables such as temperature and water content of the soil/snow/vegetation. Also, some additional fluxes/parameters (runoff, melting/thawing intensity, etc.) are calculated. Some current SVATs include not only energy/water exchange, but also carbon budget in vegetation and soil and transfer of different atmospheric pollutants (gases, aerosols) between land surface and the atmosphere (including the methane cycle in soil). It should be noted, however, that SVATs only represent biophysical effects such as transpiration as related to carbon assimilation, but not plant growth. There is work to blend SVATs into dynamic vegetation models, but almost all SVATs are still limited to the time scales that they are appropriate.

Accuracy of flux estimates with SVATs depends on (1) model complexity and assumptions used, and (2) precision in estimations of both landscape (biological, hydrophysical, etc.) and atmospheric (downward radiation, precipitation, etc.) parameters.

In most of the available 1D SVATs, horizontal homogeneity of the vegetation canopy is assumed. Internal variability of biophysical properties of vegetation and morphological properties of soils in such models are usually not directly considered. This assumption can be successfully applied to a mono-specific uniform forest plantation. However, accuracy of flux estimates with such models, e.g., for mixed uneven-aged forest stands can be significantly decreased through a variation of biological, morphological and optical properties of individual tree species (Oltchev et al. 2002; Avissar et al. 2004). Such forms of heterogeneity can be accounted by simulation models (Chertov et al., 1999).

Certain difficulties are associated with modeling water fluxes in cold regions and alpine watersheds. The control of extreme seasonal runoff by snowmelt and ice-break-up, large-scale redistribution of snow and the effects of seasonally and perennially frozen soils, water retention by the snow pack, freeze/refreeze of the melt water, glacier runoff, and ice melt under glacial moraines are the processes that need to be better studied (Bowling et al., 2000; Aizen et al., 2000; Rawlins et al., 2003). In recent PILPS (Project for Intercomparison of Land Surface Parameterization Schemes; Henderson-Sellers et al., 1995) and SnowMIP (Snow Model Intercomparison Project; Etchevers et al., 2003) experiments, special attention was paid to modeling cold season processes, and SVATs were tested against observations at NEA sites: boreal forest and grassland (Slater et al., 2001; Luo et al., 2003); boreal forest, swamps, and mountain tundra (Bowling et al., 2003; Nijssen et al., 2003); and permafrost (Gusev and Nasonova, 2004; Machul'skaya and Lykosov, 2002; Shmakin, 1999, 2003).

Shallow lakes (and wetlands) significantly affect the structure of the atmospheric surface layer and, therefore, the surface fluxes of heat, water vapor, and momentum (e.g., Vidale et al., 1997). Furthermore, wetlands are a significant source of methane for the atmosphere (3.1, 3.2). Their role in land-atmosphere interactions and gas exchange is still poorly understood. In most numerical models for environmental applications, most notably numerical weather prediction and climate models, the effects of lakes and wetlands are either entirely ignored or is parameterized very crudely. The problem calls for further investigation, in particular, due to the envisaged increase in horizontal resolution of future numerical modelling systems.

5.3.1.2. Vegetation.

Among approaches which try to model realistic mechanisms of vegetation dynamics, the most popular are perhaps the so-called 'gap'-models formalizing the major mechanism of forest dynamics, namely, formation and subsequent overgrowing of a gap in the closed forest canopy (see reviews in Shugart, 1992 and Shugart et al., 1992). During the past decade gap modeling developed from individual tree-based models to space/height-distributed ones (Smith et al., 1995; Lischke et al., 1999). Long-term dynamics, such as the vegetation succession, depend strongly on whether seeds of successive species are available at the current stage of succession (Lischke et al., 2003). Gap simulation models of forest stand dynamics with fine resolution (typically a patch of 100 m^2) can be applied at local scales. The minimum unit of vegetation can vary from different plant species (e.g. Gignoux et al., 1998) to biomes (Haxeltine and Prentice, 1996). Vegetation objects can have explicit locations or can be placed implicitly in a grid cell with the uncertainty determined by the size of the cell.

There is an understanding that creation of "hybrid" forest ecosystem models with a simultaneous simulation of tree growth, stand development, understorey and ground vegetation, and soil dynamics is a necessary approach to unite description of elements' biological turnover in the forest-soil system and biodiversity dynamics (e.g. Chertov et al., 1999). These models allow for the transition from "turbid layer" models of vegetation to individual-based models linking population and balance approaches (Komarov et al., 2003). Such an approach enables description of heterogeneity of vegetation and soils and joins models of weather and water regime with models of ecosystem dynamics.

