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Pavel Ya. Groisman
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Regional Environmental Changes in Siberia and Their Global Consequences

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Preface

The vast region of Siberia is expected to experience potentially rapid land-cover changes, which are among the earliest indicators of the Earth's response to climate warming. Moreover, climate change affects both the boreal ecosystems and socio-economic infrastructure. Projections of the future climate for the end of the twenty-first century indicate further temperature increases as well as increase in frequencies of various extreme events. Future trajectories of Siberian ecosystems will strongly depend upon a number of large-scale social and economic decisions. On the other hand, changes in Siberia are predicted to affect the climate and people on a global scale. The contributions in this volume demonstrate the utility of satellite data over Siberia for monitoring changes and trends over time, including the associations among vegetation productivity, surface temperature, biogeochemical and water cycles, and air pollution under changing climate conditions and their relation to human population dynamics.

This is a compilation of results from studies on Siberia by the institutions of the Russian Federal Service for Hydrometeorology and Environmental Monitoring (RosHydroMet) and of the Russian Academy of Sciences (in particular, of its Siberian Branch); the US universities and agencies (NASA, NOAA, and NSF); the *International Institute for Applied Systems Analysis* (IIASA, Austria); Friedrich-Schiller University, Germany; Danish Meteorological Institute; and other European institutions.

The volume was written by an international team consisting of scientists from the USA, Europe, and Russia under the auspices of the Northern Eurasia Earth Science Partnership Initiative (NEESPI). It should be of interest to those involved in studying recent and ongoing changes in Siberia, be they senior scientists, early career scientists, or students.

The book is dedicated to the memory of Dr. Don Deering – the founder of the NEESPI and its first project manager. Dr. Don Deering (NASA Goddard Space Flight Center) passed away on February 15, 2010. Below is a brief retrospective of Don's role in establishing and promoting the NEESPI program.

In the summer of 1999, Don and Dr. Garik Gutman, the program manager of the NASA Land-Cover and Land-Use Change Program (LCLUC), agreed that it would be nice if there were an interdisciplinary program in Siberia and that the ongoing NASA projects in Siberia could form a base for such a program. Several projects were being run independently in Siberia and the idea of putting them into a common framework, leveraging funds, exchanging data and information, planning measurements, etc., seemed rather appealing. They began promoting the idea to the US, European, and Russian scientists and agencies. Quite early, a decision was made that the Northern Eurasia program should encompass more than just Siberia or Russia. This was Don who delineated the present NEESPI geographic domain as the former Soviet Union, Mongolia, northern China, Scandinavia, and Eastern Europe.

It was not easy to start a program like NEESPI and to convert it into a large international, multi-institutional program with a broad scientific scope, supported by multiple agencies. However, in the spring of 2003, preliminary development of a NEESPI Science Plan in Suzdal, Russia, culminated in the review and approval of the plan by an external scientific panel in Yalta, Ukraine, that September, and the first NEESPI Science Team meeting was held in February 2006 in IIASA, near Vienna, Austria. Since then, NEESPI have held meetings on forests in the Far East, Siberia, and European Russia; on cold land regions in Alaska; on the carbon cycle in Germany and Russia; on the Baltic Sea basin in Poland; on dry lands in China, Kyrgyzstan, and Kazakhstan; on the Arctic zone in Finland; and on nonboreal Europe in Hungary and Ukraine. During the past five years, NEESPI has expanded tremendously. More than 150 projects supported by the US, Russian, Chinese, European Union, Japanese, and Canadian agencies have been conducted (half of them had been already completed) to address the NEESPI Science Plan objectives. Over 650 scientists from more than 200 institutions in 30 countries contributed or are contributing to the initiative. NEESPI has produced numerous tangible products, such as special issues of peer-reviewed journals based on the NEESPI sessions organized at American Geophysical Union and European Geosciences Union assemblies as well as on numerous NEESPI workshops, regional and thematic meetings, and summer schools. Several books based on NEESPI results have been (or are being) published. All of the above would not have been possible if not for Don's perseverance in dealing with NEESPI issues and his optimism and enthusiasm in reaching the initiative goals.

In 2006, Don was diagnosed with amyotrophic lateral sclerosis, often referred to as "Lou Gehrig's disease." In May 2007, Don joined the NEESPI team for the last time at the NEESPI Summit held in Helsinki. He gave a retrospective presentation of the history of NEESPI's inception including some great pictures highlighting the program's milestones and growing pains during its early development. All was very upbeat and humorous despite his condition. The NEESPI session at the European Geosciences Assembly in Vienna in April 2010 was dedicated to Don's memory. At that time, it was decided to dedicate this book to Don Deering, a scientist who was involved in Siberia projects before NEESPI's inception, made efforts in promoting measurements in Siberian forests by US scientists, and brought the rough idea of a Northern Eurasia program to fruition.

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- The NASA Land Cover and Land Use Change Program and its dedicated investments into decade-long studies in Siberia (http://lcluc.nasa.gov), with its core started by late Don Deering - see Preface,
- Russian Academy of Sciences, particularly its multiannual Siberian Integrated Regional Study (SIRS; http://iopscience.iop.org/1748-9326/5/1/015007),
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- International Institute for Applied Systems Analysis, Laxenburg Austria, particularly its "Ecosystems Services and Management" Program (http://www.iiasa.ac.at//Research/ESM/index.html);
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Contents

Chapter 1
Introduction: Regional Features of Siberia

Pavel Ya. Groisman, Garik Gutman, Anatoly Z. Shvidenko, Kathleen M. Bergen, Alexander A. Baklanov, and Paul W. Stackhouse Jr.

