3.6. Topics of Special Interest

3.6.1. COLD LAND REGION PROCESSES

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3.6.1.1. Introduction

Some definitions

There is no single definition of "Cold Land Regions". Climate classifications, such as Köppen's, identify tundra and polar climates as well as highlands that are cold land regions. Additional criteria might include the presence of permanent ice above, on or below the ground surface i.e. regions with permafrost, glaciers, ice caps, and long-term snowfields. We will not directly include in our assessment sea ice, although interactions in the coastal zone must take account of land-fast ice. The major thresholds affecting the development of ecosystem infrastructure are related to decadal and century time scale degradation of permafrost and glaciers, not to changes in the seasonally frozen layer. Furthermore, the degradation of ice-rich permafrost and glaciers are accompanied by distinct land surface changes that can be detected using remote sensing, whereas changes in the seasonally frozen layer do not have such a clear signature, except for changes in area and frequency of occurrence. Therefore, seasonally frozen ground processes while also relevant to "cold lands" will not be covered in this Section. Actually, all Eurasia north of Himalayas is the region where seasonally frozen ground occurs.

The discussion in this section will be on processes specific to the permafrost zone (continuous, discontinuous and sporadic permafrost), both "latitudinal" and "altitudinal" (mountain), and processes in the glacial and periglacial environments.

Geography of the Cold Regions in Northern Eurasia

[Sub-section was transferred to the Scientific Background Appendix]

Focus of this Section

Most of the physical and biochemical processes were discussed in sections 3.1, 3.2, and 3.5. From this discussion it became clear that the physical and biological systems are closely interrelated. Here we emphasize physical processes directly related to observed and predicted changes in permafrost and glaciers and the consequences of these changes that are important for ecosystems and infrastructure in the Cold Land regions. Also, we will emphasize the interrelations between changes in permafrost and glaciers, on the one hand, and in biota and disturbance regimes (both natural and human-made) on the other, as well as feedbacks between them.

The most important changes that affect permafrost and glaciers result from increases in air temperatures and intensification in the hydrological cycle that augments summer and winter precipitation, snow cover depth, runoff, and summer evaporation from the land surface. Changes in snow duration, soil moisture, and vegetation are among other important climate-related changes (Groisman et al. 1994; IPCC 2001, p. 124; see also Chapters 2, 3.3, and 3.5).

The large observed and predicted future climatic changes will inevitably change the energy and mass fluxes at the land surface and, as a result, the near-surface and subsurface physical conditions in northern Eurasia (soil temperature and moisture, availability of energy and moisture for vegetation, snow line elevation, mass and energy balance and thermal state of glaciers, freshwater ice and so on). This will trigger changes in ecosystems that will be largest in the Cold Land Regions because of

- the immense changes here in the atmosphere and soil climate, and
- the extreme sensitivity of the natural systems in these regions, making them highly vulnerable to rapid natural and anthropogenic changes because of presence of ice near the ground surface with temperatures close to its melting point.

This is especially evident in the mountain areas of central Asia where rapid glacier recession is underway over the last 30 years (Khromova et al. 2003). In the arctic tundra biome, the ground temperatures are generally low and any widespread permafrost degradation in natural condition is not expected in this area during the current century (with possible exception for the European tundra). However, the close to the ground surface location of the exceptionally icy soil horizons, that are very typical for the arctic tundra biome, makes tundra surfaces extremely sensitive to the natural and human-made changes. Any increase in the active layer depth can lead to development of superficial processes that are dangerous for ecosystems and infrastructure. In the boreal forest biome with permafrost, the ground ice horizons typically locate at some depth below the permafrost table. Because of that, the increase in the active layer depth will not lead to immediate development of destructive processes. However, because the temperature of permafrost in this biome is so close to the melting point of ice, warming of permafrost induced by the climate warming or surface disturbances will soon lead to the crossing of the 0°C threshold at the permafrost surface resulting in extensive permafrost degradation. Permafrost degradation will soon affect the deeper icy horizons and trigger numerous destructive processes.

The stability of the ecosystems in the Cold Land Regions relies on the stability of ice that so far holds these systems together. In losing the glacier ice and permafrost we are losing the stability of the systems. Thus, even if some ecosystems could avoid disintegration, their characteristics will be changed dramatically.

3.6.1.2. Contemporary and predicted permafrost changes in the Cold Land Regions

[Section was transferred to the Scientific Background Appendix]

3.6.1.3. Past changes in North Eurasian glaciers and future predictions of their dynamics

[Section was transferred to the Scientific Background Appendix]

3.6.1.4. Major Scientific questions and Their Rationale

Seasonal and long-term changes in ground temperature and depth of the active layer in Northern Eurasia occur under influence of complex hydrometeorological and landscape factors, which are extremely changeable both in time and in space (Water … 1999). Data on permafrost temperature and dynamics are still sporadic and with poor spatial and temporal coverage. Very often, these data were obtained in northern Eurasia by individual science enthusiasts, often without adequate financial support (especially during the last decade). Some sites don't show permafrost temperature increase even with warming air temperatures (Zheleznyak 1998; Skryabin et al. 2003). More studies are needed to explain these data. Orchestrated and coordinated efforts are urgently needed to establish and support comprehensive permafrost monitoring system in northern Eurasia. The emerging Global Terrestrial Network for Permafrost (GTN-P) program can help to address these problems. In 1997, the Global Climate Monitoring System (GCOS) and the Global Terrestrial Observation System (GTOS) identified the active layer and permafrost thermal state as two key cryospheric variables for monitoring in permafrost regions (WMO 1997). In 1999, the Global Terrestrial Network for Permafrost (GTN-P) was established under the GCOS/GTOS.

Following the international workshop on permafrost monitoring held at IARC in Fairbanks, Alaska in 2000, the International Permafrost Association's ad hoc GTN-P group has made considerable progress in organizing and implementing the GTN-P (Burgess et al. 2000; Burgess et al. 2001; Romanovsky et al. 2002). During the last five years, some Russian and international programs were established that could also provide some important information (Georgiadi et al. 2001; Georgiadi and Onishchenko 1998; Fedorov and Konstantinov 2003).

Significant uncertainties still exist in predictions of future changes in permafrost and the active layer. Most of these uncertainties reflect diversity in climate change projections provided by different GCMs and by scenarios of the build up of different greenhouse gases. Especially significant uncertainties exist in future snow cover change scenarios. Also, there is still no convincing evidence of the increase of the active layer depth in the polar and sub-polar regions (Pavlov 1994; Pavlov et al. 2002; Romanovsky et al. 2003; Skryabin et al. 2003). Much longer time series of the active layer measurements are needed. The Circumpolar Active Layer Monitoring (CALM) network was established ten years ago (Brown et al. 2000). This program, assuming it receives continued support, can provide these time series. There are compelling data on an increase in the active layer depth in the mountain permafrost zone (Brown 2000; Marchenko 2002; Sharkhuu 2003).

A more comprehensive evaluation of glacier changes is imperative to assess ice contributions to global sea level rise and the future of water resources from glacierized basins. For different regions, the available estimations of mass balance of glaciers based on different observational periods and have used different methods. The number of direct mass balance measurements is limited. All available long-term reconstructions of mass balance time series indicate negative values almost for all northen Eurasia glaciers during the 20th century. However, the sparse mass balance data need much more input form remote modem techniques studies to be robust in spatial and temporal coverage. The recent availability of high-resolution Landsat-7 ETM+ and ASTER images, together with new digital inventories of glaciers in the former Soviet Union, in combination with GIS techniques, affords one avenue to a practical solution of these problems. The Second Adequacy Report on the Global Observing Systems for Climate has reaffirmed the importance of glacier observations (GCOS, 2003; see also http://www.wmo.ch/web/gcos/networks.htm). The study have been planned under the umbrella of the evolving World Climate Research Programme (WCRP) Climate and Cryosphere (CliC) project (http://clic.npo-lar.no) and will also provide a contribution to the forthcoming 2005/06 assessments of the Inter-governmental Panel on Climate Change (IPCC).

Changes in the physical environment will force the Cold Land Region ecosystems to cross several very important thresholds. These are: (1) times and locations where an increase in thickness of the active layer reaches the upper surface of massive ground ice bodies or extremely ice-rich soil horizons, (2) mean annual temperature at the base of the active layer exceeds 0°C and permafrost starts to thaw from the surface downwards, (3) the complete, or practically complete, disappearance of glaciers from the mountain watersheds.
The scientific questions here are:

- ***How well do we know these thresholds? Do we know all of them?***
- ***How well we can predict the moment in time and the spatial location of the regions when and where these thresholds will be crossed?***
- ***What should be done to improve our prediction capabilities?***

The crossing of these thresholds will unleash many natural processes that will enhance changes in the Cold Land Regions of Northern Eurasia and subsequently affect the entire Earth System. Some of these processes may be quickly developing and very destructive for the northern and high-altitude ecosystems and infrastructure. Examples of these processes are: 1) surface settlement, 2) thermokarst formation, 3) swamping, 4) talik development, 5) landslides and slope failures, 6) activization of movement of the rock glaciers and rock fields; 7) thermal erosion of the river banks and deep gullies formation, 8) dramatic increase in river sediment loads, 9) desertification, 10) increase in glacier surges with increase of probability of floods and mud-flows, 11) decrease of volume of melt-water production, river runoff, drooping water level of lakes, loosing high-altitude pasture, 12) loosing attractiveness of mountains for recreation and sport.

- ***How well do we know the physical and biophysical drivers of these processes?***
- ***How well we can predict them and their ecological and societal consequences?***

The principal processes in the Cold Land Regions that affect regional and global systems are: 1) changes in hydrology, 2) changes in vegetation, 3) changes in energy and water fluxes between the land surface, Arctic Ocean, and the atmosphere, 4) changes in CO_2 and CH_4 cycles.