The concept of primary succession may be taken as a theoretical basis for calibration of the simulation models for prediction of main tendencies of forest-soil dynamics. This approach allows for the accounting of prehistory and the position of forest site in relation to the climax state. Forest site classification is very useful for distinguishing limits of changing variables, and Monte Carlo procedure allows for diminishing uncertainties in initial data.

Simulation models must account for different climate change scenarios, different levels of nitrogen deposition, changes in water regimes and consequences of different silvicultural operations (cuttings, plantings, etc.), as well as natural and human induced forest fires of different types, which are very important driving processes in vegetation and soil dynamics in NEA. Simulation models, being basic at the local scale, can help in evaluating parameters of the models at the regional and global scales.

5.3.1.3 Permafrost

Despite rapid growth in the permafrost observation network in NEA (e.g., Global Terrestrial Network-Permafrost, GTN-P, and Circumpolar Active Layer Monitoring, CALM, programs, see Section 3.6.1), geocryology remains a data-limited science. This necessitates development of methods for processing and interpreting data obtained from different sources over a range of geographical scales and combining them with mathematical modeling to make the best use of limited empirical information. The important application of numerical simulations is temporal reanalysis of usually short and sporadic observational records of permafrost parameters (e.g., permafrost temperature, thickness of the active layer) to evaluate long-term trends. At the local scale, permafrost models are also necessary to analyze physical processes responsible for spatial and temporal regularities in the permafrost conditions and their relationship to variables dominant over larger areas.

Modeling of permafrost is usually based on employing numerical multi-layer 1D models of ground heat transfer, accounting for phase transitions of moisture as well as snow and vegetation covers. A wide range of numerical simulators has been developed (Goodrich, 1978; Guymon et al., 1984; Romanovsky et al., 1997; Romanovsky and Osterkamp, 2000; Malevsky-Malevich et al., 2001; Machul'skaya and Lykosov, 2002; Ling and Zhang, 2003; Molkentin et al., 2003; Sergueev et al., 2003). Input parameters of the permafrost model include skin temperature at the upper boundary of snow or vegetation cover; the thickness of snow and vegetation covers, and physical properties of soils. At the lower boundary of the domain, the geothermal heat flux is prescribed.

At present, several well-developed 1D heat transfer numerical models are available. However, many permafrost-related processes are 2- or 3D in nature (complex geometry taliks formation, soil settlement upon thawing, thermokarst development, differential frost heave, etc). Therefore, even on the local scale, 2- and 3D permafrost models need to be developed to represent the crucial features of permafrost dynamics.

Pronounced variability of permafrost properties, even within relatively small areas, raises concerns about the ability of deterministic models, either 1D or 3D, to make accurate regional estimates of the volume of thawed soil, which are necessary to estimate trace-gas emissions in high-latitude regions. A more appropriate approach is to consider near-surface permafrost parameters as randomly, spatially distributed variables consisting of both deterministic and stochastic components and to use their probability distribution functions (PDFs) as the metric for evaluation (Anisimov et al., 2002). Within the framework of this method the divide between deterministic and stochastic components is flexible, and depends on the availability and resolution of data required to drive the models. As long as the high resolution data are available, deterministic models can be used to distinguish between permafrost sites with explicitly different soil, vegetation, and snow properties, while the "nested" stochastic models can provide insight into the sub-grid variability of the permafrost parameters. Such an approach based on combination of deterministic and stochastic modeling is yet to be developed.

5.3.1.4 Biogeochemistry (carbon fluxes)

A high resolution soil-vegetation model should provide respiration, net primary productivity, and soil decomposition carbon fluxes. It is rather important to concentrate, not only on carbon dioxide, but methane and water vapor fluxes as well, which are products of microorganism activity in permafrost soils of NEA. Soil temperature and moisture strongly affect the rate of CO_2 emission from soil and methanogenesis and can change the total methane emission to the atmosphere and, therefore, modify the GHG forcing (3.2, 3.5, 3.6.1). It is still unclear how these emissions would respond to climate change and, thus, the methanogenesis should be properly parameterized in models. These local scale biogeochemistry models should capture non-homogeneities of landscapes and incorporate outputs of SVAT models for assessment of drainage and soil moisture conditions. Local resolution biogeochemistry models can be validated against tower flux observations and compared with high resolution atmospheric inverse models.

