CHAPTER SEVEN

Cities of the Russian North in the Context of Climate Change

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Introduction

In addressing Arctic urban sustainability, one has to deal with the complex interplay of multiple factors, such as governance and economic development, demography and migration, environmental changes and land use, changes in the ecosystems and their services, and climate change.[1] While climate change can be seen as a factor that exacerbates existing vulnerabilities to other stressors, changes in temperatures, precipitation, snow accumulation, river and lake ice, and hydrological conditions also have direct implications for Northern cities. Climate change leads to a reduction in the demand for heating energy, on one hand, and heightens concerns about the fate of the infrastructure built upon thawing permafrost, on the other. Changes in snowfall are particularly important and have direct implications for the urban economy, because, together with heating costs, expenses for snow removal from streets, airport runways, roofs, and ventilation spaces underneath buildings standing on pile foundations built upon permafrost constitute the bulk of a city's maintenance budget during the long cold period of the year. Many cities are located in river valleys and are prone to floods that lead to enormous economic losses, injuries, and in some cases human deaths. The severity of the northern climate has a direct impact on the regional migration of labor. Climate could thus potentially be viewed as an inexhaustible public resource that creates opportunities for sustainable urban development (Simpson 2009). Long-term trends show that climate as a resource is, in fact, becoming more readily available in the Russian North, notwithstanding the general perception that globally climate change is one of the greatest challenges facing humanity in the twenty-first century.

Like the rest of the world, Russian society is divided between those who believe that climate change will have a major impact on the planet and those who doubt such predictions: alarmists and skeptics as the media often describes them. Public opinion polling shows that there is no consensus and identifies various cleavages in Russian society. According to a 2008 survey of more than 1,000 people from different regions of Russia (WCIOM 2008), 48 percent of people have heard something about climate change, while 8 percent do not know what it is; 51 percent believe that global climate change has already started (compared to 48 percent in 2007); 57 percent associate climate change with human influences, whereas 29 percent believe it is caused by natural factors; 50 percent (up from 45 percent in 2007) believe that climate change may have catastrophic impacts, while 27 percent think it will not have any serious environmental consequences, and another 7 percent believe that some regions could benefit from the changing climate.

Researchers conducted another survey in September 2010, immediately following an unusually long heat wave in central Russia, which sparked numerous forest fires over large swathes of land (WCIOM 2010). Data from this survey indicate that most people (57 percent) associated the increased number of fires with inappropriate management and the so-called human factor, which in Russia generally indicates a lack of discipline, responsibility, and proficiency, as well as the unwillingness and/or inability of individuals and officials to follow established regulations. Only 34 percent of those polled equated the increased frequency of fires to global climate change.

Andrei Illarionov, founder and director of the Russian Institute of Economic Analysis (IEA), best exemplifies the climate skeptics who are most prominent in the political arena. From 2001 to 2005, he served as economic adviser to President Vladimir Putin. As a political and social leader, Illarionov is known in Russia for his public statements, many of which tend towards sensationalism. His views on climate change are in conflict with the accepted scientific consensus, as can be seen in numerous media interviews and in distilled form in the paper "How to Spin Warming: The Case of Russia."[2] Interestingly, the paper was released on 16 December 2009, at the peak of the "Climategate" campaign in which a hacker gained access to and published some e-mails exchanged by climate scientists on the eve of the Copenhagen summit on climate change. Climate change skeptics claimed that the e-mails demonstrated that climate change was a hoax. In his paper, Illarionov accused the Intergovernmental Panel on Climate Change (IPCC) of selective use of data from approximately 25 percent of Russia's weather stations. According to the IEA, the selected stations overestimate the rate of warming in Russia, questioning the credibility of the IPCC findings. His paper provoked extensive discussions in the media and had a pronounced societal impact, particularly on those who claim that climate change is simply a matter of belief.