- ***What are the special problems of global change in permafrost and mountain regions given the close proximity of biotic zones, biodiversity, heterogeneous terrain (water cycle and extreme events)?***
- ***How will the local and regional changes in hydrology and vegetation feed back to the permafrost and glacier degradation?***

3.6.1.5. Impact of permafrost degradation on surface hydrology

Permafrost degradation can substantially change the surface hydrology in many ways. Within the area with ice-rich permafrost and poor drainage conditions permafrost degradation will lead to significant ground surface subsidence and pounding ("wet thermokarst"). The ground will become over-saturated, which could cause trees to die (Osterkamp et al. 2000; Jorgenson et al. 2001). Standing water covers a large portion of these areas, which changes surface albedo, evapotranspiration and heat exchange conditions. This kind of terrain will be developing within some portions of floodplains, low terraces and at some places within the highlands and plateaus. Permafrost degradation on well-drained portions of slopes and highlands will proceed in a form of "dry thermokarst". This process will further improve the drainage conditions and lead to a decrease in the ground water content (Hinzman et al. 2003; Hinzman et al. 2004).

Changes in the active layer thickness and permafrost continuity will affect ground water and river runoffs. Since permafrost is the single most dominant control on arctic terrestrial hydrological processes, it is important to achieve a better understanding of how permafrost will change with changing climate and how these changes in permafrost will affect the arctic and sub-arctic hydrology. In time, the Arctic Ocean watershed will change from the recent condition, when the continuous permafrost is typical for most of the area, to a watershed less and less affected by permafrost. In the future, the larger portion of the watershed will be covered by discontinuous permafrost and this portion will be expanding. Changes in river runoff (both the total discharge and the seasonality) will be different for different parts of Northern Eurasia due to differences in permafrost, hydrological and geomorphologic conditions and vegetation (Georgiadi 1997; Water … 1999). The major question is how Northern Eurasia river discharge will be affected by these changes and what changes in discharge will be observed during the current and the following centuries. Changes in permafrost continuity and in seasonally thawed/frozen layer characteristics will affect the conditions of the groundwater recharge. Furthermore, permafrost degradation will affect ground water flow and storage, significantly changing the portioning of water between evapotranspiration, surface runoff, and ground water flow. However, the changes in ground water storage and discharge (hydrogeology) related to permafrost degradation are not very well understood and much more research is needed.

Current climate warming as well as anthropogenic impacts on river channels are the main reasons of recent catastrophic floods in Eastern Siberia caused by ice dams (Lobanova 2000; Lenskie waters 2003). Their frequency during last decade increased in comparison with previous long-term period. These events led to a significant damage and loss of human lives. Mechanism of such phenomenon is not clear yet. It is not clear now how the frequency and size of catastrophic ice dams and related floods could change under future climate conditions.

3.6.1.6. Impact of glaciers and mountain permafrost degradation on surface hydrology

Glaciers provide from 20 to 45% of total river runoff in alpine central Asia (Aizen et al. 1995b; 1996; Aizen and Aizen 1998). In the Northern Tien Shan, the volume of stored ground ice, both seasonal and perennial is comparable with that of modern glaciers. Melting of this ice accounts for up to 20% of the total runoff (Gorbunov et al. 1997). The recent decrease in the volume of glaciers in this region is equivalent to the mean annual runoff of the Sir-Darya River nourishing the Aral Sea. Glacier melt and permafrost thaw are increasing only in the heads of the river basins of large-scale glaciation or extensive permafrost presence. In the river basins with relatively small glacial coverage, the increase in glacier melt has led to a decline in the area covered by glaciers and has thus reduced the contribution of glacier melt to river runoff. At the same time, the permafrost thaw causes the development of large aquifers that may absorb and store large volumes of water. Therefore, assessment of the decadal changes in glaciers and mountain permafrost in this the world largest closed drainage basin (Aralo-Caspian and Tarim) could help to elucidate some hydro-climatic questions in this region and improve our knowledge of other environmental problems such as drought in the Aral Sea region and Lobnor lakes, and the Caspian Sea and Issyk Kul lakes rise.

Combined changes in glaciers and permafrost share in river runoff modify water cycling and storage in terrestrial reservoirs affecting water supply, flood magnitude and frequency, stream chemistry, impact on chemical species, nutrients in lakes, streams, and soils. Forecasted increase in evaporation and liquid precipitation, degradation of glaciers and permafrost should change the moisture exchange between external and internal water cycles and water resource redistribution in the central Asian lakes and watersheds. Disappearance of glaciers collapses the natural storages of solid precipitation and intensive permafrost thaw increases water seepage to the deep ground systems destroying the surface runoff.

Runoff from the glaciers and thawing permafrost at the northern edge of Central Asia in the Altai-Sayni Mountains has a significant influence on the hydrological regime of the large Siberian rivers such as the Ob', Yenisey and Amur Rivers and plays a part in regulating the global thermohaline circulation through the hydrological cycle of the Arctic Ocean (Wang and Cho 1997). According to Barry et al. (1993), the continental runoff amounts account for about 53.9% of the total freshwater inflow into the Arctic Ocean, and the water flowing from the Ob and Yenisey rivers accounts for 40% of the total river inflow into the Arctic (Aagaard 1980). We expect that modern climate change that impacts runoff in the headwaters of these rivers have a considerable influence on the freshwater budget of Arctic Ocean. However, the scale of this influence is unknown and the specific physical processes involved are very poorly understood.

3.6.1.7. Impact of permafrost degradation on ecosystems

Northern ecological systems depend on permafrost conditions. Permafrost controls plant communities and biomass production by soil temperature, active layer thickness, moisture content, presence of unfrozen water, and surface hydrology. The changes in the permafrost thermal regime and active layer thickness can affect plant diversity and biomass (Walker et al., 2003). There is some available data showing that various changes have already occurred to the vegetation in the recent past (Silapaswan et al. 2001; Sturm et al. 2001a; Zamolodchikov et al. 1998). Degradation of permafrost in the southern tundra zone often creates local well-drained microsites favorable for the establishment of tree and tall shrub species at the arctic treeline (Lloyd et al. 2003).

The thawing of the ice-rich permafrost within the boreal forest biome can lead to destruction of the substrate and major changes in ecosystems. In case of the "wet thermokarst" scenario of permafrost degradation, changes can result in replacement of the boreal forest with wetlands (Figure 3.6.6)[56], and changes in wildlife habitats (Osterkamp et al. 2000; Jorgenson et al. 2001; Zamolodchikov and Karelin 1999). In case of "dry thermokarst", the boreal forest ecosystems may be replaced by steppe-like habitats (Figure 3.6.7). As a result of these changes, the area of boreal forest can be reduced; the habitat area for caribou and other terrestrial mammals and terrestrial birds will be shrinking, while the area favorable for aquatic birds and mammals will be increasing.

Figure 3.6.6. Thawing of permafrost in poor drainage conditions converts boreal forest into wetlands in the Tanana Flats, Fairbanks, Alaska (photo by T. Jorgenson).

Figure 3.6.7. Thawing of ice-rich permafrost, triggered by the forest fire in Central Yakutia, transforms boreal forest into steppe-like habitats (photo by V. Romanovsky).

Long-term permafrost degradation (even without active thermokarst processes) will continuously improve conditions for the subsurface water drainage (especially in sandy soils) that will lead to increased dryness of soils, putting significant stress on vegetation. Improved drainage conditions will also lead to shrinkage of numerous ponds within the degrading permafrost area dramatically affecting aquatic ecosystems (Yoshikawa and Hinzman 2003; Hinzman et al., 2004). Increased thermal erosion of slopes and riverbanks will increase flux of sediments into the river systems affecting the riverain aquatic ecosystems and clogging the salmon spawning streams with sediment and debris.

[56] Figures 3.6.1 through 3.6.5, 3.6.11 through 3.6.15, and Table 3.6.1 are in Scientific Background Appendix.

3.6.1.8. Impact of glaciers and mountain permafrost degradation on ecosystems

Climate warming and glaciers and permafrost degradation will change the mountain and foothill ecosystem dramatically. Landscape and morphology in postglacial environments will be dominated by the eroded landforms (e.g., such as eroded bedrocks, rock knobs, striated rock surfaces, roches mountonees, cirques and troughs), creating some of the most spectacular landscapes on the Earth. Large and small lakes are and will be developing in deglaciated valleys. A current and further expected drop in the water resources of the Central Asian Mountains, such as degradation of glaciers and alpine permafrost, and an increase in seasonal soil thawing will promote development of adverse cryogenic processes (thermokarst and thermal erosion) and entail catastrophic phenomena (landslides and glacial mudflows). The changes in precipitation partitioning among land surface storages with different residence times, evaporation fluxes, and subsurface storage and flow significantly affect mountain river runoff, lake water stores and ground water reservoirs in the Aral-Caspian, Balkhash, Issyk Kul and Tarim basins. The water resources in mountains are the main source of water and are especially important now, when severe drought in Central Asia has persisted for several years (Agrawala et al., 2001). The ice loss will also open up new terrain lead to plant and animal migrations and expose new mineral resources (gold mining in the Tien Shan).