5.3.1.5 Priorities

Priorities for local-scale modeling include recognizing the most important processes specific for different NEA regions, as well as those affecting the regional and global climate and environment, e.g. biogeochemical feedbacks that change the gas composition and aerosol loading of the atmosphere (3.5, 3.6.1, 3.6.3) and landscape change (Eugster et al., 2000) – to be modeled in more detail. NEESPI local-scale modeling is focused on developing:

- detailed parameterization of the SVAT processes crucial for different NEA regions (e.g. non-uniform vegetation and soil, swamps, lakes and wetlands, high level of ground water, insufficient soil water content, permafrost, complex relief, etc.);
- advanced algorithms to describe impacts of anomalous weather and climate events (e.g. droughts, floods, etc.) on water and carbon cycles of different vegetation types;
- sophisticated approaches (1- and 3D) to describe energy, water, and carbon exchanges between soils, mixed (e.g. coniferous and broadleaf species) forest stands, and the atmospheric boundary layer;
- parameterizations to describe exchange of atmospheric pollutants (GHG, aerosols) between land surface and the atmosphere;
- 2- and 3D permafrost models that will include the thermal effect of changing vegetation, moving ground waters, and changing ground surface geometry;
- models of coastal zone evolution under climate and sea-level changes;

- new methods to describe spatial heterogeneity of the land cover and meteorological input parameters that allow up-scaling heterogeneity effects to the regional scale.

5.3.2. Regional scale modeling

A regional scale signifies a range 10-10^6 km^2. At this scale, local-scale processes are integrated over heterogeneous land surfaces. Interactions in the horizontal between the local scale processes come to a focus. The horizontal interactions can be either direct (e.g. horizontal flows within river catchments), or indirect (e.g. between land surface points via atmospheric circulation). Regional scale modeling provides a bridge between local ecosystem behavior and sub-continental through global-scale phenomena. The finer spatial scales are particularly important for assessing extreme events.

5.3.2.1 Atmospheric regional modeling

Three-dimensional regional atmospheric models, or Regional Climate Models (RCMs), are supposed to have a resolution on the order of 10^1 km and domains of up to a sub-continental size. Depending on the problem to be solved at their lateral boundaries, RCMs can be driven by (or, in other words, downscale) either GCM outputs or global atmospheric reanalyses. Finer scale RCMs can be nested into coarser scale RCMs. Though dependent on the quality of driving GCMs, RCMs allow for meaningful utilization in a broad spectrum of applications, particularly in climate change projections. Usually, an RCM will undergo a complex procedure of calibration and testing before it can be used for a certain region (i.e. it is “customized” to the region). If compared to other parts of the world, NEA (especially its northeastern part) is a region for which few RCMs exist (e.g. Shkolnik et al., 2001).

Among the most evident applications of RCMs within NEESPI are studies of deforestation and forest succession, forest fires, land use changes, climatic zone shift effects on atmospheric general circulation, and chemical composition. RCMs are a valuable tool in air pollution studies. In the framework of NEESPI, RCMs will be used both as drivers of and in a coupled mode with SVAT models, hydrological models, dynamic vegetation models, models of joint forest-soil and biodiversity dynamics, permafrost models, etc.

5.3.2.2. Catchment modeling

A significant part of the NEA drainage area is ungauged, and the temporal and spatial variability of runoff there is not known. The most feasible option for estimating runoff in the ungauged areas, as well as to increase our understanding of different processes, is hydrologic modeling. Current hydrological models demonstrate a skill in replicating timing and variability of terrestrial freshwater fluxes from large river systems. However, there are problems in capturing spatial variability of surface water impoundment by lakes and wetlands and frozen soil by parameterizations that represent spatially averaged processes at the resolution of the model grid cell. Regional hydrological models of varying complexity are used to estimate the projected impact of climate change on runoff characteristics. A number of such models have been developed and adopted for NEA (e.g., Georgievsky et al., 1999; Aurora and Boer, 2001; Georgiadi and Milyukova, 2002).

Accurate estimation of energy and water fluxes demands the precise extrapolation of meteorological parameters within the catchment from data available either from RCMs or from meteorological stations. Spatial patterns of temperature, solar radiation, and precipitation depend on many factors such as regional atmospheric circulation, surrounding relief, and land properties (Oltchev et al., 2002). Thus, development of adequate algorithms for downscaling and extrapolation of meteorological information based on both statistical approaches and process-oriented (e.g., large-eddy simulation) models is required.

Local soil properties are crucial for spatial distribution of ground water flows and infiltration rate within catchments. In many models, the infiltration rate is used for calibrating parameters which is estimated from a water balance equation using results of field measurements of precipitation, physical evaporation, transpiration, soil water content and runoff, and assumption of ideal closure of the annual catchment water budget.

Developing and employing comprehensive river routing models combined with SVATs and comprehensive permafrost models for NEA sub-regions will allow for linking hydrology at the regional scale directly to ecological concerns about the role of water in ecosystem functioning, spatial patterns of habitat condition, and the effects of land-use and climate change on nutrient cycling and water stress in NEA.