Meanwhile, the majority of the scientific community addresses the problem from the other end, considering climate change as a matter of fact. The idea for global climate change and its scientific basis can be traced back to the 1960s, when Russian professor Mikhail Budyko published his papers on what is now called "geoengineering" (Budyko 1962). In that work, Budyko proposed that it was possible to alter the global climate through the mechanism of changing the albedo of polar ice by dispersing soot. In the following years he developed the first numerical climate model, which was published in 1969. For the first time ever, he linked the anthropogenic combustion of fossil fuels with the growing atmospheric concentration of CO_2 and global air temperatures. Budyko lived long enough (he passed away in 2001 at the age of 80) to witness the end-of-century patterns of a changing climate, which he had successfully predicted in 1969, at least in general terms sufficient for large-scale adaptation planning. In the 1970s, he published articles describing his ideas in popular magazines, which is why both the general public and authorities in Russia were relatively well aware of climate science much earlier than their counterparts in the West, where the first publications and public debates started later. In the mid-1980s, well before the IPCC came into existence, Soviet authorities charged Budyko's department of climatology at the State Hydrological Institute in St. Petersburg with the task of assessing the implications of climate change and contracting sea ice for Arctic marine navigation. Their particular interest was in strategic planning to develop the icebreaker fleet with an optimal split between nuclear and conventional vessels to serve the transportation needs of the Northern Sea Route, as well as those on Siberian rivers. Research along these lines was unfinished at the time the USSR collapsed, and the subsequent political and economic breakdown of the country led to its early cessation.

In the decades following the 1960s, climatology evolved from a descriptive and mostly empirical discipline to a highly comprehensive science with a strong computational component. Currently, it operates with fundamental and complex physical equations, and employs sophisticated three dimensional thermodynamic modeling. Models account for numerous interacting components of the climatic system, and ultimately generate millions of digital parameters in order to draw climatic pathways from the past to the future. The amount of data generated by climate models is enormous, and not surprisingly, the general public as well as scientists outside the climatological community often lack the scientific background to engage with climatological models.

The purpose of this chapter is to provide a scientifically comprehensive yet nontechnical overview of the current and projected climate in the northern Russian regions. It places particular emphasis on the climatic parameters that have potential implications for cities in the Far North. As discussed in the introduction to the book, we intentionally define the boundary of what we call the "North" loosely to include mountainous regions occupied by permafrost in southern Siberia, Altai, and Kamchatka. Largely in response to the criticism expressed in Illarionov's papers, we pay special attention to the evaluation of observation certainty and the identification of gaps in the climate data. This analysis is based on Russian hydrometeorological service data and the results from the latest generation of the most sophisticated Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models. To minimize the subjective component, standard IPCC methodology has been employed. The analysis begins with a discussion of regional features in the temperature and precipitation patterns using observations from the twentieth and early twenty-first centuries, an evaluation of predictive climate models in a regional context, and construction of comprehensive climatic projections for the future on the basis of the best models. Subsequently, key regional concerns and opportunities associated with climatic changes are identified, concluding with an assessment of the direct and indirect impacts climate change may have on the cities of the Russian North.

Regional Climatic Changes in Russia in the Context of Global Warming

Global climate change in the twentieth century was characterized by warming through all seasons, changes in seasonality, an increased frequency of extreme weather events, and increasing durations of periods with the temperatures above or below prescribed thresholds.

Many regions, including Russia, demonstrated discernible changes in the intensity and frequency of precipitation. Changes were uniform neither across space nor over seasons; in Russia, however, many of the changes exceeded global means.

Observational records contain two periods of pronounced hemispheric-scale warming in the early and late twentieth century (Hansen et al. 2010). The first period of warming started in the 1920s and lasted for nearly two decades. The second warming began in the late twentieth century and continues through the present, with unequivocal evidence demonstrating a combination of natural and anthropogenic factors driving these changes (Solomon et al. 2007). In this section, we compare variations in the global temperature and regional climate in Russia.

The problem is threefold: First, it is essential to establish whether records at Russian weather stations point to discernible signals of climate change, and if so, what type of change it represents. The second task is to develop a regionalized analysis to characterize the pattern of modern changes. Last, we need to analyze regional-mean trends, compare them with the changes at a global level, and build regional projections for the future.