3.6.1.9. Impact of permafrost degradation on carbon cycle

Significant amounts of carbon are now sequestered in perennially frozen soils (permafrost) and within the active layer, which thaw every summer but completely re-freeze during the following winter, where the organic matter decomposition is slow. This may lead to additional carbon accumulation (Michaelson 1996; Bockheim et al. 1999). That is why the majority of northern ecosystems are apparently carbon sinks at present time. Climate warming and caused by this warming permafrost degradation will change this situation. A thicker, warmer and dryer active layer will be much friendlier for microbial activities during the summer. Significantly later freeze-up of this layer in winter and warmer winter temperatures (that means much more unfrozen water in it) will considerably enhance the microbial activities during the winter. So, the arctic and sub-arctic ecosystems could turn into a source of CO_2 (especially on an annual basis) very soon. Actually, this is already happening (Oechel et al. 1993 and 1995). Further permafrost degradation and formation of taliks will amplify these changes because a layer that will not freeze during the entire winter (talik) will appear above the permafrost, where microbial activities will not cease during the winter. In the area of “wet thermokarst” formation, new and significant sources of CH_4 will be developing. There will be a considerable difference in greenhouse gas production from degrading permafrost depending on a different type of substrate and soil carbon quantity and quality. This point is very well appreciated. However, there will also be a substantial difference, depending on the age of thawing permafrost. Many areas of present-day permafrost degradation involve permafrost that was formed during the Little Ice Age. This permafrost was in existence only for the last 200-300 years. During the previous several thousand years this material was not frozen. In this case, we should not expect any significant changes in carbon fluxes from these areas upon thawing. Much more dramatic changes in the emission of greenhouse gasses will be observed when old syngenetic permafrost (e.g. “Ice Complex”) would start to thaw (Zimov et al. 1993, 1996 and 1997).

The local and regional changes in hydrology and vegetation will strongly feed back to the permafrost and glacier degradation, significantly increasing nonlinearity of the major ecological and societal processes in the Cold Land Regions of Northern Eurasia. It was well established in permafrost science that vegetation (especially ground surface vegetative layer) plays one of the most important roles in forming permafrost characteristics (permafrost temperature and the active layer thickness) and in determining permafrost stability

(Kudryavtsev et al. 1974; Luthin and Guymon 1974; Brown et al. 2000; Sturm at al. 2001b; Walker et al. 2003; Sazonova and Romanovsky 2003). The major effect that vegetation change inserts on permafrost manifests through changes in insulative properties of the ground vegetation. Another important outcome of changes in vegetation is the alternations in winter snow cover depth and its thermal properties. However, very limited data are available on thermal properties of the ground vegetation cover (Feldman et al. 1988; Gavriliev 1998; Beringer et al. 2001). Also, there are many uncertainties in the future projections of the ground vegetation evolution in response to changing climate.

Even more uncertain is the feedback effect of changes in surface and subsurface hydrology on permafrost. There are some data available that the development of both “wet” and “dry” thermokarst creates a positive feedback in the process of permafrost degradation (Kudryavtsev et al. 1974; Yershov 1998; Fedorov and Konstantinov 2003). However, the dryness of the active layer can trigger some negative feedbacks to the permafrost temperature and, under some conditions, can increase the permafrost stability. Much more research on this topic is needed.

NEESPI program can contribute significantly in resolving these uncertainties by development a truly integrated study that will include remote sensing, field and laboratory experiments and physical and ecological modeling.

3.6.1.10. Impact of permafrost and glaciers’ degradation on infrastructure

Thaw settlement related to permafrost degradation is presently responsible for damage to houses, roads, airports, military installations, pipelines, and other facilities founded on ice-rich permafrost (Osterkamp et al. 1997). Any natural increase in the mean annual surface temperature of permafrost and subsequent thaw settlement would create severe maintenance problems for facilities in the Arctic and Sub-Arctic, adding to effects already being observed. Some structures, airports, and roads might have to be abandoned if funds are not adequate to continue repairs (Esch and Osterkamp 1990). The physical and mechanical properties of permafrost are generally temperature dependent and, for warm permafrost (permafrost within one or two degrees of thawing), dependent strongly on temperature. Most of the engineering concerns related to a climatic warming can be classified into those related to an increase in permafrost temperatures, those related to increases in the active layer thickness, and those related to the degradation of the permafrost.

Engineering concerns related to a general warming of the permafrost result primarily from the decrease in mechanical strength, especially compressive and shear strengths, and the increase in creep rates of frozen ice-rich soils. Systematic increases in the thickness of the active layer may be expected to lead to thaw settlement. Increased frost heaving during winter may also be expected. Continued climatic warming and increases in the depth of the snow cover will eventually cause much of the discontinuous permafrost to thaw. Continued thawing at the permafrost table results in progressing thaw settlement in ice-rich permafrost. Thermokarst terrain, increased downslope soil movement and landslides, and other terrain features common to degrading permafrost may be expected to appear. Roads, airfields, railway embankments and other foundations on degrading permafrost may be subject to continuing deformations as a result of the thaw settlement. Accurate predictions of the climate-permafrost response at a regional level are needed to assess the timing, duration, and severity of these problems. New and innovative engineering design will be required to solve them.

In mountainous regions of Central Asia and Caucuses, the warming climate caused activization of slope instability processes including solifluction, landslides, debris flows, catastrophic rock glaciers moving, catastrophic events, such as the rock-ice avalanche at Kolka Glacier, northern Ossetia, Russia, in September 2002 (Institute of Geography 2002; Kääb et al. 2003), and development of thermokarst depressions. Development of thermokarst lakes on moraines can lead to mudflows, which a hazard to ecosystem, population and infrastructure of high mountain regions. The development and growth of dangerous glacier-dammed lakes, due to the progressive disintegration of debris-covered glacier tongues pose major societal and economic hazards. In the mountains where gravitational processes play a decisive role in mobilizing the material, the differences in the physical and mechanical properties between frozen and thawed soils control the susceptibility of slopes to natural and man-made impacts. Anthropogenic modification of the landscapes in the permafrost areas together with recent warming often triggers destructive natural processes.

The impact of glacier runoff changes for streamflow, stream chemistry, and soil moisture may be severe in the productive yield-growing regions and quality water supply in down-river villages and towns. The air masses polluted over the Central Asia are the source of thousands of tons of toxic chemicals and radionuclides in snow/ice accumulation areas poisoning glacier water resources for several generations. Decrease in glacier river runoff has a formidable impact on hydropower, melioration system, lake level and water supply in alpine villages and down-river towns. The consequences could be so sever that it will require removing existing settlements or search for other sources of water.

Protection of the quality and supply of Freshwater resources is the issues in disputes concerning trans-boundary water resources. The water-issued problems are extremely important for Kyrgyzstan and its neighboring countries because Kyrgyzstan has key geographic position in water sources and water distribution. Although small, land-locked, and bereft of major resources, Kyrgyzstan has an important location at the headwaters of major river systems in Central Asia, streamed from high mountain cold regions of the Tien Shan and Pamiro-Alay mountain ranges, which enables it to affect critical and sensitive issues such as agriculture, electricity generation, and the environment in the down-river countries of Kazakhstan, Uzbekistan, and Turkmenistan. Kyrgyzstan's neighboring countries depend upon water resources originating in Kyrgyzstan to meet their agricultural and domestic water supply needs. Furthermore, Kyrgyzstan depends on its water resources for a large portion of its electricity requirements. Consequently it is important that Kyrgyzstan, in cooperation with its neighbors, manage its water resources in the most sustainable manner possible.

Socio-economic consequences of the ongoing changes in permafrost and glaciers in the Cold Land Regions of Northern Eurasia are paramount and are further discussed in Section 3.6.2 and, mostly, in Section 3.4.

3.6.2. COASTAL ZONE PROCESSES

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3.6.2.1. Definition of Coastal Zone

The coastal zone can be defined in many ways depending upon the perspective of the individual. In this plan, the coastal zone is defined as the area near the shore that experiences the interaction of land and sea, both during the past several millennia (4-5,000 yrs) and during the next century. This zone extends seaward and inland, due to the interaction of waves, tides, sediment erosion and deposition, and freshwater flux from rivers and groundwater. In the ocean, the limit of the coastal zone is arbitrarily specified as the point where riverine effects are only 10% of similar marine processes. In the Arctic, this boundary frequently coincides with the 20 pro mille isohaline in the sea surface layer. Landward, the zone is limited by the extent of extreme storms, wave and wind surges, saline groundwater intrusion and other related processes. Practically speaking, the coastal zone may stretch from 5 to 200 km seaward and from 10 to 100 km landward from the shoreline (Figure 2.5a).

3.6.2.2. Importance of coastal zones of Northern Eurasia

Presently, coastal zones of Northern Eurasia include over 40% of the population and more than half of the area's economic resources. The recent trends of increasing population and economic activity accompany degradation of the coast due to erosion, denudation, and slope processes. Prospecting and exploitation of oil and gas fields, both onshore and offshore, also affect this zone.

In the whole coastal zone of Northern Eurasia, economic development and natural processes have already resulted in dramatic conflicts between various economic and environmental interests. Industrial, port, and oil and gas field development may conflict with recreational use and the necessity to conserve unique ecosystems; living conditions for local people may be enhanced, or degraded. Due to all these factors, the risk of catastrophic events in the coastal zone of Northern Eurasia has increased and will inevitably increase further. Under present and anticipated future levels of anthropogenic impact, the major regions at risk are coastal zones of the Pechora, Kara, Laptev, East-Siberian, and western Chukchi Seas in the Arctic Ocean, the northeastern Black Sea, the Sea of Azov, the north Caspian Sea, and the Sea of Japan in the south of the region. Furthermore, protection of the Baltic Sea coastal zone is a matter of great concern to all the Baltic Sea states.

3.6.2.3. Past and present changes in the coastal zones of Northern Eurasia

Coastal zones of Northern Eurasia underwent drastic changes during the last millennia. The shoreline of several coastal areas migrated landward by 300-400 km (especially in low-lying Arctic areas and on the North Caspian) during the past 10,000 years after the continental glaciation in the Northern Hemisphere had totally disappeared. This landward migration was a result not only of sea-level rise but also, even more importantly, of coastal processes

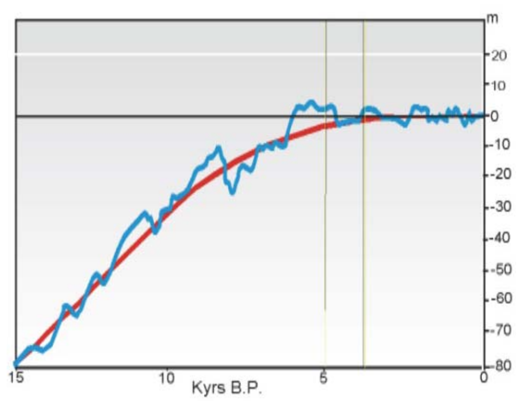

Figure 3.6.8. Global mean sea-level rise during the past 10,000 yrs. The general trend (red line) and fluctuations are shown. The period of sea-level rise deceleration indicating the beginning of the present period of coastal zone evolution (nearly 5-4,000 yrs B.P.) is shown by vertical bars (adapted from Selivanov 1996; Kaplin and Selivanov 1999).