5.3.2.3 Dynamic vegetation

Many important processes that control the water exchange between forest ecosystems, rivers, and the atmosphere and feedback effects of changes of moisture conditions on forest functioning are poorly understood. Studies are mostly focused on individual experimental sites and on individual components of the hydrological balance without integrating the processes into a system approach on a regional scale. Moreover, it is still not clear how significantly various factors influence the water budget of forest areas (e.g. deforestation, forest succession, and environmental changes). The latter is particularly important with respect to climate change and variability as well as for planning rational forest management regionally. It is necessary to understand the features of water-regulating and water-protecting functions of forests under climatic changes.

Dynamic general vegetation (or ecosystem) models (DGVM, or DGEM, Woodward et al., 2000; Kucharik et al., 2000) are designed in a modular framework in which different ecological and physical processes, depending on weather conditions and previous stages of soil and vegetation, interact with each other. The main DGVM components include canopy physiology, vegetation phenology, population dynamics and competition, terrestrial carbon balance, soil hydrology, and soil biogeochemistry. Vegetation cover is described in a grid cell as a set of plant functional types (PFTs) (Smith et al., 1997). The definition of plant functional types is based on a few important characteristics of vegetation morphology and ecology: physiognomy (trees and grasses), leaf habitat (evergreen and deciduous), photosynthetic pathway (C_3 and C_4), and leaf form (broad-leaf and needle-leaf) (Haxeltine and Prentice, 1996). Variation in composition of PFTs and associated variation in water, carbon, and energy fluxes provide important input to climate and impact models.

A regional DGVM model for NEA should describe important feedbacks between soil-vegetation and the atmosphere and provide a basis for an improved land surface scheme in RCM. In order to make a synergetic assessment of environmental status of NEA and provide the land surface-atmosphere feedbacks for RCM, the following important ecosystem components are necessary:

- vegetation, particularly larch forest, with competition and population dynamic processes;
- organic floor with different types of lichen, moss, and grass layer communities, providing a regulating role for population dynamics and fire disturbance;
- forest and tundra fires with associated changes in vegetation dynamics, biogeochemical, water, and energy fluxes;
- permafrost, seasonally frozen soils, and wetlands with adjacent heat and mass transfer processes, as well as microorganism communities driving aerobic and anaerobic decomposition and regulating the trace gas fluxes;
- snow with accumulation, melting, and thermophysical regulating.

5.3.2.4. Air pollution

One possible regional impact of projected environmental changes is related to changing the pattern of the wind flows and, therefore, the atmospheric transport and dispersion of natural and anthropogenic air pollutants. It could result in changing the loadings on the ecosystems, including forests and surface waters, risks of morbidity and mortality for humans, and so on. Corresponding assessments can be done using dispersion modelling.

Existing models of atmospheric thermodynamics include advection-diffusion equations (ADEs) that describe transport and dispersion as well as physical and chemical transformations of gases and aerosols influencing the atmospheric temperature distributions, dynamics, and, finally, climate. Corresponding effects are especially important on the global scale. On smaller scales, the feedbacks are frequently neglected and ADE is considered as a client of the numerical weather prediction or climate GCM (RCM). In such a case, output of GCMs is considered as an ADE input. The input, however, should satisfy certain requirements (see Genikhovich and Sofiev, 2003). Specific features of the dispersion model as a client of a GCM/RCM are: (i) variable filtering of turbulence, (ii) variable spatial resolution, and (iii) Lagrangean process modeled, even when using an Eulerean description.

Input fields from GCM/RCM drivers are: 3D wind velocity field, precipitation (type and intensity), surface conditions (land use, snow cover), clouds (type, water content), solar radiation, temperature, and humidity. ADEs need additional input fields, like the eddy diffusivity, mixing height, surface fluxes, and surface conditions (wetness, vegetation), that should be reconstructed from available input data and/or physical parameterizations.

Monitoring networks existing in NEA, especially in its Asian part, are too sparse to provide reliable estimates of anthropogenic and natural pressure of the atmospheric pollution on the environment and human health, both on the impact and background levels. Even less are the monitoring data applicable for estimating possible changes in this pressure due to projected climate changes. In the NEESPI framework, local- and regional-scale dispersion models should be used for generating the state-of-the-art estimates and providing this information for environmental authorities and scientific communities. For the past and present conditions in the European part of NEA, this work will overlap with activities going on in the framework of EMEP (see 3.6.3).

5.3.2.5. Permafrost

Investigation of the temperature and spatial distribution of permafrost is an important problem, assuming a particular significance under the conditions of a warming climate. When setting a problem related to changes of permafrost parameters due to climate change, it should be taken into account that continental permafrost boundaries are rather conventional. When speaking about a shift in permafrost boundaries, a total disappearance of relict permafrost is not implied, but rather a detachment of the permafrost “table” from the bottom of the active layer and a transition from the regime of seasonal thawing to the regime of seasonal freezing in a region between the two conventional boundaries.