We address the first task—determining whether the information collected by Russian weather stations point to climate change—through the analysis of temperature data. The rationale behind this choice is that temperature is the only climatic parameter that responds directly to changes in the radiative forcing (the difference between sunlight received by the earth and radiated back to space) produced by greenhouse gases through well-understood physical mechanisms. Temperature is thus the ultimate factor governing the cascade of changes in atmospheric and oceanic parameters and processes, which in their totality constitute climate change. We tested three types of statistical models to select the one that provides the best fit to the observations:

- A stationary time series model that rejects the concept of climate change, suggesting that observations correspond to the stationary regime characterized by the natural variability and the same mean value
- A time series with linear trends
- A time series with stepwise changes from one stationary regime to another

We applied each of the three types of model to century-scale temperature data from Russian stations and used the standard deviation of the simulated time series from observations as a metric of the model fit. The stationary model demonstrated the worst fit; on average it had an 11.2 percent higher deviation than the linear trend model and 10.3 percent higher than the stepwise-change model, while at many stations the difference in deviation was more than 20 percent. As for the other two models, the linear trend model consistently demonstrated a better fit with slightly lower deviation. We thus conclude that there is observational evidence of a changing climate in Russia, which could be best approximated by a linear rise in temperature over time.

To address the second task, describing the pattern of change across regions, we combined the records from individual stations into groups and developed a climatic regionalization based on the coherence of the temperature variations. Averaging data over the coherent regions allows the signals of climate change to be highlighted by minimizing the stochastic component, which is present in the individual station records.

We tested several classifications consisting of different numbers of regions using data for different periods. The regional delineations were based on the federal administrative units of Russia, which were in some cases divided into smaller subunits to achieve homogeneity of bioclimatic and topographic conditions. The optimal climatic classification for the modern period is shown in Map 7.1 and consists of

Map 7.1. | *Location of Weather Stations, the Main Population Centers in the Russian North (defined here as the area within permafrost boundaries and/or northward of 60°N), and the Southern Permafrost Boundary; Map Partitioned into Regions with Coherent Temperature Changes in the Period 1970–2010*

seventeen regions, of which 1–14 are in the Russian Federation. In the context of the present study, regions 1, 7, and 9–13 located within the Russian permafrost area and/or northward of 60°N are of prime interest. Map 7.1 also shows the location of the permafrost boundary, weather stations, and main population centers in Northern Russia.

The coherence of the temperature changes in Russia (regions 1–14) following the early-century peak is illustrated in Figure 7.1. The upper left plot was constructed using the CRUTEM3 data and shows the hemispheric-mean mean annual air temperature (MAAT) smoothed by an eleven-year running window. Curves in plots 1–14 represent MAAT changes at individual stations (grey lines) and the regional-mean (black line) smoothed by an eleven-year running window. Although not shown here, similar plots were constructed for precipitation and other temperature characteristics, such as seasonal temperatures and temperature sums above and below prescribed thresholds that have direct implications for city management. Table 7.1 provides a sum-