(erosion, denudation, slope processes). Specific coastal segments, such as river deltas, advanced seaward by several dozen kilometers due to heavy sedimentary inflow. During the past 4-5,000 years, the rate of sea-level rise slowed (Figure 3.6.8) and sea coasts reached some sort of equilibrium. This situation was disturbed during the 20th century primarily by anthropogenic activity. By the end of the 20th century, over 70 percent of the Northern Eurasian coasts had undergone erosion and degradation (Bird 1993; Pirazzoli 1996; Kaplin and Selivanov 1999).

The increasing depth of coastal waters, and changes in their salinity and chemical composition already has resulted in significant coastal ecosystem changes. Presently and in the decades to come, Northern Eurasia is/will be one of the most important natural systems to study because of the area's widely increasing economic development and high sensitivity to anthropogenic impact from local, regional and global sources. Furthermore, in the next few decades, the Eurasian Arctic coastal zone will be a critical natural system to monitor because of polar amplification of projected climatic changes (IPCC 2001), and the possibility that changes in the highly sensitive Arctic coastal zone may feed back to the global oceanic ecosystem (ACIA Report 2004).

The extremely high vulnerability of the Arctic coastal zone is determined by the following factors:

- intensive prospecting for, developing, and exploiting oil and gas fields, both offshore and onshore, and accompanying pipelines, refineries, infrastructural and other engineering development in the coastal zone;
- high natural sensitivity of seacoasts due to intensive retreat of sea coasts (in some places over 10 m yr^{-1}) as frozen ground warms and is lost, and the resulting degradation of unique ecosystems and lower living conditions for the local population.

Recent changes in Arctic climate are leading to increased frequency of cyclones, warming, melting of permafrost, and increased river runoff that can lead to environmental changes in the Arctic seas. Increased atmospheric forcing and runoff have caused an increase in the flux of dissolved and solid terrestrial material to the Arctic Seas, especially the Laptev and East-Siberian Seas. Increased offshore transport of terrestrial material is expected to contribute significantly to sediment accumulation and carbon, nitrogen and phosphorus (CNP) cycling in the Arctic Ocean (Semiletov et al. 2000; Peterson et al. 2002).

Other areas of risk are the northern Black Sea, the Sea of Azov and the Baltic Sea coastal zones with their very high level of economic development and coastal materials composed primarily of loose sediments. Economic development includes port facilities, heavy industry, recreation and also, during the past decade, oil and gas pipelines crossing the coastal zone. Various types of economic activities and specific hydrographic characteristics of the Baltic Sea determine the high vulnerability of the Baltic Sea coastal zone. In the Caspian Sea, the problems are aggravated by oil prospecting and development immediately in the coastal zone (Kaplin and Selivanov 1999).

The northern Black Sea and the Sea of Azov also need immediate attention because of their high vulnerability to changes in biogeochemical processes and water salinity. Anoxic water horizons in the Black Sea episodically influence coastal waters and this effect may increase in the future. In the Sea of Azov, bioproductivity of "beach-builder" mollusks and their shells, which depends upon water salinity, affects the rate of coastal erosion (see **Box insert A3.6.1**).

3.6.2.4. Major research problems:

What were the changes in coastline position, environment, and population migration and adaptation strategies in Northern Eurasia during the past 5,000 yrs? Proper consideration will be given to the following:

- estimation of changes in shoreline position during this period in the coastal zones of Northern Eurasia, especially in highly climate-dependent areas such as the low-lying Arctic and north Caspian Sea.. The intensively eroding northeastern Black Sea, the southern coast of the Baltic Sea, and the eastern Sea of Azov should be closely monitored.
- application of important lessons learned from our experiences with population migration, ethnic evolution and past cultural adaptation strategies in order to create successful strategies for future coastal development during the present century.

How do human modifications of land use and land cover during the last 50-100 years affect the state of the inland waters, marine and coastal environments, ecosystem functions and ecosystem feedback, and to what extent can anthropogenic impacts influence these processes in the upcoming decades?

What is and will be the impact of climate change on the quality and supply of freshwater, and on coastal saline water quality? Answering this question requires determination of:

- the initial conditions (i.e., the "quasi" equilibrium state of the coastline),
- the present trends,
- the connection between atmospheric processes, river discharge (liquid and solid), transport and fate of fluvial and particle transport to the marine coastal zone, and
- projection of future changes.

What is and will be the effect of climate, sea-level and related changes on biogeochemical cycles in semi-enclosed seas like the Black Sea and the Sea of Azov and enclosed lakes like the Caspian Sea?

It is of particular importance in Global Biogeochemical Cycle studies to include the coastal zone of the Arctic Ocean. This ocean accounts for 20% of the world's continental shelves. The amount of terrestrial organic carbon stored in the wide circum-Arctic shelf and slope areas is certainly of importance for calculation of organic carbon budgets on a global scale (Macdonald et al. 1998; Aagaard et el. 1999; Gobeil et al. 2001). More than 90% of all organic carbon burial occurs via sediment deposition on deltas, continental shelves, and upper continental slopes (Hedges et al*.* 1999), and a significant portion of organic carbon withdrawal occurs over the Siberian shelf (Fahl and Stein 1999; Bauch et al. 2000). Determining the magnitude of particulate and dissolved fluxes of organic carbon and other terrestrial material from land is critical to constraining a range of issues in the Arctic shelf-basin system, including carbon cycling, the health of the ecosystem, and interpretation of sediment records**.** The role of the coastal zone in the transport and fate of terrestrial organic carbon has not been discussed sufficiently, although it has been stated that coastal erosion plays an important role in the dynamics of coastal permafrost, bathymetry, and transport of terrestrial material (Reimnitz et al. 1988; Are 1999). Studies conducted along the North American shelf (Schell 1983; Reimnitz et al. 1988; MacDonald et al. 1998) indicate large volumes of, and significant variability in sediment contribution by coastal erosion, riverine runoff, and *in situ* primary production within 10 km offshore. Biogeochemical consequences of coastal erosion play a significant role in the formation of a net primary production, (NPP) with a terrestrial signature that has been found in the food web over the narrow North American shelf (Schell et al. 1983). This terrestrial signal should be most pronounced in the near-shore zone of the Eurasian Arctic where rates of coastal erosion are highest and the shelf is the widest and most shallow (Semiletov 2003). However, biogeochemical consequences of coastal erosion may be more pronounced over the wide, shallow East Siberian shelves in comparison with the narrow Arctic Alaskan and Canadian shelves, because distribution of the stable carbon isotope data shows a westward increase in "light" terrestrial organic carbon from the Beaufort shelf to the East Siberian and Laptev Sea shelves (Semiletov 1999a,b; Naidu et al. 2000). The above indicates that the coastal zone plays a significant role in the regional budget of carbon: transport, accumulation, transformations, seaward export, and atmospheric carbon dioxide (CO_2) emission. Therefore, ***biogeochemical consequences of changing coastal erosion and fresh water input in the Arctic coastal zone need to be investigated on a priority basis.***

What is and will be the effect and intensity of coastal inundation, erosion and related processes in the terrestrial part of the coastal zone? Proper consideration should be given to the following major issues:

- possible intensified erosion of coastal escarpments and depositional bodies (barriers, spits, etc.);
- degradation of unique natural coastal ecosystems;

- damage to local and regional infrastructure (ports, industrial structures, shelf and coastal oil and gas fields and respective pipelines, transport, and utilities);
- possible decrease in the quality of life for local populations due to inundation, erosion, salinization, and contamination of underground and coastal waters; and
- change of bottom topography due to coastal and bottom erosion of permafrost rocks that may be significant for the future use of the Northern Sea Route.

What are the reasonable, regionally oriented strategies of (economic) development in the coastal zone of Northern Eurasia? This problem includes the following aspects:

- a preference for environmentally sound future development within the key study areas (see 3.6.2.5 below), including the necessity to preserve unique ecosystems;
- economically advantageous further development of agriculture, heavy and light industry, port facilities, infrastructure, oil and gas extraction, etc.

3.6.2.5. Key study areas

Several areas of high intensive economic development and/or heavy population and intensive present and anticipated future coastal zone deformations require special attention because of the extreme risk of their degradation in the following decades. These key coastal areas recommended for detailed studies (Figure 2.5a) include in clockwise order:

(1) **The southern Pechora Sea (literally, the southeastern part of the Barents Sea) near Naryan Mar.** This area is extremely important for its ice-rich coastal scarps which are highly vulnerable to global/regional warming (annual retreat by over 15 m in some coastal areas) and its intensively exploited and developed oil and gas fields, with their respective infrastructure and pipelines which extend across the coastal zone (see **Box Insert A3.6.2**).

(2) **The south-western Kara Sea west of the Yamal Peninsula.** As the ice-rich coast rapidly retreats (by over 10 m/yr), the Ob River delta degrades both morphologically (literally, loses its area) and environmentally (as habitat for unique fish and bird communities is degraded and lost). Developing the oil and gas fields in the shelf area near the Ob River delta will inevitably contribute significantly to decreased water quality, shore retreat and accompanying processes.