As a first approximation, impact of climatic changes on permafrost can be estimated using diagnostic indices based on surface air temperature and/or precipitation. Such approach allows for projection of permafrost evolution under specified scenarios of anthropogenic climate change and compares them with the palaeoclimatic warm epochs (Demchenko et al., 2002; Anisimov et al., 2002b).

Within the general framework of global-change studies, permafrost models currently used for regional, continental, and circumpolar calculations are the most appropriate tools for providing realistic description of climate-permafrost interactions over NEA. Currently available techniques for spatial permafrost modeling, however, rely on regular grids with a cell size comparable with GCM resolution or resolution of fields of required input parameters and an assumption of homogeneity of all geosystem components within each grid cell (e.g., Sazonova and Romanovsky, 2003). This assumption results in uniformly distributed estimates of permafrost parameters within each grid cell, regardless of the level of natural variability. A challenging task would be to account for such variability by means of stochastic modeling. This newer approach has been successfully implemented to a regional study of permafrost in the Valley of Kuparuk River in Alaska (Anisimov et al., 2002a) and will be adjusted to NEA.

At present, very little is known about the spatial heterogeneity of thaw depth at scales beyond those that can be explicitly resolved by existing spatially distributed permafrost models. General hierarchical modeling principles adopted by NEESPI should employ a multiscale permafrost modeling approach to provide transitions between spatial scales at which major geocryological processes operate, data are available, and models are formulated. The linkages between observational data and continental-scale permafrost models should be provided by a series of high-resolution meso-scale regional models. The selection of modeling approach and modeling domain is likely to depend on availability of spatially distributed information required to characterize environmental conditions of the area. Such information includes landscape characteristics derived from remote sensing images and spatial fields of climatic and subsurface variables. Output generated by regional models can be used to characterize sub-grid spatial variability of models operating on a continental scale. They can also be used to provide necessary input parameters for watershed-scale hydrologic and regional atmospheric and ecosystem models.

5.3.2.6. Priorities

Within NEESPI, priorities for regional-scale modeling include direct incorporation of improved parameterizations approbated in local-scale studies and developing different types of models and techniques:

- atmospheric regional models customized to NEA sub-regions (including assessment of RCM skill at improving simulations for NEA that are obtained from GCMs);
- comprehensive river routing models combined with SVAT and permafrost models;
- dynamic general vegetation models;
- comprehensive air pollution models;
- newer permafrost modeling approach that accounts for both deterministic and stochastic (sub-grid) variability of sub-surface, vegetation, and snow properties;
- advanced one-way and two-way nesting techniques for nesting hydrological, permafrost, dynamic general vegetation, and other environment component models into RCMs;
- data assimilation schemes that seamlessly incorporate modern satellite products and ground-based observations.

5.3.3. Global scale modeling

Direct and feedback effects of NEA environmental system within the global Earth system are the main foci of the NEESPI modeling component at the global scale. The relevant studies require employing comprehensive Global Earth system Models (GEMs, based on AOGCMs with advanced biospheric components) and those of intermediate complexity (EMICs, Claussen et al., 2002, 2004). These studies are closely connected with simulating observed and projecting future climates. A major emphasis within the NEESPI modeling component is given to developing and improving global climate model representations of land surface including terrestrial cryosphere, aerosols, carbon cycle, dynamic vegetation, and atmospheric chemistry. Progress in improving the corresponding model components is heavily dependent on the progress in local and regional modeling described above.

5.3.3.1 Effects of vegetation dynamics and interaction with land-surface on NEA energy and water cycles

Climate changes can impact rapidly (through changes of heat and water budgets, air and water pollution) to the intensity at which forest species reproduce. Many studies of forest dynamics showed that boreal forests would be more strongly affected by climate changes than forests in other latitudinal zones (IPCC, 2001). In the view of studies of the response of boreal forest ecosystems to global changes, it is necessary to understand how terrestrial water balances of NEA sub-regions change with time as a function of external factors, such as climatic and land-use influences, and what the effects are of these changes on forest ecosystem functioning.

Representation of the boreal forest and tundra land surfaces within AOGCMs has been, at best, incomplete and, at worst, incorrect (Harding et al., 2001). This is particularly true for wintertime conditions where the snow distribution and its interaction with vegetation are poorly understood and modeled. DGVMs are supposed to be applicable for investigation of the time-dependent behavior of vegetation in NEA affecting Earth system dynamics when climate and land use are changing rapidly. This is because only DGVMs are designed to describe transient (and not equilibrium) changes in vegetation cover and soil in response to changing environmental conditions. Indeed, a number of field observations show that the response of fragile northern ecosystems (tundra, taiga) to possible climate changes may be highly variable and have a multidirectional character. The incorporation of DGVMs into AOGCMs has only recently started. However, even early experiments with the sophisticated land-surface schemes interacting with AOGCMs demonstrated importance of representing feedbacks between boreal vegetation and the atmosphere (Betts, 2000).