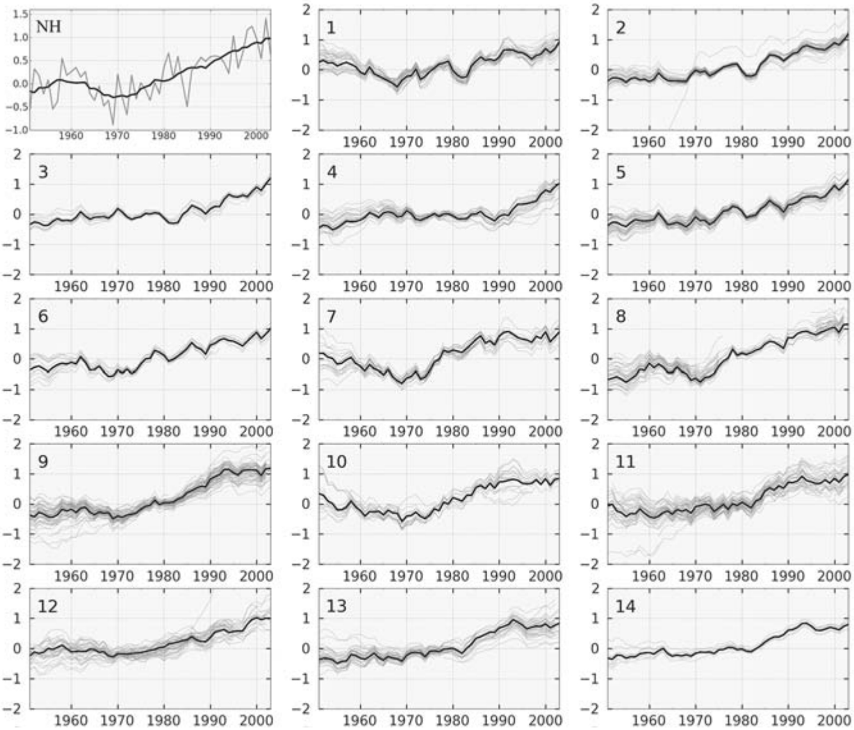


Figure 7.1. | *Temperature Variations at Individual Stations (thin grey lines) and Regional-Mean MAAT (solid black lines) Smoothed with an 11-year Running Filter*

Table 7.1. | *Linear Trend Coefficient for Regional-Mean Air Temperature and Precipitation for the 1976–2010 Period*

	Temperature, °C/100 years					**Precipitation, mm/month/100 years**				
Region	***Winter***	***Spring***	***Summer***	***Fall***	***Annual***	***Winter***	***Spring***	***Summer***	***Fall***	***Annual***
1	9.2	2.9	4.3	5.0	5.3	17	19	8	5	14
2	11.4	3.7	4.9	4.7	6.3	10	15	4	–8	7
3	9.2	5.1	6.5	6.8	6.9	–20	–2	–41	8	–13
4	4.4	3.2	5.7	6.0	4.9	–3	20	–18	42	11
5	6.9	4.5	3.9	7.3	5.8	4	31	–23	–20	–1
6	5.7	4.0	1.8	7.1	4.5	5	40	–3	–6	9
7	4.8	4.7	2.2	3.5	3.4	9	24	2	3	11
8	3.2	7.8	0.9	3.3	3.5	12	16	10	1	10
9	5.0	7.2	5.2	2.4	4.7	7	8	17	16	11
10	5.0	7.4	2.7	2.8	4.7	1	5	17	9	7
11	2.5	5.4	5.3	6.4	5.1	–2	12	23	24	14
12	–0.9	8.9	4.1	8.5	5.4	–9	18	–21	5	1
13	4.5	4.2	2.3	5.1	4.1	8	7	–8	2	3
14	5.9	2.9	2.8	4.6	4.0	11	45	34	–36	15
Average	5.8	5.0	3.8	5.3	5.0	4	17	–2	3	6

Note: Highlighted lines designate regions in the Russian North (see Map 7.1 for region key) mary of results illustrating seasonal temperature and precipitation trends. All trends were calculated using the 1976–2010 data.

Data in Table 7.1 indicate year-round warming trends all over Russia except for Chukotka (region 12), where winter temperatures have exhibited large interannual variations with near-zero or slight negative trends in the past three decades. Rates of change and seasonal features are not uniform over regions. Winter warming is most pronounced in North-European Russia (region 1), with the temperature trend up to 9.2°C/100 years, nearly twice the trends in summer and fall (4.3 and 5.0°C/100 years, respectively), and more than three times that of spring (2.9°C/100 years). The maximum in seasonal trends shifts gradually from winter to spring along the West–East transect in the Russian Arctic (from the upper to the lower lines in Table 7.1). In Western and Central Siberia (regions 7 and 10), the summer temperature changes are least pronounced, while the rest of the Russian Arctic demonstrates noticeable summer warming.