(3) **The Laptev Sea, especially the area adjoining the Lena River delta, and the western East Siberian Sea, especially the Dmitry Laptev Strait and Sannikov Strait**. The area is characterized by the very high ice content in coastal sediments, and it is therefore intensely dynamic. An entire archipelago disappeared in this area due to climate changes and wave/surge action during the past century. The highest rates of coastal erosion in the Arctic region (Figure 3.6.14) were observed in the western East Siberian Sea. Unique ecosystems within the presently established state coastal reserve encompassing the Lena River delta already suffer from sea-level changes and economic development and could totally degrade in the next few decades if we do not take protective measures. Dynamics of the bottom topography in the Seas already affects the transportation between the Lena, Kolyma, and Indigirka Rivers, the most active portion of the Northern Sea Route in Eastern Siberia.

(4) **The western Chuckchi Sea between Pevek and Uelen.** This area is generally economically undeveloped at present but is extremely vulnerable because of its specific geomorphological structure (intensively degrading gravel barriers that separate extensive lagoons). Settlements are generally situated on capes composed of ice-rich sediments where the shoreline retreats very fast. Entire blocks of houses were destroyed during recent decades. Sea-level rise and related processes will inevitably bring catastrophic consequences for these areas, which are favorable for oil and gas prospecting.

(5) **Apsheron Peninsula near Baku in the south-western Caspian Sea faces problems similar to those discussed for the previous area.** Here, high population density, extreme

water and air pollution and fast retreat of coastal scarps and beaches composed of sand and sandstone aggravate the problems.

(6) **The Volga River deltaic area and adjacent areas in the northern part of the Caspian Sea.** Drastic (and unpredictable) water-level change in the Caspian Sea exceeded a rate of 15 cm/yr (100 times more than global sea-level changes) during recent decades. The low-lying areas in the Volga River delta and adjacent areas, including unique ecosystems, human communities, industrial structures, oil and gas fields, refineries and pipelines, all suffer greatly from these changes.

(7) **The northeastern Black Sea between Novorossiisk and Sochi.** This area represents the most important sea resort in modern Russia. A strong conflict between recreational use and industrial development, including development of port facilities and the creation of pipelines across the coastal zone, exists presently against a background of swiftly retreating coastal scarps and damage to unique ecosystems.

(8) T**he Taganrog Gulf, Sea of Azov** suffers much from coastal erosion of high scarps on which the most important industrial, living and recreational facilities are situated, from contamination of coastal waters, industrial pollution (Figure 2.5b), and damage to one of the richest bio-resources in the world (**see: Box insert A3.6.1**). These processes have already, or will soon cause a "coastal disaster" across many stretches of this coastline (Selivanov 2001).

(9) **The Odessa Gulf, north-western Black Sea**. This area is traditionally highly developed (heavy industry, port facilities, shipping, sand extraction, agriculture, recreation) and suffers from coastal erosion, lack of freshwater supply, atmospheric pollution, sea water contamination from big rivers such as the Danube, the Dnepr, the Dniester, and the Southern Bug, eutrophication processes in the coastal zone, etc. The respective problems were aggravated during recent decades due to intensive economic growth of the area (Figure 3.6.10).

(10) **The Bosporus Strait connecting the Black Sea and the Sea of Marmara, near Istanbul,** is an overpopulated area of extreme economic activity (sea traffic, industry). Changes in the coastal zone in this part of the world will affect water quality, cause damage to ecosystems, degrade living conditions, and may affect one of the most important regional sea traffic routes.

(11) **The Finnish Gulf near St. Petersburg, Baltic Sea.** This heavily populated and highly economically developed shallow area suffers from water contamination (due to insufficient waste water treatment capacity for the city of 5 million inhabitants), coastal erosion, rise of the groundwater table, salinization of underground waters and related processes. Current construction of new ports potentially increases the risk of coastal zone oil slick pollution (**see Box Insert A3.6.3**).

(12) **The southern Baltic Sea between Kaliningrad and Kiel.** This heavily populated and industrially developed area of a very shallow sea is subject to coastal erosion, water and air pollution, and related processes. These processes are/will be additionally aggravated by increased erosion of coasts composed of loose sediments (high sandy scarps alternating with beaches, barriers and spits) due to the decrease of sediment supply both from rivers and from offshore(**see Box Insert A3.6.3**).

3.6.2.6. Future changes in the coastal zones of Northern Eurasia in the 21st century.

Based on long-term assessment of future changes in the coastal zone of Northern Eurasia, predictive estimates of coastal zone changes in the area by 2050 and 2100 are selected as benchmarks for projections. The latest internationally approved estimates for 2050 vary from 0.08 to 0.24 m of the sea level rise with a central value of 0.17 m and for 2100, from 0.11 to 0.77 m with a central value of 0.48 m, which corresponds to an average rate of about two to four times the rate that occurred during the 20th century (IPCC 2001; Figure 3.6.9). The respective rise in globally averaged surface air temperature is projected to increase by 1.0 to

5.8°C by 2100 with a high probability of twice as much warming in the most sensitive Arctic areas (ibid.). Of greatest importance will be the inevitable amplification of extreme events, such as "passive" inundation of low-lying coastal lands, storm surges, and river floods, with resulting excessive input of water and sediments into the coastal zone.

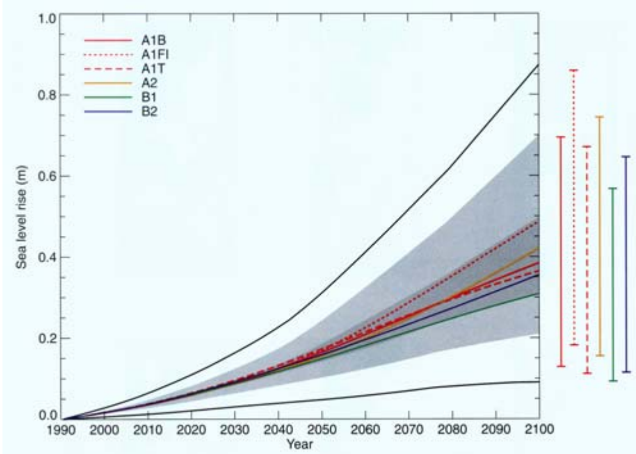

Figure 3.6.9. Shaded area shows global average sea level rise simulated by a global climate model (GCM) according to several climate change scenarios for the 1990-2100 period (a total of 35 scenarios were employed). Range of uncertainty in 2100 for six selected scenarios is shown by vertical bars on the right. (Figure 11.12 from IPCC 2001).

Some negative effects on the coastal zone could be significantly reduced if countermeasures are implemented. Preliminary estimates for the Sea of Azov and some other areas clearly demonstrate that direct economic losses can be significantly reduced (Selivanov 2001). If indirect effects are included, even more resources can be saved.

Arctic coast of Northern Eurasia

Under these conditions, catastrophic changes are likely to occur during the present century in most Arctic coastal zones of Northern Eurasia. The most prominent and dramatic changes include:

- drastic retreat of ice-rich coasts caused by thermoerosion, thermodenudation, influence of waves, tide surges, and sea level rise. By 2100, this retreat could exceed 200-300 m in several coastal sectors (e.g. Pechora Sea, southwestern Kara Sea, Laptev Sea, and East-Siberian Sea)
- intensive inundation of low-lying coasts, especially tidal flats, river deltas and estuaries, under accelerated long-term sea-level rise and higher risk of extreme events. The shoreline retreat by 2100 could be as much as 800-1500 m over several coastal stretches of the White, Barents, Pechora, Kara, Laptev, and East-Siberian seas. River deltas (Pechora, Ob, Yenisey, Lena, Indigirka, and Kolyma rivers) will suffer from these processes to the greatest extent
- intensive movement and general destruction of coastal depositional bodies, such as barriers and spits (especially in the White Sea, Pechora Sea and Chuckchi Sea). Due to the lack of sediment supply, important barriers and spits where several economically important structures are situated or planned will be partially or totally destroyed
- degradation of unique ecosystems (primarily fish and bird habitats)
- bearing in mind that most economic activity occurs near the present shoreline, a direct loss of economic and living structures in populated areas as well as damage to pipelines and other engineering structures is anticipated
- indirect decrease in the quality of living conditions for local populations
- increasing offshore transport of fluvial and eroded material, causing changes in food webs and formation of net primary production with a "terrestrial signature"
- extensive erosion of coastal and bottom permafrost along the Arctic Eurasian coast changes the bottom topography which must therefore be surveyed again and again to

plan Northern Sea Route activity (both transportation routes and mining and oil exploration over the shallow shelf).

Densely populated and economically developed areas of coastal zones

Densely populated and economically developed coastal areas in various parts of Northern Eurasia, namely in the south (the Black Sea, north Caspian Sea and the Sea of Azov), the west (Baltic Sea) and, partially, in the eastern sector (the Vladivostok and Nakhodka areas in the Sea of Japan) will inevitably suffer from climate changes, sea-level rise and related environmental processes. The principal negative processes include:

- erosion of high coastal slopes comprised of rocks of varying hardness under conditions of sea-level rise and increasing storm activity. This is especially important on the northeastern (Novorossiisk-Sochi) and northwestern (Odessa Gulf) Black Sea, and in the eastern and northern parts of the Sea of Azov, especially in the heavily economically developed Taganrog Gulf. The shoreline retreat might exceed 300-400 m by 2100 in several coastal areas
- biogeochemical instability in the Black Sea (Figure 3.6.10) and the Sea of Azov resulting from the possible rise of an anoxic water horizon in the former, and lower bioproductivity of ”beach-builder” mollusks in the latter

Figure 3.6.10. Phytoplankton distribution in Dnepr Estuary, retrieved from a Landsat 7 image, demonstrates eutrophication processes in the area. August 10, 1999 (Bands ETM+: 3,2,1)

- inundation of low-lying areas, including deltaic and estuarine parts of the northern Caspian Sea (the Volga River delta and adjacent areas) and the Gulf of Finland near St. Petersburg
- degradation of beaches and other depositional coastal features that are extremely important for recreational and other uses (the northern Black Sea, Sea of Azov, Baltic Sea). Some of these areas, especially in the Sea of Azov and in the eastern Baltic Sea (Kaliningrad area, Lithuania, Latvia) may be totally destroyed during the next few decades
- degradation of unique ecosystems, including those in the protected areas (reserves)
- highest population density and most economic activity exist near the present shoreline and a direct loss of economic viability and structures in densely populated and economically developed areas is inevitable

- general decrease of living conditions for the local population due to coastal erosion and direct loss of property; decreasing quality of potable water and other factors due to the rise of the underground water table, increasing industrial activity, and higher population density.