Abstract In this introduction chapter, we describe geographical, climatic, environmental, and demographic characteristics of Siberia and outline major problems dealt with in regional studies of this vast region including those important for the Global Earth System. The science questions, which are put in this chapter, are further addressed in detail throughout the book.

Siberia has increasingly been the focus of attention in the context of global change due to ongoing changes including increases in surface temperature, deepening of permafrost active layer depths, shifting vegetation zones, and declines in snow and sea ice extent (ACIA 2005; IPCC 2007). Numerous studies indicate that the global climate change signal in Siberia is pronounced and has already exceeded natural climate variability (NEESPI 2004).

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1.1 Siberia Defined

The historical name, Siberia, comes from "Sibir Khanate," a small Tatar kingdom founded in the fifteenth century and located in the middle reaches of Ob and Irtysh Rivers eastward of the Ural Mountains. The Khanate was conquered by Russian Cossacks at the end of the sixteenth century. In the following decades, Russian explorers, adventurists, and administrators moved eastward across northern Asia several thousand kilometers, establishing forts (*ostrogs*) and settlements on their way (e.g., Yakutsk, the current capital of the Sakha Autonomous Republic, was founded in 1632) and by 1639 reached the Pacific Ocean. Mapping and further colonization followed. However, it was not until the nineteenth century that large-scale agricultural development and industrial exploration of Siberia gained a significant foothold. Development at this time was predominantly focused in the south, along the Trans-Siberian Railroad which was begun in the late nineteenth century and completed in 1916. Over the past (twentieth) century including during the Soviet era (1922–1991), large reserves of oil, gas, gold, and other minerals as well as forest resources became the backbone of the region's economy. Still, today these resources contribute a disproportionally large (compared to the population fraction) input to the economy of the Russian Federation (1991–present). Severe climate conditions restrict the population growth in Siberia. As of 2009, only ~25% of 141 million of the Russian Federation population resided east of the Ural Mountains. In addition to climate-related conditions, socioeconomic changes of the past two decades took a heavy toll on the region's population (cf. Chap. 7 of this book).

With its 10 million km² of land, Siberia comprises almost 60% of the total land area of the Russian Federation, with the latter comprising approximately 11% of global terrestrial land area. Geographically, the area of Siberia extends from the Ural Mountains on the west to approximately the divide between the Arctic and Pacific watersheds on the east and north to south from the Arctic Ocean (~75°N) to the mountains and steppes bordering China, Mongolia, and the Central Asian states (~45°N). Siberia as defined in this book is comprised of the entire area of the contemporary Russian Federation Siberian Federal *Okrug* (Federal District), the Sakha Republic (Yakutia, administratively part of the Russian Far Eastern Federal *Okrug*), and the majority of the land area of the Urals Federal *Okrug*. Based on this definition, Siberia is comprised of the entire area of Russian Federation east of the Ural Mountains except for the monsoon climatic areas of the Russian Far East and Beringia (Fig. 1.1). The physical characteristics of this vast region are described below.

1.2 Geographic and Physical Characteristics

1.2.1 General Characteristics

Geographic and physical descriptions of Siberia can be found in many monographs (see, e.g., Lydolph 1977; Shahgedanova 2003; Balzter 2010). The Siberian landscape is large and geographically varied, and so it has typically been treated using regional

Fig. 1.1 The hybrid land-cover dataset of Siberia. This blended dataset was built as a synergy of remote sensing products, land statistics, and in situ measurements (Schepaschenko et al. 2010). The dataset contains the most accurate land-cover information for Siberia, updated for 2009. Resolutions and uncertainties of the dataset satisfy the requirements of a verified terrestrial ecosystems full greenhouse gas account (more, cf. Chap. 6). This land-cover dataset is also considered as a platform for an integrated observing system for the country

divisions based on a combination of geography and terrain. The geographic division of *West Siberia* is generally understood to extend from the Ural Mountains on the west to the Yenisei River on the east. Comprised primarily of the West Siberian Lowland, this is the vast basin of the Ob and Irtysh Rivers. Swamps and bogs are the dominant land cover; taiga forest grows in belts primarily along the many river courses which flood annually over large expanses. The geographic division of *East Siberia* is generally considered to extend east from the Yenisei over the Central Siberian Plateau to the divide between the Arctic and Pacific drainage basins. Here the terrain trends toward higher relief north- and eastward.

A significant diversity of climatic conditions and affiliated processes are found in Siberia. The large landmass of Siberia causes an extreme range in seasonal temperatures, especially in its central part, where the difference between summer and winter reaches a record high in comparison with any other nonmountainous climatic region on the planet. The important climate-forming factor of central Siberia is the Arctic Ocean. Cold and dry air masses may form over the Arctic in summer as well as in winter. Siberian rivers, in turn, discharge relatively warm water back to the Arctic Ocean, playing a critical role in the delicate energy and freshwater balances of the oceanic thermohaline circulation.