The insulating effects and change of surface albedo due to terrestrial snow cover are of particular importance for climate change projections. Current AOGCMs demonstrate varying degrees of sophistication in their snow parameterization schemes (IPCC, 2001). Advanced albedo schemes incorporate dependences on snow age and temperature. However, a major uncertainty exists in the ability of current AOGCMs to simulate terrestrial snow cover, particularly its albedo effects and the masking effects of vegetation that are potentially important for the surface energy budget (e.g., Strack et al., 2004).

5.3.3.2. Effects of cryospheric and vegetation changes on the chemical composition of the atmosphere.

It has been estimated that the ***boreal forest*** regions may currently sequester a substantial amount of carbon, but the non-forest regions may be losing carbon due to the effect of warming in these regions (Apps et al., 1993; Oechel et al., 1993; 3.2). It is not yet clear whether long term increased carbon dioxide levels and associated global warming will increase carbon dioxide release due to increased soil decomposition or increase its uptake due to increased plant growth (Oechel et al., 2000; 3.5.1). The timing of spring ***snow*** melt may be crucial, because in the most northerly sites this can change the length of the active growing season by as much as 50% (Lloyd, 2001). Further south, the variation in the date of snowmelt can change the active season carbon accumulation by more than 100% (Aurela et al., 2001). The processes determining the summer exchanges of carbon are comparatively well understood. On the contrary, the winter carbon exchanges are poorly described. However, they might be important, owing to the 8 to 9 month winter duration in the north of NEA.

An effect of climate change on *forest fires* needs to be studied. On one hand, fires result in additional emission of carbon dioxide whose quantities remain to be evaluated. On the other hand, black carbon released during these fires may have an important additional effect on the atmospheric energy budget. Interaction of fire regimes and thaw/freeze processes are very important for vegetation structure in the permafrost zone and should be directly implemented into a land-surface scheme when making any integrated climate change projections/climate variability simulations.

Permafrost changes may have an effect on the atmospheric chemical composition, particularly GHG concentrations such as CO_2 and CH_4. While some climate models do now incorporate explicit parameterizations of permafrost processes (Volodin and Lykosov, 1998;

Alexeev et al., 1998), the feedback between thawing permafrost and warming climate through released GHG is currently not taken into account in climate simulations.

5.3.3.3. Effect of changes in NEA river runoff on the thermohaline circulation of the North Atlantic Ocean.

The freshwater budget of the Arctic Ocean (and its possible link to the intermittence of the North Atlantic deep water formation) integrates the hydrological cycle modeling problems not only in the Arctic, but also far beyond it – over the vast terrestrial watersheds of the Arctic Ocean (3.3.2). The river discharge into the Arctic Ocean must be properly represented in the AOGCMs in order to maintain its observed stratification and sea-ice distribution and transport. Land surface components of AOGCMs are now including simple river routing schemes able to provide reasonable yearly means of discharge, but not its seasonal cycle. This is particularly the case for the Arctic Ocean terrestrial watersheds where the discharge is highly seasonal (Kattsov et al., 2000). It is not clear, however, whether incorporating more comprehensive river routing schemes, ensuring proper seasonality of the discharge, would result in a significant improvement of the Arctic Ocean general circulation simulated by AOGCMs. A more intriguing question is how terrestrial hydrology-vegetation and hydrology-permafrost feedbacks, particularly in NEA, will affect river water inflow into the Arctic Ocean in the changing climate, and how this, in turn, will influence the global THC.

5.3.3.4. Other effects

Effects of changes in NEA (e.g., land use/albedo) on climate in other regions (teleconnections) should receive particular consideration in the framework of NEESPI (e.g., monsoons, changes in macrocirculation characteristics, such as Arctic Oscillation, North Atlantic Oscillation, Pacific Decadal Oscillation, El Niño/Southern Oscillation). Significant energy and water cycle changes over NEA become part of the global Earth System change and, therefore, their effect is global by definition. Such teleconnections could permit large changes in climate remotely from the study area. Whether this is true or not (and the magnitude of any effect) is a critical research topic (e.g., Arpe et al. 2000; Mokhov et al. 2003).

5.3.3.5. Priorities

Within NEESPI, foci of global-scale modeling should be:

- incorporation of improvements in process understanding at local and regional levels into comprehensive hydrological, vegetation, cryospheric components of GEMs;
- studying effects and feedbacks of environmental changes in NEA in the global context at the decadal, centennial, and millennial time scales and comparison with instrumental, historical, and palaeo data;
- estimates of extreme ranges in climate change impacts in past and in present for the entire NEA;
- assessing the predictive skill of GEMs and projecting the future.