3.6.2.7. Unresolved issues that should be addressed during the NEESPI implementation

Arctic coast of Northern Eurasia

- Dependence of coastal dynamics, including retreat of coastal scarps in thawing ice-rich loose permafrost sediments (ice complexes or yedoma) and destruction of depositional features (including sea bottom erosion), upon present and possible future climate, sea-level, and related changes has not yet been adequately studied. An "ice-complex" is Pleistocene permafrost soil enriched by organic carbon (usually between 1 and 20% by weight) that contains huge ice wedges (up to 60-80 % by volume) (3.6.1; Tomirdiaro 1974; Are 1999; Romanovsky et al. 2000; Semiletov 1999b). The methodology of these studies has been developed (Selivanov 1996; Kaplin and Selivanov 1999), but the necessary data base describing coastal changes in the past using instrumental, historical and other documentary information has yet to be compiled.
- Connections among atmospheric forcing (air temperature, major circulation patterns), oceanographic regime (sea ice, sea level, water mass, hydrochemistry), and the food web in the near-shore zone are not well understood. The fieldwork to extend the existing data sets for assessment of this relationship (ACIA Report 2004) would be a prospective research area within the framework of NEESPI.
- The coastal zones of the eastern Laptev and East Siberian Seas correspond to a number of geographically critical contrasts in the Arctic system. The highest rates of coastal erosion (Tomirdiaro 1990; Romanovsky et al. 2000) and most pronounced biogeochemical consequences (Semiletov 1999a) have been found there. This area remains largely understudied and provides an excellent natural laboratory that can be used to achieve an improved understanding of the interactions across the atmosphere-land-ocean system and the impacts of those interactions on freshwater dynamics and biogeochemistry.

Densely populated areas of coastal zone and estuaries

In most cases, it is not known whether changes in coastal morphology, water salinity and quality, and related environmental processes observed during the past decades were connected with natural changes or with economic development and urbanization of these coasts. This lack of understanding prevents us from predicting environmental changes in these coastal zones under anticipated climate, sea level, and related changes. Changes in water salinity and its chemical composition, due to both natural and anthropogenic processes, and the effect of those changes on coastal biogeochemistry and dynamics have not been adequately analyzed. This is especially true for semi-enclosed and enclosed seas such as the Sea of Azov, the Baltic Sea, and the Caspian Sea. Historical aspects of the influence of environmental change upon economic strategies have not been analyzed. ***These studies, carried out under the NEESPI umbrella, will help in the establishment of sustainable development strategies for these areas.***

[All Box Inserts of this Section were transferred to the Scientific Background Appendix]

3.6.3. ATMOSPHERIC AEROSOLS AND POLLUTION

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Contributing author: M. S. Zalogin

Atmospheric aerosols, or fine particles in solid, liquid or mixed phase, come from a wide variety of natural and anthropogenic sources. Primary aerosols are produced via direct emission of particles (e.g., wind-blown dust from arid and semi-arid regions, carbonaceous particles from fires), whereas so-called secondary aerosols are formed via the chemical reactions of gaseous precursors emitted into the atmosphere (e.g., sulfates formed by gas-to-particle conversion of SO_2). The lifecycle of natural aerosols is closely related to the cycles of energy and water, and main biogeochemical cycles of the Earth's climate system, whereas anthropogenic aerosols are associated with various human activities, ranging from industrial processes to human-induced land-use changes. Once lifted into the atmosphere, both anthropogenic and natural aerosols play an important role in the Earth's energy balance, major biogeochemical cycles, cloud formation and precipitation, ecology, air quality and human welfare. Given the high abundance of atmospheric aerosols and air pollutants in Northern Eurasia, a better understanding of climate change in this region will require the understanding of adverse effects of aerosols in connection with other climatic factors.

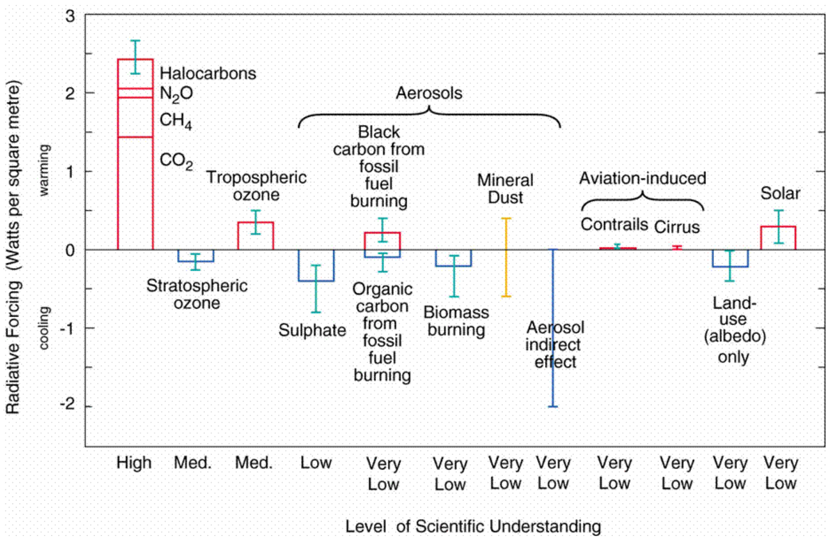

Figure 3.6.16. Main factors controlling climate change (IPCC, 2001). The global mean radiative forcing of the climate system for the year 2000, relative to 1750.

Atmospheric aerosols may affect the Earth's energy balance directly by scattering and absorbing solar and terrestrial radiation, or indirectly by affecting other radiatively important atmospheric constituents (e.g., affecting the properties and amount of clouds). Recent assessments of the radiative forcing of the climate system carried out by the Intergovernmental Panel on Climate Change (IPCC, 2001) reveal that anthropogenic aerosols are a significant radiative-forcing agent. Figure 3.6.16 shows the range of the global mean radiative forcing for the direct and indirect radiative effects of five distinct aerosol types. Anthropogenic aerosols can cause either a positive or negative direct radiative forcing. Comparing to other climatic factors, it becomes clear that the radiative forcing of anthropogenic aerosols represents one of the largest uncertainties in the prediction of climate change. The uncertainty is related to the great variability and complex nature of aerosols which make it difficult to accurately characterize aerosol properties and predict their impacts. Because aerosol distribution and effects are heterogeneous, both spatially and temporally, the radiative forcing due to anthropogenic aerosols has a complex geographical distribution. To illustrate, Figure 3.6.17 shows the examples of the spatial distribution of the direct radiative forcing due to several types of tropospheric aerosols. Although different modeling studies predict somewhat different spatial patterns, they all agree that climate change in Northern Eurasia could be strongly affected by the aerosol radiative forcing. In turn, climate change in this region would lead to changes in the sources, properties and loadings of atmospheric aerosols. Thus, there is a clear need for an integrated study of aerosol-climate interactions in Northern Eurasia to improve our understanding of current and future climate, not only in this region, but also on the global scale.

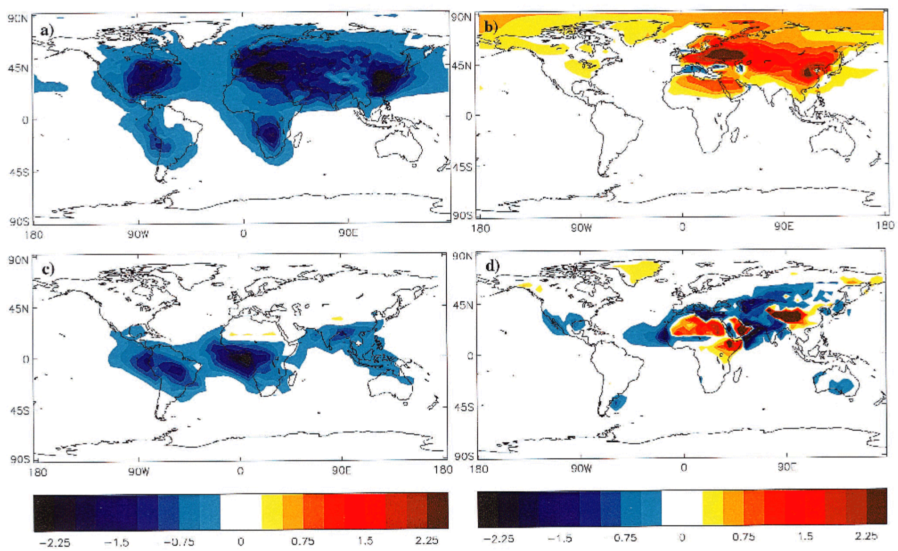

Figure 3.6.17. Model predicted direct radiative forcing (W/m^2) due to (a) sulfates, (b) organic and black carbon from fossil fuel burning, (c) organic and black carbon from biomass burning and (d) mineral dust (Haywood and Boucher, 2000).