Ongoing global change is an integral and inherent feature of the dynamics of Siberian ecosystems. Major drivers which impact the Siberian ecosystems include (1) dramatically increasing temperature coupled with diverse regional trends of

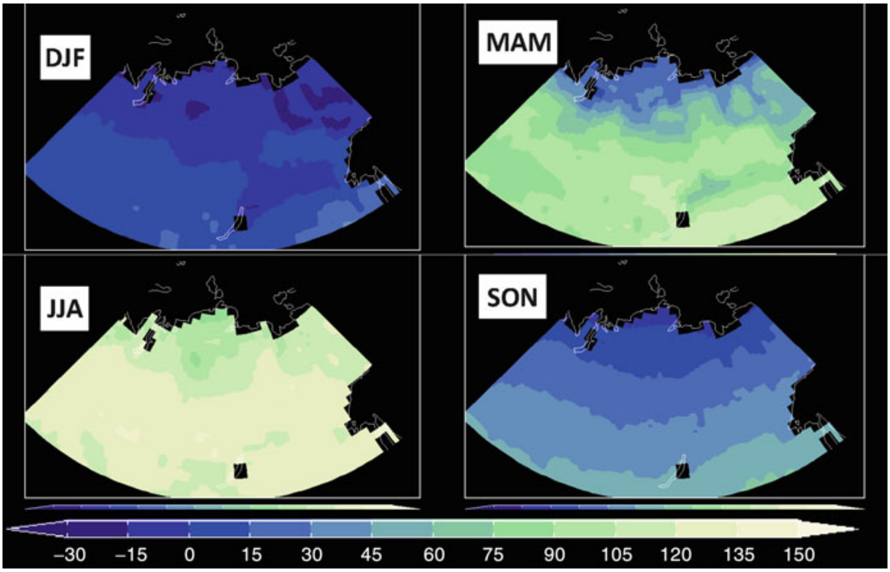

Fig. 1.2 Contemporary mean seasonal total net surface radiation budget (SRB; average for the 1884–2007 period) over Siberia as determined by the GEWEX SRB project (Gupta et al. 2006), W m^{-2}

changes of precipitation; increasing aridity of climate was observed in vast continental regions; (2) increasing seasonal variability of weather; (3) changes in surface albedo due to regional variations in snow cover; (4) changes in disturbance regimes, basically in extent and severity of wildfire and insect outbreaks, following changing of the temporal dynamics of temperature and precipitation; (5) changes in hydrological regimes connected to permafrost thawing and land-use changes; and (6) increasing and mostly unregulated anthropogenic impacts (McGuire et al. 2006; Soja et al. 2007; Vygodskaya et al. 2007; Shvidenko 2009; Quegan et al. 2011).

1.2.2 Surface Energy Balance

The land surface is a focal area where (a) most of the solar energy absorption and a significant fraction of reflection occur, (b) a significant fraction of the outgoing long-wave radiation forms, and (c) atmospheric warming by turbulent and long-wave radiation fluxes is generated. The surface heat exchange defines temperatures at the surface and above and below ground, and changes the surface substance by snowmelt and evaporation as well as by providing the energy for the functioning of the biosphere. While at the top of the atmosphere above Siberia, the annual radiative budget is negative, the surface is a heat sink only in the winter season and for northern Siberia in the autumn season also (Fig. 1.2). The negative heat balance in Siberia is compensated by transport of latent heat from more temperate regions, a considerable part of which comes from northern Atlantic region via the westerly atmospheric circulation (Pavlov 1984).

Siberia is sparsely populated (and therefore sparsely covered by in situ observations) and has harsh weather conditions most of the year. Therefore, the use of remote sensing from space is a natural choice to document climate conditions in this part of the world. Moreover, the remote sensing products corroborate quite well with regionally averaged in situ data (when they exist and can be directly compared, cf. Chap. 3). Chapter 2 describes the available remote assets in detail.

1.2.3 Water Cycle

Advection processes (mostly westerlies, but Arctic effects are also present) modify the climate of Siberia, reduce its continentality, and are the source of water for interiors of the continent. Weather conditions favorable for cloud formation and precipitation are highly variable in time and space. Thus, atmospheric circulation is a major source of the variability in land surface processes. Siberia is "protected" by mountain ridges from the direct influx of water vapor from the tropics (Kuznetsova 1978; Shver 1976). Major sources of water vapor in that area include the Atlantic Ocean, the Arctic Ocean, and their coastal seas. Large interior lakes like the Caspian Sea, Baikal, and (up to the recent years) the Aral Sea also contribute. The advection by extratropical storms is the major means of moisture transport. This makes precipitation conditions of Siberia highly variable and very sensitive to circulation changes. Thus, relatively modest changes in the global circulation of the atmosphere and ocean may substantially affect climate and environmental conditions in Siberia.

Historically, small shifts in storm tracks resulted in enormous variations in water balance of interior lakes, in deep ground water circulation systems, and in corresponding shifts of the ecosystem boundaries. Paleoclimatic, archeological, and historical records indicate propagation of forested and steppe areas far southward into the desert and semidesert areas during "wet" epochs and their retreat and desertification during the prolonged periods of insufficient precipitation. These changes were quite swift (with a time scale of several decades) and were accompanied by prosperity and/or collapse of local agricultural and nomadic civilizations (Wigley et al. 1981; Lamb 1988; Gumilev 1990; Kaplin and Selivanov 1995; Pirazzoli 1996; Selivanov 2000).