Air temperature extremes have exhibited much greater changes: annual minimum and maximum temperatures and the temperature range, as well as number of days per year with temperatures above or below certain thresholds (Meleshko 2008). Over large territories in the Russian Arctic, minima rose at a higher rate than maxima, except for in Chukotka (region 12), where annual minima decreased in accord with colder winters. The largest annual temperature minima trends over the past three decades were detected in North-European Russia (14–26°C/100 years) and in Central Siberia (10–14°C/100 years). At the same time, annual temperature maxima did not change in Siberia. Elsewhere in the Russian Arctic, trends never exceeded 10°C/100 years and on average were about 6°C/100 years. Apparently, one can say that rather than getting warmer, the regional climate in Russia is getting less cold.

Annual amounts of precipitation have increased everywhere in the Russian Arctic, with large regional and seasonal variations. Similar to the air temperature pattern, seasonal precipitation maxima have shifted from the cold to the warm period along the West–East transect, with a pronounced snowfall increase in North-European Russia and West Siberia and mostly summer precipitation increase in east Siberia (Table 7.1). In the context of our study, snowfall is particularly important, due to its profound impacts on the urban environment.

There is compelling observational evidence that during the twentieth century, warming patterns in the Russian Arctic, like the rest of the Arctic, have been more pronounced than in other regions of the world. Warming has accelerated in the past thirty years, with the

MAAT northward of 60°N rising at approximately twice the global rate, a phenomenon known as "Arctic amplification" (AMAP 2011). One of the consequences of the concentrated regional warming is a dramatic decline of sea ice in the Arctic Ocean, with an average shrinkage rate of 13.4 percent per decade in the period 1978–2015. In September 2012, Arctic sea ice decreased to a record low level since satellite observations began in 1979, reaching 3.6 million km^2 (about half of the average of the 1980s and 1990s). Remarkably, the period from 2007 to 2011 has had the second through fifth most pronounced warming on record. Sea ice is getting thinner and younger; about 70 percent of it is one to two years old, and 95 percent is younger than five years (AMAP 2011). These trends are projected to increase in the future, opening new opportunities for navigation along the Northern Sea Route (NSR), but as Scott Stephenson discusses in Chapter 8, these accessibility increases will also bring new challenges to the transit regimes of the Russian Far North.

Regional Climatic Projections for Russia

It is possible to develop shorter-term climate projections by extrapolating the trends displayed in Figure 7.1 and the data in Table 7.1 over the next few years. These data characterize statistics of the current trends, which are prone to changes with time, and thus are not necessarily illustrative of the longer-term climate variations at decadal and centennial scales. Long-term projections must include a greater range of data, which can be accomplished by using general circulation models (GCMs). This section provides an overview of recent results from the CMIP5 family of comprehensive GCMs that were used in the preparation of the Fifth IPCC report. The experimental design of the CMIP5 was presented by Tailor, Stouffer, and Meehl (2012). This section evaluates the model's accuracy in a regional context by contrasting results with observations in Northern Russia.

While GCMs are generally acknowledged as the most effective tools for predicting future climate, they should always be viewed critically. Even the most sophisticated computer algorithms are not capable of accounting for the full range of complexity and uncertainty in the climate system. Climate change is governed by the interplay of numerous factors, many of which are stochastic and thus can only be addressed probabilistically, while the mathematical formalism of GCMs is intrinsically deterministic. It is thus not feasible to discern the accuracy of the models through direct comparison with observations of specific months and years sequentially over decadal and centennial time scales. In contrast to weather models, GCMs should not necessarily be judged by their ability to replicate real-time changes in climatic parameters. Instead, one has to look at the difference between statistics in the time series of climatic parameters that are based on observations and model simulations. Robust statistics could only be obtained if continuous observations over a period of twenty-five to thirty years or longer were available, which sets up a minimum time scale at which model results could be viewed as "projections." It could not reasonably be expected that GCM-based climatic projections would be credible at shorter time scales, implying that, at best, they could be used to characterize general future trends. Standardized time periods that have been used in numerous studies are centered on 2030, 2050, and 2080. Alternatively, slices could be bound to a certain period in the future, when the prescribed magnitude of global warming is likely to be reached. The later approach could give insight into the 2°C warmer world (with respect to the preindustrial level), which corresponds to the threshold set by the European Union as a target for its adaptation and mitigation strategies (EU Climate Change Expert Group 2008).