Table 3.6.2. Major radiative effects caused by atmospheric aerosols and their importance (modified from Sokolik, 2003)

Impacts	***Importance***
Direct radiative impacts	
Cause the radiative forcing at the top of the atmosphere	Affect energy balance of the Earth's climate system by causing either a warming or cooling (depending on the aerosol types and environmental conditions)
Alter the energy balance at the surface	Affect surface temperature and surface-air exchange processes
Cause radiative heating or cooling within an aerosol layer in the atmosphere	Affect temperature profile and atmospheric dynamics and thermodynamics
Alter photosynthetically active radiation (PAR)	Affect net ecosystem productivity of the terrestrial biosphere and CO2 concentration, and, hence, Earth's climate
Affect visibility	Decrease visibility and degrade air quality
Indirect radiative impacts	
Serve as ice nuclei	Affect the properties and amount of ice and water clouds and hence their radiative effects
Serve as cloud condensation nuclei	
Promote or suppress precipitation	Affect the lifetime of clouds and hence their radiative effects
Alter actinic flux	Alter the abundance of radiatively important atmospheric gases
Absorb chemically important gases	
Provides particle surfaces for heterogeneous chemical reactions	

In addition to the radiative forcing at the top-of-the-atmosphere analyzed in the IPCC report, atmospheric aerosols cause other important radiative effects summarized in Table 3.6.2**.** The presence of aerosols alters the surface radiation budget, affecting surface temperature and various surface-air exchange processes (e.g., evaporation). By altering the amount of light reaching the surface, aerosols can significantly affect the ability of plants to undergo photosynthetic reactions and absorb CO_2. Radiative heating or cooling occurring within the aerosol layer itself affects the temperature profile and, hence, atmospheric dynamics and thermodynamics. The direct radiative impact of aerosols is augmented by indirect radiative effects such as aerosol-induced variations in clouds and radiatively active atmospheric gases. Some aerosol particles result in brighter clouds that may produce less precipitation.

Furthermore, atmospheric aerosols can cause various adverse impacts: pose a health threat, affect biogeochemical processes in the oceans, affect terrestrial systems, cause property damage, affect agricultural production, etc. Traditionally, these issues are studied by scientists from very different and poorly-connected fields. *It becomes apparent that improvements in the quantification of overall aerosol impacts on the climate system will require joint efforts from the interdisciplinary scientific community.*

The magnitude of the aerosol impacts is controlled by the type and amount of aerosols, as well as environmental conditions. Complex spatial and temporal dynamics of atmospheric aerosols in Northern Eurasia render predictions of aerosol impacts particularly difficult. Assessment of aerosol-climate interaction in this region will require an understanding of the factors that determine the abundance and properties of anthropogenic sulfates, black and organic carbon, and mineral dust, as well as gaseous air pollutants. Potentially important effects caused by these aerosols and gaseous air pollutants in Northern Eurasia are discussed below.

Anthropogenic sulfates are formed mainly from SO_2 emission from fossil fuel combustion, though SO_2 has several other sources (e.g., biomass burning). In contrast to greenhouses gases, sulfates cause a negative radiative forcing by reflecting a portion of incident solar energy back to space. Sulfates also cool the climate system indirectly through their role in cloud formation. Emissions of anthropogenic sulfur compounds not only compensate for some fraction of warming associated with greenhouse gases, but also contribute to air quality problems along with other air pollutants (such as O_3, CO, NO_x, carbonaceous particles, trace metals and hydrocarbons, including toxic organic compounds).

The spatial distribution of the emission of SO_2 and air pollutants varies significantly across Northern Eurasia. To illustrate, Figure 2.6a shows the emissions (by volume) of some major air pollutants in Siberia. Air pollution emissions in Siberia tend to be higher in the vicinity of the major industrial centers (Irkutsk, Krasnoyarsk, and Novosibirsk). The most polluted areas are Tyumen oblast and Krasnoyarsk Kray. Based on volume-based emissions data for 1992-1993, Warner-Merl (1998) estimated that anthropogenic activities in these regions contributed over two times the volume of pollution as any other area in Siberia. The next high polluted areas are Irkutsk oblast and Kemerovo oblast. This map shows that sulfur-containing air pollutants are the most serious threat in many regions of Northern Eurasia. Recent estimates show that Siberia accounts for about 30% of SO_2 release from the FSU territory or about 10% of overall anthropogenic sulfur emission (Koutsenogii and Koutsenogii, 1997).

Emissions of anthropogenic sulfur compounds also contribute to the so-called acid rain problem, causing harmful effects on human health, plant growth, and corrosion of building material. Nilsson and Shvidenko (1999) estimated that there are about 230 million ha of forested areas at risk from sulfur depositions, which is 30% of the total forested area of

Russia. Table 3.6.3 shows that the problem of sulfur and nitrogen depositions is greatest in Asian Russia, mainly due to the higher sensitivity of ecosystems in this region.

Table 3.6.3 Forest area and growing stock at risk from sulfur and nitrogen depositions in Russia (Nilsson and Shvidenko, 1999)

	Forested area (in million ha)	Growing stock (in billion m^3)
Sulfur		
European Russia	21.5	2.8
Asian Russia	210.0	24.5
Total	231.5	27.3
Nitrogen		
European Russia	1	0.2
Asian Russia	87	11.4
Total	88	11.6

Two other important types of aerosols in Northern Eurasia are black and organic carbon. The main sources of these carbonaceous particles are fossil fuel and biomass burning. Black carbon, produced from incomplete combustion, is a key aerosol type which strongly absorbs solar radiation, contributing to climate warming. In addition, black carbon (soot) may warm the climate via so-called “semi-direct effects” in which the absorption of solar radiation by soot-containing aerosols heats the atmosphere layer and thereby suppresses cloud formation. This effect is also important for the hydrological cycle because it presumably decreases cloud cover and hence precipitation. Given a high frequency of forest burning and wide spread industrial combustion in Northern Eurasia, the role of black carbon in climate change processes in this region is of special importance.

Natural fire (caused by lightning), being the main source of natural black carbon, is an important ecological factor in the boreal forest system. Fires play a crucial role in determining the distribution of boreal species and improve forest vitality by removing old trees weakened by drought, storm, insect infestation or extreme cold. However, only 15% of the recorded fires in the Russian Federation are caused by lightning. Thus, a large fraction of black carbon emitted from the forest fires has anthropogenic origin. Also, increased temperatures caused by climate change could lead to fires occurring considerably more than past and present natural frequencies (2.8, 3.5.2). Satellite remote sensing provides a valuable tool in detecting fires. To illustrate, Figure 3.6.18 shows a MODIS image of thick smoke from fires near Lake Baikal on July 6, 2003. Smoke from fires in Northern Eurasia can be transported over large distances as confirmed by satellite observations. It will be critical to identify the area affected by long-range transport of smoke from Northern Eurasia and quantify the associated effects on air quality and climate.

The recent study by Menon et al. (2002) of climate effects of black carbon in China and India showed that black carbon absorbing aerosols heat the air, alter regional atmospheric stability and vertical motions, as well as affect the large-scale circulation and hydrological cycle with significant regional climate effects. It will be important to perform a similar study over Northern Eurasia to quantify the effects of black carbon on the environmental systems and climate in this region. Such an analysis would require the data on temporal variations of black carbon and organic carbon from both natural and anthropogenic sources. The fraction of black carbon from fossil fuel burning was estimated recently by Novakov et al. (2003) (see Figure 3.6.19). The trends of black carbon show the rapid increase in the 1800s, the leveling off in the first half of the 1900s, and the increase during the past 50 years as China and India developed. The recent decrease of black carbon emissions from fossil fuel burning in FSU is associated with a slow-down of the economy. It is likely that sulfur emission has similar temporal dynamics. It will be important to reconstruct the historical trends of total black carbon emissions due to both fossil and anthropogenic biomass burning in Northern Eurasia to evaluate the role of black carbon in climate change and constrain the warming associated with black carbon and greenhouse gases (Hansen et al. 2004).

Figure 3.6.18. The MODIS image of smoke near Lake Baikal on July 6, 2003.

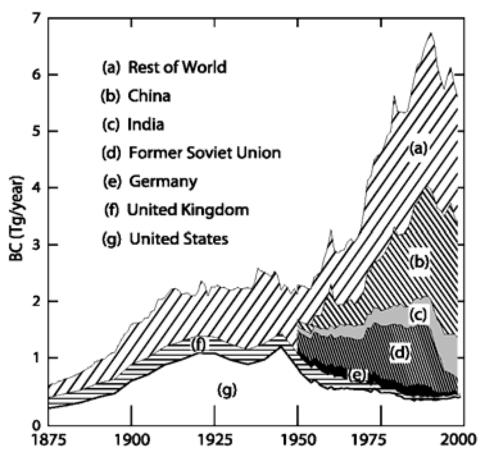

Figure 3.6.19. Estimated regional emissions of black carbon from fossil fuel burning (Novakov et al., 2003).

Another anthropogenic source of carbonaceous aerosols and gaseous air pollutants (especially, hydrocarbons) is petroleum gas flares in the oil fields. Oil industry is a key component of Northern Eurasia's economy. Several recent studies addressed the ecological impact of these pollutants on the forests and wetlands in Western Siberia (Bulgakova et al., 2003) and on the coastal zone of the Russian Arctic (3.6.2; Kaplin and Selivanov 2003). Figure 3.6.20 shows the relative forest and wetlands area affected by air pollutants from burning flares in oil fields of the Vasyugan group and the Igolsko-Talovoe oil field. The planned increase in oil production in the Igolsko-Talovoe oil field, reaching the level of 1,850,000 ton per year by 2005, will affect the large area of forest ecosystem in the Tomsk Region.

In addition to sulfate and carbonaceous aerosols, aeolian (wind-blown) mineral dust plays an important role in controlling climate change in Northern Eurasia. The vast arid and semi-arid regions of Central Asia (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan), Mongolia and Northern China are a prodigious source of mineral dust. Although it has long been recognized that Central and East Asia are the world's second largest source of atmospheric dust, emissions of dust and its diverse impacts on the environmental systems and climate in this region remain highly uncertain.