Six of the ten great rivers of the Russian Federation are located in Siberia: the Ob, Irtysh, Yenisei, Angara, Lena, and Amur (Antipov et al. 2006). The Yenisei-Angara-Selenga Rivers, which drain northern Mongolia and Siberia northward toward the Arctic Ocean, comprise the world's fifth longest river system; the Ob-Irtysh is the seventh longest. The largest lake in Siberia (and the world's deepest and largest freshwater reservoir) is Lake Baikal (31,500 km^2 with a maximum depth of 1,680 m). The relatively flat and poorly drained west Siberian lowlands consist of over one million lakes along with significant groundwater resources and peatlands (Antipov et al. 2006). Details on the regional water cycle are given in Chaps. 3 and 4.

1.2.4 Carbon Cycle

In the biomass, soils, and peatlands of Siberia, boreal Russia holds one of the largest pools of terrestrial carbon (see Chap. 6). Because Siberia is located where some of the largest temperature increases are expected to occur under current climate change scenarios, stored carbon has the potential to be released with associated changes in disturbance regimes. Carbon cycle of Siberian land is basically driven by interconnection between net primary production and ecosystem's heterotrophic respiration and fluxes due to disturbances. A recent study that is based on a detailed full carbon account has estimated net ecosystem productivity at 671 ± 168 Tg C yr^{-1}. The emission caused by disturbances is estimated at 145 Tg C yr^{-1}. Taking into account wood decomposition (134 Tg C yr^{-1}), lateral fluxes (43 Tg C yr^{-1}), and consumption of plant products (105 Tg C yr^{-1}), the net ecosystem carbon balance has been estimated at 245 Tg C yr^{-1}. On average for the region, forest is estimated as a net sink (336 Tg C yr^{-1}), and the rest of land categories (except wetlands) – as a relatively small source (see more details in Chap. 6). The above results have been obtained for 2009. In addition, Russian land (including interim water reservoirs) has been estimated as a source of methane at 16.2 Tg C-CH_4 $year^{-1}$, a greenhouse gas 23 times more powerful than carbon dioxide. Of this total amount, 65% is delivered by wetlands. Assessment of carbon budget of forest ecosystems for 1990–2007 based on forest inventory data also estimated the region's forests as a sink of 255 ± 64 Tg C yr^{-1} and 264 ± 66 Tg C yr^{-1} for 1990–1999 and 2000–2007, respectively (Pan et al. 2011). Overall, these results are consistent taking into account that different definitions of forest (national and FAO's) have been used in the above studies.

Interannual variability of carbon emissions is basically defined by seasonal weather specifics and disturbances. While average values of net ecosystem carbon balance (NECB) for Russia as a whole usually vary in limits of 10–15%, the variability of emissions for individual regions and reasons (e.g., wildfires) could be substantial. For instance, vegetation fire carbon emissions varied from 50 (2000) to 231 (2003) Tg C yr^{-1} during 1998–2010 (Shvidenko et al. 2011). The large variability of direct fire fluxes has been reported by different authors (e.g., Soja et al. 2004; Van der Werf et al. 2006).

Gas locked inside Siberia's frozen soil and under its lakes has been seeping out since the end of the last ice age 10,000 years ago. But in the past few decades, as the Earth has warmed, the icy ground has begun thawing more rapidly, accelerating at a perilous rate the release of methane (cf. Forster et al. 2007). Furthermore, this permafrost thaw began affecting Siberian infrastructure (cf. Chaps. 5 and 7).

1.3 Human Geography

While Siberia's land area is larger than the conterminous United States, Siberia is inhabited by only an estimated 33 million people and has a population density of about 4.5 person per km^2 in the Siberian and Urals Federal *Okrugs* and 0.3 in the

Sakha Republic (Europa Publications 2010) – this is compared with mean population densities 8.3, 32, and 139 in the Russian Federation as a whole, the United States, and China, respectively. Siberia is more densely populated in the west and in the south than in the east and north. Overall, the human geography is also fragmented and concentrated in a handful of large cities, and much of the region is virtually uninhabited. Five of the 20 largest (by population) cities in the Russian Federation are in Siberia: Novosibirsk (1.4 million), Yekaterinburg (1.3 million), Omsk (1.1 million), Chelyabinsk (1.0 million), and Krasnoyarsk (0.9 million), and five others have populations over 0.5 million, although none can rival Moscow at 10.5 million (Europa Publications 2010). About 70% of Siberia's people live in these and other cities, and within cities, most of the population live in apartments. However, urban Siberians have long had a tie to the forest, and *dachas* (rural second dwellings with a small plot of land) have allowed many urban residents over the past decades to maintain connection with the forests and nature and to raise their own vegetables and fruits. Permanent inhabitants of rural areas live in small settlements and simple houses. In the nineteenth and twentieth centuries, some smaller settlements have been supported by forestry or other state operations. During several decades of the twentieth century, some of these settlements were hubs of transportation and supervision of convicts and exiles from the European part of Russia. The majority of the population of Siberia today is of Russian, Ukrainian, or other western descent. A minority of the current population are descendants of Mongol or Turkic peoples (e.g., Buryats, Yakuts) or northern indigenous peoples.