Global climate models have a typical horizontal resolution of about 2° by latitude and longitude, which corresponds to a spatial unit with a size of 200–250 km. Complicating the problem, the results of any individual model for any single grid node are not robust, and the entire pattern contains many unreliable small-scale details, often interpreted as if it is affected by stochastic "noise" (Räisänen and Ylhäisi 2011). This imposes limitations for projecting climatic changes at specific locations, such as individual cities. Similar to observations at individual stations, "noise" may be reduced by averaging several neighboring grids (spatial smoothing), or by applying the same procedure to several models. The ensemble approach is used to minimize the uncertainty of the climate projections. While early studies postulated decreasing uncertainty with the increase in the number of models in the ensemble, more recent papers suggest eliminating outliers, GCMs that demonstrate poor performance in comparison with observations. Model discrimination and construction of optimal ensemble projections for regional studies could be based on the consistency with observations of the specific climatic parameters and indices governing key regional impacts. There is no universal metric for model skills, and numerous procedures have been developed and used to evaluate and rank the models in both the global and regional context. This study uses an ensemble climatic projection that has been optimized for the Russian northern regions using the method described below (Anisimov and Kokorev 2013).

This study used the full set of 36 CMIP5 climate models[3] and evaluated each model's accuracy by comparing calculated trends in the climatic characteristics with observations in the fourteen Russian regions. Tests have been performed using the 1976–2005 data for the seasonal and annual temperatures and sums of precipitation, temperature sums above and below prescribed thresholds, and the dryness index (the ratio of the positive temperature sum to the annual amount of precipitation). Original data have been harmonized by subtracting the "baseline" values averaged over the 1961–1990 period individually for each model. This procedure eliminates systematic biases, which individual models are prone to. Results were averaged over the grid nodes that fall over each of the regions, and compared with the regional observations. Ultimately, models were ranked according to their capability.

Table 7.2 illustrates the disparity between the modeled MAAT trends and observations in the 1976–2005 period for selected regions in the Russian North and in the areas underlain by permafrost. Although not shown in the table, similar results were obtained for other climatic parameters and indexes. Models are classified by their relative errors, defined as the ratio of the difference between the calculated and observed trends of any given climatic parameter to their sum. The threshold for the relative error is set at 0.25 to distinguish between the highly accurate models and those that poorly represent observed regional trends.

Table 7.2. | *Differences Between the Modeled MAAT Trends and Observations in the 1976–2005 Period for Selected Regions in the Russian North, °C/100 years*

Model	Pfrost	1	7	9	10	11	12	13
ACCESS1.3	−1.5	−2.1	0.4	−3.4	−1.7	0.1	0.8	−1.8
ACCESS1–0	0.4	2.6	2.4	−1.7	0.1	0.0	2.5	−1.7
bcc–csm1–1	4.5	7.3	8.0	−2.1	3.9	1.5	−0.6	−0.7
bcc–csm1–1–m	−0.5	−2.4	−0.5	−2.9	0.2	2.8	5.0	2.7
BNU–ESM	0.4	−4.0	0.1	1.0	1.1	2.3	4.4	2.1
CanCM4	−0.2	2.8	2.3	−5.2	−1.2	−0.8	−0.2	−2.1