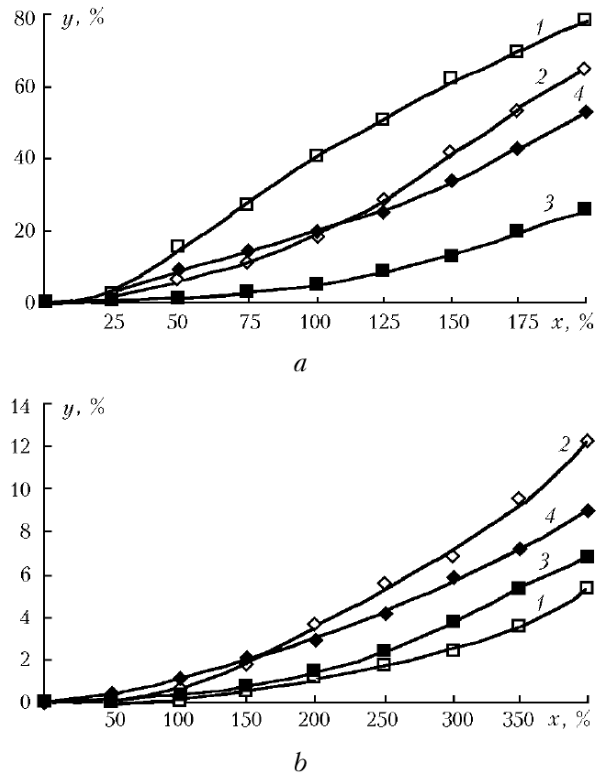

Figure 3.6.20. Relative area of the forests and wetlands contaminated by air pollutants as a function of oil production volume for (a) oil fields of the Vasyugan group and (b) the Igolsko-Talovoe oil field: (1) dark coniferous forest, (2) pine forest, (3) small-leaved forest and (4) wetlands (Bulgakova et al., 2003).

Dust particles are not only natural phenomena, but they are also produced as a result of various human activities. Over-cultivation of poor soils, inappropriate irrigation practices, human-induced wind erosion, severe trampling and heavy grazing, deforestation, urbanization, building and road construction, mining and industry, off-road vehicle use, and tourism are among the major factors which contribute to anthropogenic dust loading. Recent estimates show that the anthropogenic fraction of dust could be as much as 20% to 50% of total dust production, but this remains uncertain. The dependence of dust emissions on climatic parameters, such as wind speed and precipitation, strongly suggests that the atmospheric dust load could be significantly affected by any climatic change that may result from human activities. This fraction of the dust particles is considered as anthropogenic dust too, but it is largely unquantified.

The striking example of a human-made source of dust in Northern Eurasia is the drying up of the Aral Sea, one of the most staggering environmental disasters of the 20th century (Box insert A2.1). Due to improper irrigation practices, by 1999 the sea level dropped more than 18 m and the width of dried seabed reached 120 km, having a total dry area of about 40,300 km^2. The seabed has become the world’s newest sandy-solonchak desert, emitting tremendous amounts of salt and dust into the atmosphere. Salt and dust from the Aral Sea cause not only local problems, but affects the large geographical region. The traces of pesticides carried by dust particles from the Aral region were found in the blood of penguins in the Antarctic, and typical Aral dust has been found on Greenland's glaciers and in Norway's forests, thousands of kilometers from Central Asia. A new qualitative phase of desertification is now occurring in the Near-Aral ecosystem. Degradation takes place that affects regional climate, mountainous flow-forming systems, and water quality in the densely populated agricultural zone of Central Asia (Zolotokrylin 2003, Kust 1999, Aizen et al. 2003).

In recent years, severe dust storms in Central and East Asia have intensified in frequency, duration, and area of occurrence (Sun et al. 2001). It is unclear, however, whether the increase is driven by land surface degradation, drought or by changes in atmospheric circulation or a combination of the above. Rapid desertification in this region is also a plausible factor. It will be critical to establish how the sources and transport routes of Asian dust are affected by climatic changes taking place in Northern Eurasia. In turn, the diverse impacts of dust on regional and global climate must be quantified to provide an improved understanding of the main mechanisms controlling climate change in the region.

Mineral particles exert more complex impacts on the environment and climate than those caused by sulfate and carbonaceous aerosols. Dust can cause either positive or negative radiative forcing at the top of the atmosphere, leading to a warming or a cooling of the climate system. The sign of the direct radiative forcing is determined by the optical properties of the dust as well as atmospheric conditions and surface reflectance. For instance, dust plumes over dark surfaces such as the ocean result in negative forcing (contributing to a cooling), while their radiative forcing is positive over bright surfaces such as bright deserts, snow and ice. The land use practices of converting the darker vegetation areas to brighter lands may also change the sign of direct radiative forcing of dust. In addition, the presence of dust strongly alters the surface radiation budget, affecting the surface temperature and water cycle among other important surface-air exchange processes. Overall, the radiative impact of dust is important relative to that of other types of aerosols, such as sulfates and carbonaceous particles, due to its widespread distribution and large optical depth.

Recently, considerable progress has been made in utilizing satellite observations to characterize dust transport on a global scale. As an example, Figure 3.3.3 shows the transport route of Asian dust in April of 2001 reconstructed from satellite data. Each year, large quantities of dust, originating in Asia, are carried out over the North Pacific to the west coast of the United States. Given that the dust plumes are readily observed by satellite sensors operating in the UV, visible and IR spectral regions, satellite imagery can be used to guide the development of the model of dust sources, transport and deposition.

Of special importance is deposition of atmospheric dust to the ocean that plays a key role in several major biogeochemical cycles (such as the C and S cycles). In the 1930s it has been suggested that deposited dust affect the phytoplankton growth in the so-called high nutrient, low chlorophyll (HNLC) areas of the oceans, whose concentrations of dissolved iron, an essential micronutrient, are much lower than in other regions. By dissolving carbon in seawater and by fixing it as biomass or inorganic particulate matter, phytoplankton regulates carbon dioxide in the atmosphere and thus helps regulate global climate. With the ocean currently consuming 25-35% of the CO_2 emitted into the atmosphere, there clearly is a strong need to quantify the iron supply to the oceans associated with Asian dust transport.

Modeling studies suggested that the diverse effects of dust may trigger various feedbacks on the climate system. Several competitive feedbacks were proposed. For example, a reduction of the surface winds likely has a negative feedback, whereas a decrease in precipitation may lead to a positive feedback. It will be important to explore how climate change in Northern Eurasia might be affected by these and other aerosol feedbacks to better understand the overall impacts of tropospheric aerosols on the environment and climate.

In addition to tropospheric aerosols, Northern Eurasia is affected by a large-scale aerosol perturbation such as stratospheric aerosols from volcanic eruptions. Major volcanic eruptions increase the stratospheric aerosols mass loading by tenfold or more background levels, the three most recent events of this magnitude being the eruptions of Agung in 1963, El Chichon in 1982 and Pinatubo in 1991. An increase in the aerosol optical depth following a volcanic eruption recorded by ground-based monitoring stations in Russia is illustrated in Figure

3.6.21. It has been demonstrated that volcanic aerosols have important impacts on both solar and thermal radiation, affecting surface temperature and atmospheric circulation (Robock, 2002).

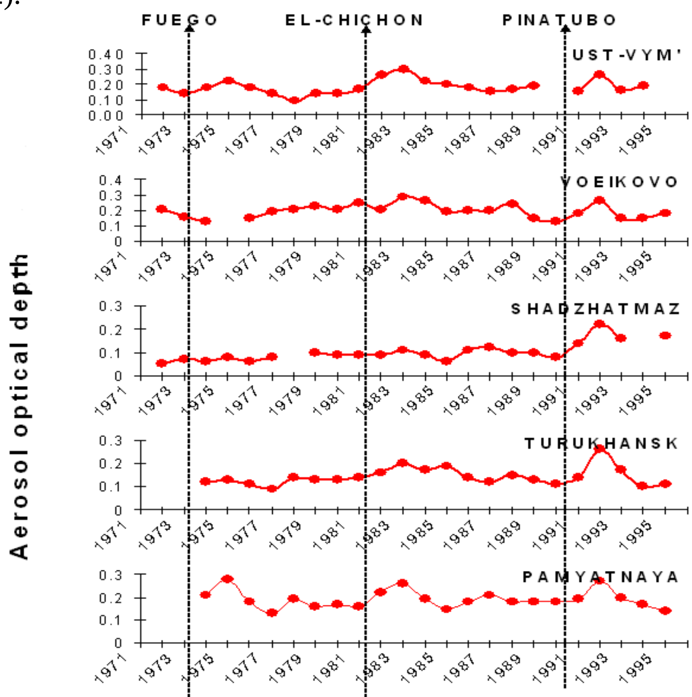

Figure 3.6.21. Long-term time series of the aerosol optical depth at the 500 nm wavelength observed at Russian mid-latitude monitoring stations (Rusina et al. 2001).

The above discussion demonstrates the importance and complexity of the effects caused by aerosols in Northern Eurasia. This complexity underlies several important research questions that need to be addressed to quantify the impacts of the specific aerosol types, as well as their net effect on the environment and climate:

- *How have the sources, distributions and properties of aerosols in Northern Eurasia changed in recent years, and to what extent are these changes attributable to natural variability and human causes?*
- *How will the future land-use and land cover changes, industry development and other human-induced changes affect emissions of different aerosol types in Northern Eurasia?*
- *What are the magnitude and spatial/temporal distribution of the radiative forcing caused by atmospheric aerosols over Northern Eurasia?*
- *To what extent do atmospheric aerosols affect the surface radiation balance in Northern Eurasia?*
- *What are the effects of changes of aerosol concentrations and properties on the formation of clouds, precipitation, and the overall hydrological cycle in Northern Eurasia?*
- *How do atmospheric aerosols affect the terrestrial and aquatic ecosystems in Northern Eurasia?*
- *How do atmospheric aerosols affect air quality and human health?*
- *What are the main feedback mechanisms among climate change, aerosol and air pollutions, and the environmental systems in Northern Eurasia?*

Climate change and population development in the 21st century are expected to cause increases in atmospheric aerosol concentrations. Greenhouse gases and atmospheric aerosols cause competing effects on climate and hydrological cycles. There is a clear need for improved knowledge of interactions of atmospheric aerosols with the climate system to increase confidence in the understanding of how and why climate and environmental systems have changed.