In terms of the geographic distribution of populations, in West Siberia, lowlands and permafrost inhibit settlement in large areas; primarily only the south has major cities (such as Omsk and Novosibirsk) and these are largely within the corridor of the Trans-Siberian Railroad (considered completed in 1916). The oil town of Khanty-Mansiysk is in north-central West Siberia, north of the historic industrial town of Tyumen. Novosibirsk is located on the Ob River in southern West Siberia and is the largest city in Siberia. Only the southern parts of West and East Siberia are suitable for agriculture and this area was settled starting in the eighteenth to the nineteenth century by farmers in search of available agriculture lands.

East Siberia, while containing more inhabitable uplands, is also sparsely settled, and much of the area is remote and permafrost-affected. Larger settlements in East Siberia are located in the southern taiga zone along the Yenisei and Angara Rivers. The city of Krasnoyarsk lies at the western doorway to East Siberia on the Yenisei. The hydropower center of Bratsk and the Bratsk reservoir is found to the east of Krasnoyarsk on the Angara and on the Baikal-Amur Mainline Railway (BAM), which diverges from the Trans-Siberian at Tayshet between Krasnoyarsk and Bratsk. Further to the east but also in the south and on the Trans-Siberian railway route are Lake Baikal and the city of Irkutsk. Irkutsk lies on the Angara just to the west of Lake Baikal and is the principal service center for the regions to the north and east. Mining, lumbering, and farming occur in the valley hinterlands of southern taiga cities in East Siberia such as Krasnoyarsk and Irkutsk. The Buryat Republic lies east of Lake Baikal and is home to the Buryats, Siberia's largest ethnic minority. In the Arctic part of East Siberia just to the east of the Yenisei as it makes its almost due northward journey is the industrial nickel-smelting city of Norilsk.

In the vast northeastern part of East Siberia and in the Sakha Republic, permafrost and remoteness again have mitigated against significant human settlement. An exception, the sizeable city of Yakutsk (population over 200,000), lies as a port on the Lena River more than halfway between its headwaters in the highlands west of Lake Baikal and the Arctic Ocean. Yakutsk has, among other things, the RAS Permafrost Research Institute for the study of built infrastructure on permafrost substrates. The smaller city of Lensk in The Sakha Republic lies west of Yakutsk. Formerly known for diamond processing, Lensk is now a key point on a new oil pipeline linking the oil fields of East Siberia with the Far East and China.

1.4 Natural Resources

Siberia is a veritable "storeroom" of natural resources for Russia. Its contents include almost the majority of Russian reserves of natural gas and oil as well as the majority of ores, metallic minerals, and precious minerals. Siberian forests are part of the "world's largest forest," the northern Eurasian boreal taiga that extends from the Pacific to Atlantic Oceans. The region has huge resources of renewable energy, e.g., installed capacity of hydroelectric power stations of the Angara-Yenisei basin comprises half of the capacity of all hydroelectric power stations of Russia.

The majority of the Russian Federation's known energy sector reserves are located in Siberia (and the Russian Far East), including 85% of its prospected gas reserves, 75% of its prospected coal reserves, and 65% of its prospected petroleum reserves (Oldfield 2006). Approximately one-third of the world's reserves of natural gas are located in Russia, and these are predominantly within Siberia. The Central Siberian Plateau is also exceptionally rich in ores and metallic minerals, containing some of the world's greatest deposits of manganese, lead, zinc, iron, platinum, nickel, palladium, cobalt, and molybdenum. As a proportion of the Russian Federation total reserves, Siberia has more than 90 and 75% of coal and lignite, respectively; more than 95% lead; approximately 90% molybdenum, platinum, and platinoids; 80% diamonds, 75% gold, 70% nickel and copper; 50% tin and zinc; etc. (Korytny 2009). The world's largest nickel deposits are those of the Norilsk site in Siberia, and the Norilsk industry currently produces over 20% of nickel and 40% of palladium globally. Siberia is also known for diamonds, gold, graphite, and semi-precious stones; gold is mined in the Sakha and Buryatia Republics, in the Krasnoyarsk region, and in other locations.

The forests of Siberia represent up to approximately 65% of the Russian Federation's forest area (Fomchenkov et al. 2003). Across the geographic regions of Siberia, there exists a north-south gradient, which patterns its primarily boreal forest resources and their suitability (or lack of) for timber exploitation, conversion to agriculture, or even susceptibility to fire (Antipov et al. 2006; Walter and Breckle 2002; also, see Chap. 6). Human management and logging of these forests over the past century is described in Chap. 7 of this book. In addition to their role as timber resources, Siberian forests sequester carbon and provide other sustenance for humans in rural areas (mushrooms, berries, pine nuts, game) plus habitat for fur-bearing animals and other biodiversity (Krankina and Dixon 1992). While boreal regions are generally not as biologically diverse as temperate or tropical biomes, Siberia has some of Earth's largest intact landscapes (critical for migratory herds such as caribou, *Rangifer tarandus*) and is habitat to internationally important species such as the Siberian tiger (*Panthera tigris altaica*), the snow leopard (*Panthera uncial*), and the Siberian crane (*Grus leucogeranus*; Dinerstein 1994).