5.3.4. Integrated assessment modeling

Nowadays, environmental policy is internationally and intra-nationally negotiated and climate impact assessments are part of political processes. From this perspective, the future of ecosystems in the NEA in conditions of the changing environment should be accurately investigated and adaptation and/or mitigation options should be elaborated.

The ultimate goal of an Integrated Assessment (IA) study is to represent the environmental change problem within the framework of a quasi-closed system such that the social and environmental consequences of policies to adapt to or to limit environmental change are seen in their totality. The need to include a variety of biophysical process characteristic to cold and dry continental regions in global integrated assessment studies is well recognized. However, a systematic, environmental change IA study has never been conducted for the whole circumpolar zone, or any of its continental parts (like NEA). Furthermore, an explicit mechanism for incorporating and addressing stakeholders' (decision-makers) questions and concerns regarding global change is required to carry out an IA. In application to NEA, such a mechanism should provide, first at all, for the interests of the major industry/agricultural sectors (oil and gas industries, energy production, forestry, and agriculture) and related societal and economic activities.

There are three categories of challenges for IA efforts to actively incorporate stakeholders in application to NEA: (1) an institutional fit problem – matching the scales of the biogeographical systems and the management system; (2) a scale discordance problem – matching the scales of the assessment and the management system; (3) a cross-scale dynamics problem – understanding the linkages between scales and how they affect decision-making, information flows, and the integration of information into the decision making process. A resolution of the problems may suggest substitution of the unidirectional flow of information from research to management (the pipeline model) to boundary organization of IA, which facilitates the multidirectional flow (needs, output formats) between science and decision-making and across scales.

In order to conduct an environment impact assessment, it is necessary to satisfy a strong desire among stakeholders for a qualitative explanation of the various forms that a future world may look like. To provide a framework for the policy makers to respond, the identification of vulnerabilities of key resources to environmental change and variability needs to be developed. Such a framework has been proposed in Pielke and Bravo de Guenni (2004), which includes examples from high latitude regions.

Climate, landscape, and ecosystem changes and variability can be described as a set of several world views, representing the societal values (ranging from consumerist to conservationist) and level of governance (ranging from local to global) in terms of climatic and impact variables. Finally, the world views and their consequences should be presented to locally important stakeholders in more than 20 countries of NEA via a series of individual interviews and group discussions for further corrections of assessment studies (see example of boundary integrated climate impact assessment study in the UK; Lorenzoni et al., 2000). These vulnerabilities should be identified and prioritized.

An IA study should not only present spatial and temporal dynamics of a metric representative for NEA, but also estimate uncertainties related to negligence of some environmental impacts, various aggregation schemes, and explicit or implicit assumptions on methods including possible specifications of non-linearity and synergy effects. The recommended modeling paradigm for an IA study in NEA can be 'strategic cyclical scaling' (Easterling, 1997) which demands the sequential pairing of bottom-up and top-down models over a set of common attributes/metrics determined in collaboration with stakeholders.

5.3.5. Developing strategy for environmental prediction in the framework of NEESPI

In the NEESPI modeling component, a general approach to environmental prediction is synergy that allows and accouts for numerous feedbacks that modify (and may even reverse) the state of the global Earth system. Recent attempts to regulate GHG emissions, to control pollution, changes in agriculture and irrigation practices, and forest management are vivid examples of the changing human activity *in response* to the global climate changes.

The NEESPI strategy for research of impacts of the 21st century environmental changes on ecosystems (e.g., forests, tundra, aquatic systems, agriculture, fire) and the resulting impacts of the changes in ecosystems on the global Earth system (i.e., feedbacks in the coupled Earth system) implies using and including: (a) selected use of GEMs (AOGCMs) and other models (e.g., RCMs, EMICs, nested high-resolution hydrological models, DGVMs, permafrost models, etc.), (b) integrated assessment models, (c) uncertainty (probability) analysis, (d) concentration on extremes such as droughts, floods and heat waves, (e) organization of a seamless observational data flow via data assimilation schemes, and (f) working toward upscaling and downscaling of model outputs to assess the value added and skill of their performance. At the moment it is not clear e.g. how AOGCM projections of future climates can skillfully account for local and regional feedbacks simulated by RCMs or impact models. This problem should be considered in the framework of NEESPI.

There is a large, natural variability in the NEA climate system and this part of the uncertainty cannot be eliminated simply by model development. Instead, one needs to focus on the climate predictability problem and probe the inevitable natural uncertainty through a systematic search in probability space. To do this we need to make ***ensemble simulations*** where both initial states and uncertain model parameters are varied within a realistic range associated with a probability distribution.