Approximately 27% of the utilized arable farmland in the Russian Federation is in Siberia, with 7% and 20% located in the Urals and Siberian okrugs, respectively, and a negligible amount in the Sakha Republic (Oldfield 2006). Because of the short growing season in the north, most agricultural production in Siberia is concentrated in the southern part of the region in the forest-steppe and steppe zones. These zones are the regions of increased societal water demand (Vörösmarty et al. 2000). Unfortunately, most of agricultural fields and pastures in these zones are not irrigated and are prone to frequent droughts. Water availability has become a central issue for social and ecological sustainability.

Recent developments of industry in Siberia, man-made changes of environment and ecosystems, as well as ongoing and expected climate change generate many risks to the Siberian landscape. Current state and recent tendencies of dynamics of terrestrial ecosystems, particularly forests, are negatively impacted by increasing anthropogenic pressure and insufficient governance of natural resources in many large Siberian regions. Construction of hydroelectric power stations on large Siberian rivers leads to large land-use changes that substantially impact regional and local climates. The significant impacts of global change on the Siberian environment and human health, as well as on the social and economic safety of human well-being, are very likely in terms of short-term impacts and become crucial when assessing the long-term consequences. Overall, the region is one of the most vulnerable vast territories on earth and is indicated as a "hot spot" by the ESSP Global Carbon Project (2010).

1.5 Types of Environmental Changes

A prerequisite to understanding of human-driven change is knowledge of natural environmental dynamics; these are discussed in greater detail in Chap. 6. Up to the industrial era, humans minimally altered the Siberian environment through fishing, hunting, and limited permanent and shifting agriculture. Subsequent to industrialization, the human impact has been significantly greater, including fire, logging, pollution, and industrialized agriculture; these are discussed in greater depth in Chap. 7.

In general, natural dynamics of the boreal forests include gap dynamics, fire, wind throw, plant-animal interactions, and growth and succession. Fires occur largely in conifer and mixed forests, ranging in severity and size from small light surface fires to large stand-replacing crown fires (Conard and Ivanova 1997). The Siberian silk moth (*Dendrolimus superans sibiricus*) is one of the principal causes of disturbance in conifer forests (Kharuk et al. 2007). In the middle and southern taiga zones, following stand-replacing disturbance, the most widespread successional pathway is from young birch-aspen regeneration, through maturing deciduous forests, to mixed and conifer forest (Hytteborn et al. 2005; Schulze et al. 2005). However, in the larch-dominant (*Larix sibirica, L. gmelinii*) as well as in some Scotch pine-dominant (*Pinus sylvestris*) communities, sites often are regenerated directly to larch and pine, respectively (Kharuk et al. 2010).

Human-driven changes in forests include fire, logging, post-logging succession, and agriculture development and abandonment. Within Siberia, the three administrative units with the largest forest industries have been Irkutsk Oblast, Krasnoyarsk Kray, and Tomsk Oblast (these have been followed by Khabarovsk Kray in the Russian Far East). In the middle and southern taiga, logging has historically occurred most often as clear-cuts in conifer forests, with most sites left to natural regrowth and succession. Natural fire return cycles may be significantly modified by human-ignited fires (Achard et al. 2008; Korovin 1996). Establishment of agriculture has incurred large-scale conversion of temperate and southern boreal forests in the more arable southern portions of Siberia; however, more recently, abandonment of farming areas contributes to forest regrowth (Bergen et al. 2008).

Characteristic environmental changes associated with energy and mineral resources include development and growth of large urban centers (including many of Siberia's largest cities); establishment of large industrial complexes; mines and mining-dominated landscapes; air and water pollution from petrochemical and smelter industries; hydropower complexes including dams, reservoirs, and hydroelectric power stations; and transportation infrastructures. In West Siberia, the Khanty-Mansi region has historically contained 70% or more of Russia's developed oil fields, with the Samotlor field being the largest in Russia. Other regional cities developed large petrochemical industries (e.g., Tomsk, Tobol'sk, and Omsk). Large coal and iron ore deposits (used in steel production) are located in southeastern West Siberia in the 27,000 km^2 Kuznetsk Basin. Production of natural gas is concentrated near Urengoy (the world's second largest gas field) and the Yamal Peninsula in northern West Siberia. More recently, oil reserves have been explored in East Siberia including the Yurubchen-Tohomo oil fields (cf., synthesis case study in Chap. 7) north of Krasnoyarsk and a cluster of others further east and north of Lake Baikal. Because urbanization and industrialization require power, Siberia's great rivers have been harnessed for hydropower. The upper reaches of a number of rivers, including the Yenisei and Angara, have strong gradients and flow, making them especially conducive to development of hydropower.

Environmental changes of consequence to plant and animal biodiversity are generally similar to those of forests: conversion of steppe and forest lands to agriculture, fire, logging, insects, mining, and pollution. Additionally, there is the added threat of hunting and poaching to animal biodiversity. Given such threats, there are a number of protected area types in Siberia that are intended to limit human-driven environmental change: strict nature reserves (*zapovedniki*), national parks (*natsional'nye parki*), natural landmarks (*pamyatniki prirody*), natural reserves and hunting grounds (*zakazniki*), global heritage sites, wetlands, regional natural parks, and traditional nature management zones. As of 2001, in Siberia there were estimated to be 30 *zapovedniki* and nine *natsional'nye parki* out of about 135 total combined in Russia (Oldfield 2006), and the number of protected areas has been increasing since that time.

Requirements for large-scale agriculture (wheat and other grains, potatoes, grazing of sheep and cattle) include fertile soils, absence of significant permafrost or more moderate climate conditions, or both. These are met primarily in the steppe zone of southern Siberia; thus, this area has largely been converted to agriculture, as have floodplain valleys of rivers in the southern taiga zone. When abandoned, agricultural areas in the taiga zones may revert to forest (Krankina et al. 2005; Bergen et al. 2003, 2008; Chap. 7 synthesis case study). In more mountainous areas, pasture is also established on hillsides. In the northern taiga and Arctic zones, reindeer pastoralism and breeding have long been human subsistence activities and continue today with fairly minimal environmental consequences.

1.6 Impacts of Environmental Changes

The state and dynamics of ecosystems are a product of the sophisticated interplay and mutual conditionality of impacts, responses, and feedbacks of natural, economic, and social components; environment; and human society. An important feature of the region is the fragility of ecosystems, which in evolutionary terms developed under a rather stable and cold climate. Ecological thresholds and buffering capacity of ecosystems under rapid substantial warming have no precedent in recent history and are poorly understood. This generates major challenges for understanding the current and future state, vitality, and resilience of ecosystems of Northern Eurasia.

Global changes provide direct and indirect effects on Siberian ecosystems, and these interact with multiple natural and anthropogenic disturbances and other ecological processes. Some of these changes may be irreversible on century time scales and have the potential to cause rapid changes in the earth system (McGuire et al. 2006). The impacts of both global and regional change on ecosystems often cannot be understood within the simple "cause-and-effect" paradigm. Understanding and appropriate description of these changes require us to take into account many climate-forming factors of cosmophysical (including heliospheric), geospheric, biospheric, and anthropogenic origin, to determine not only changes of state of the climatic system but also evolution of these physical processes and phenomena, which may be regionally specific. Predicting the cumulative impacts of such complex interactions is difficult and usually requires an integrative modeling approach (Vygodskaya et al. 2007; Milne et al. 2009) that would combine different types of models (empirical, process-based, etc.) and involve different dimensions of the surrounding world – ecological, social, and economic.

Increasingly, Siberian ecosystems become socioecological systems taking into account the transformation of vegetation cover through development of previously untouched territories and the diverse destructive anthropogenic impacts on the environment and natural landscapes. For example, the following types of oil- and gas-related complex impacts on the environment, quality of life, and ecosystems are most dangerous: (1) infrastructure-related ecological impacts that lead to destruction of soil cover and changes of hydrological regimes; (2) ordinary ecological impact caused by pollutants during extraction and transport of oil and gas; such impacts cannot be eliminated by current technologies of oil and gas exploration and extraction; (3) extraordinary ecological impacts caused by accidents and technogenic catastrophes; and (4) impacts on ecosystems by population outside of industrial areas (Sibgatulin et al. 2009).

Methods practiced today of industrial exploitation of northern territories in the region are wasteful and often provide extremely negative impacts on the environment and ecosystems. For example, the Siberian Federal *Okrug* (including part of West and the entire central Siberia) is second in the Russian Federation in terms of total emissions from stationary sources (5.8 million tons in 2007 that is 28% of the total emissions of the country; cf. Fig. 1.3). An abundance of large industrial enterprises is a specific feature of the region. For instance, the company "Norilsk Nickel" that emits about 2 million tons of pollutants per year (mostly sulfur dioxide) generated about 2 million ha of technogenic desert during the last 40 years, of which about 500 thousand ha were forests (this is addressed in detail in Chap. 8). In regions of intensive oil and gas extraction of West Siberia, (1) up to 35,000 breaks of oil pipelines occur annually; of this number, about 300 accidents are officially registered with oil spills >10 000 tons each, (2) the tundra surface is destroyed for more than 15%, and (3) physical destruction of natural landscapes exceeded 30% of the total area of the territories of middle and southern taiga. Utilization and use of oil casinghead gas is unsatisfactory. By different estimates, from 15 to 25 billion m^3 of such gas are burnt in flares annually. The Government Commission on Fuel and Energy reported that the amount of extracted casinghead gas in 2007 comprised 61.2 billion m^3 with 16.7 billion m^3 burnt in flares (Kryukov and Tokarev 2010). The quality of river water, specifically in industrial areas and southern regions with high population density, does not correspond to the norms of water use for drinking and fisheries. The governance of natural resources (in particular, forests) and the control of natural resource management are below any acceptable levels.

The level of atmospheric pollution and soil contamination in major regions of intensive oil and gas extraction substantially exceeds acceptable limits (see Chap. 8 for details). Soil pollution and water contamination are widespread in some regions and high in industrial populated territories. For instance, the following share of area which did not correspond to requirements of the health code of populated areas was observed in central Siberia: Minusinsk district 71.4%, Krasnoyarsk 61.1%, Norilsk 12.3% (but 83.0% in 2006), etc. (Kaliagina 2009). The impacts of toxic anthropogenic water contamination, the decline of the human immune system, increasing stress, impacts of many negative social phenomena connected, among others, to intensification of migration processes, will likely accelerate the negative impacts of climatic change on the standards of life and health of the population, as well as enforcing undesirable feedbacks.