5.4. Observational needs of NEESPI modeling component

GEM-based scenarios of the Earth system evolution in the future can only be credible if the models simulate the present and past states and evolution of the system realistically – globally and in the region of interest. While an accurate simulation of the present-day state of the Earth system does not guarantee a realistic sensitivity to an external forcing (e.g. higher GHG and aerosol concentrations, land use change, etc.), a grossly biased present-day simulation may lead to weakening or elimination of key feedbacks from the simulation of change, or an exaggeration of them.

To validate coupled high-resolution models in NEA we need improved and extended ***observational data sets***. *In situ* observations are publicly available for a few locations and restricted time periods and more such data sets (including palaeo-data) are needed. There is an urgent need for a better historical database, especially for the low-populated areas (e.g., Siberia). A link is needed for modern monitoring tools to the historical databases.

A high priority is development of data sets of input landscape, atmospheric, vegetation, and other characteristics with enough temporal and spatial resolution for NEA. To obtain a better coverage in space and time the remote sensing products (6.2) should be utilized in full strength. For the NEA region, gaps exist in the present remote sensing instrumentation capabilities (Chapter 4). They should be recognized (e.g., the absence of reliable precipitation information) and remedies should be researched.

A good opportunity for validating RCMs and driving other types of models (hydrological, permafrost, ecosystem) is provided by reanalyses, employing numerical weather prediction models to convert irregularly spaced observational data into complete global gridded temporally homogeneous data (currently – for periods of several decades). Reanalysis data include both observed (assimilated) variables (e.g. temperature, geopotential height) and derived fields (e.g. precipitation, cloudiness), for some of which direct observations are almost non-existent (e.g. evaporation). Reanalyses have a potential to provide high-resolution validation data, which are not available from the raw observations, as well as provide an effective tool to monitor long term weather changes globally and regionally (e.g. Chase et al., 2000). Reanalyses at a fine scale resolution for the study area seem to have no alternatives in RCM validation. Within NEESPI, a possibility should be investigated of undertaking a ***Regional Reanalysis*** of NEA, similar to North American Regional Reanalysis (Cosgrove et al. 2004), conducted by NCEP and the Arctic System Reanalysis, planned by SEARCH (Overland et al., 2003). This activity could capitalize upon existing global and regional reanalyses and employ a regional NWP model incorporating advanced terrestrial, river-routing, etc. modules customized to the NEA region.

Finally, employing models in planning and directing observational campaigns and experiments and optimizing observational networks should be considered as promising and potentially important interaction between modeling and observational components of NEESPI.

5.5. Links with other programs

NEESPI modeling activity inevitably overlaps with modeling components of a number of already existing programs and, thus, should include learning from them. Evidently, links should be established between the NEESPI modeling component and modeling groups of the World Climate Research Programme (WCRP), Working Group on Numerical Experimentation (WGNE), and Working Group on Coupled Modeling (WGCM), as well as modeling groups and panels of major WCRP programs such as Climate Variability and Predictability (CLIVAR), Climate and Cryosphere (CliC), Global Energy and Water Experiment (GEWEX), and, probably, SPARC. Water fluxes between forest ecosystems and the atmosphere, the interactions of water resources of the land surface with the forest canopy for different spatial and temporal scales, and responses of water-regulating functions of forests on the global climate change are key topics of several major international programs and projects, e.g., International Geosphere-Biosphere Programme (IGBP), International Hydrological Programme (IHP), Global Change and Terrestrial Ecosystems (GCTE) (IGBP Core Project), recently completed Biospherical Aspects of Hydrological Cycle (BAHC), and Boreal Ecosystems Atmosphere Study (BOREAS). The NEESPI modeling component could capitalize upon the knowledge and experience of some national (regional) programs, researching the same or different regions than NEA, but having similar objectives and approaches: Community-wide Hydrological Analysis and Monitoring Program (CHAMP), Study of Environmental Arctic Change (SEARCH), Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), etc. Expectations of model improvement should be associated with the increasing international activity in the field of model intercomparison exercises helping to identify model errors, their causes, and how they may be reduced. NEESPI-oriented diagnostic subprojects should be initiated (if not already) in major on-going Model Intercomparison Projects (MIP), e.g. Atmospheric MIP (AMIP, Gates, 1992), Coupled MIP (CMIP, Meehl et al., 2000), Paleo MIP (PMIP, Braconnot, 2002), PILPS (Henderson-Sellers et al., 1995), SnowMIP (Etchevers et al., 2003), and similar international efforts, e.g. the Climate of the 20th Century (C20C) experiment (Folland et al., 2002).