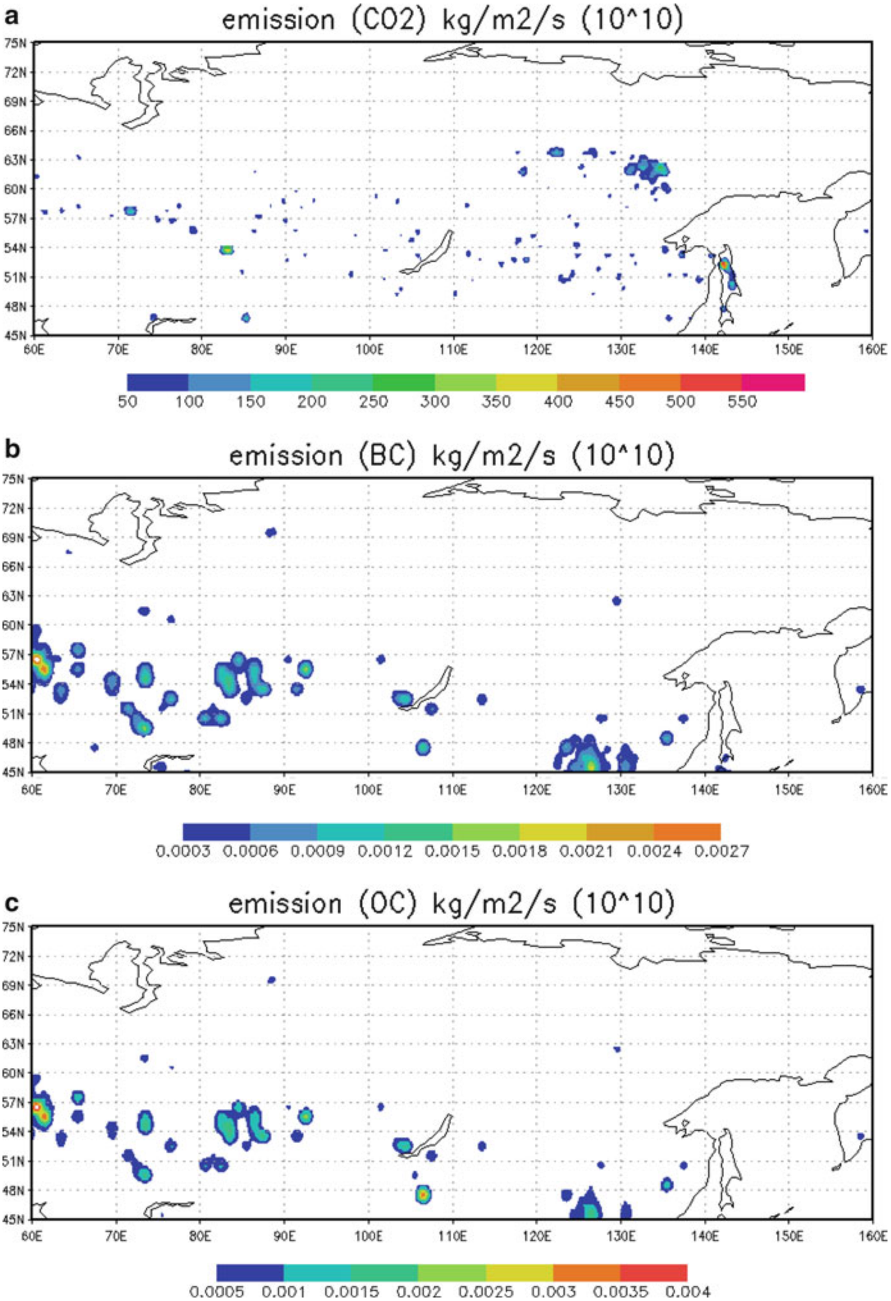

Fig. 1.3 Emissions of main pollutants in Siberia based on different global emission inventories (Extracted by A. Zakey, see Chap. 8)

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

1.7 Structure of the Following Book Chapters

Above, we briefly described several features of Siberia that make it a special and important area of the globe. This is a region with severe continental climate that:

- Is harsh as well as sensitive to changes
- Is quite dry and exercises controls both on the Arctic freshwater budget (and thus to the global thermohaline circulation) and on the regional ecosystem well-being and is capable to quite quickly change the land cover from taiga to steppe or even to semidesert
- Has a unique storage of carbon in the frozen ground and across the expansive taiga zone that can change (be burned, or simply be released from thawing permafrost) creating potential positive feedback to the global Earth system
- Has experienced dramatic changes in human-driven resource exploitation and management over the past century.

Chapter 2 contains descriptions of the tools (information systems and their content) accumulated for the Siberian domain in its national institutions as well as abroad in Europe, Japan, and the United States. In the following six chapters, we assess environmental changes in Siberia. We start with a description of the regional climate changes and their projections (Chap. 3), paying a particular attention to changes in the water cycle of the region (Chap. 4) and cryosphere impact on the regional infrastructure (Chap. 5). Changes in the ecosystems and carbon cycle of Siberia are described in Chap. 6. Human dimensions of environmental change in the context of land-cover/land-use change during Soviet, early post-Soviet, and emerging eras are the subject of Chap. 7. Atmospheric pollution, soil and water contamination issues are addressed in Chap. 8. Chapter 9 provides the summary of findings described in the previous chapters.

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