CanESM2	2.1	0.7	2.3	−1.3	1.1	1.0	3.4	1.0
CESM1–CAM5	−4.4	−5.1	−3.6	−2.8	−3.7	−2.3	−3.9	−3.9
CESM1–FASTCHEM	1.1	0.0	4.4	−2.9	3.8	1.9	−1.2	−1.6
CMCC–CESM	−2.7	−1.0	1.2	−4.7	−0.5	−2.8	−3.9	−5.8
CMCC–CM	1.4	2.3	4.1	4.0	3.3	1.0	−3.3	0.5
CMCC–CMS	−3.6	−5.6	−2.9	−1.2	−3.1	−2.3	−2.0	−1.8
CNRM–CM5	4.4	5.0	7.7	1.4	6.7	4.1	6.7	2.0
CSIRO–Mk3–6–0	0.2	−0.6	2.6	−1.4	1.6	−0.7	−0.8	0.2
EC–EARTH	1.6	−1.7	3.3	−0.9	3.2	0.7	0.6	2.1
FIO–ESM	−0.6	−3.6	2.8	−1.8	2.5	−0.1	−0.2	−2.4
GFDL–CM3	−3.2	−6.5	−1.2	−3.2	−2.9	−3.2	4.0	−1.7
GFDL–ESM2G	1.7	1.6	4.8	−1.4	3.3	3.6	7.4	1.5
GFDL–ESM2M	−1.0	−5.8	−0.6	−0.7	0.6	−0.3	−1.8	−0.8
GISS–E2–H	0.3	3.1	2.5	−4.2	0.1	−0.2	−1.3	0.0
GISS–E2–R	0.3	−0.7	2.2	−1.7	2.5	1.7	0.8	−0.7
HadCM3	1.3	3.0	2.3	−3.0	−0.2	4.1	2.6	0.9
HadGEM2–AO	2.0	1.3	5.3	1.4	5.8	3.4	1.1	0.6
HadGEM2–CC	1.5	−0.3	3.6	−3.0	1.1	1.0	2.3	0.7
HadGEM2–ES	3.0	1.8	2.8	0.4	2.9	3.9	3.9	2.3
inmcm4	−3.3	−5.6	−1.1	−5.3	−2.6	−3.9	−4.0	−4.6
IPSL–CM5A–LR	−1.0	−1.6	1.0	−0.1	−0.6	0.0	0.1	0.9
MIROC4h	−2.7	−3.5	−1.0	−1.8	−1.1	−0.5	−0.2	−2.8
MIROC–ESM	−2.4	−3.3	−0.4	−1.4	−0.6	−0.9	0.2	−0.6
MIROC–ESM–CHEM	0.4	0.5	2.8	−4.2	0.2	−1.9	−1.0	−2.6
MPI–ESM–LR	−3.8	−8.0	−2.7	−4.1	−3.4	−0.9	0.0	−0.5
MPI–ESM–MR	−0.3	−0.3	1.8	−2.1	0.2	0.9	2.5	−2.5
MPI–ESM–P	−1.1	−2.0	2.7	0.4	2.6	0.1	−1.3	−2.3
MRI–CGCM3	−4.6	−5.7	−3.6	−5.9	−3.6	−3.0	−1.4	−4.2
NorESM1–M	0.8	2.4	3.0	0.3	0.7	−0.3	3.8	0.0
NorESM1–ME	−2.9	0.7	1.5	−5.3	−3.8	−6.8	−3.9	−5.4

Source: Based on data from CMIP5 historical runs

Some questions remain open, such as how to treat models that demonstrate a high accuracy with respect to certain climatic parameters in one region but perform poorly when other parameters in other regions are considered. These instances are displayed as grey cells in Table 7.2, which indicate that the relative model error is above the prescribed threshold for at least one of all tested parameters in the corresponding region. One solution to this problem is to eliminate such models and to combine the remaining ones into the optimal regional ensemble. The other option would be to keep them in the ensemble while assigning them a smaller weight. In the latter case, efforts should be made to avoid biased weighting. As was demonstrated by Weigel et al. (2010), if weights do not appropriately represent the full range of skills with respect to various parameters as well as associated uncertainties in these parameters, ensembles with weighted models perform on average worse than those in which all models have equal weights. When actual and modeled climate variability is large, as is the case in our study regions, more information may be lost by inappropriate weighting than potentially could be gained if weighting is optimal. Largely due to these considerations, this study uses only ensembles with equally weighted models (Weigel et al. 2010). Another question is how to evaluate the projected changes of climatic parameters for individual cities. In accord with what has already been said, the ideal would be to calculate climatic norms using local observational data, and to superimpose the trend averaged over one of the selected large regions.

Plots in Figure 7.2 show the variety of regional-mean MAAT projections from individual CMIP5 models (light grey curves), the ensemble of all 36 models (dark grey curve), and the optimal ensemble of models with the best regional accuracy (black curve) for selected regions in the Russian North, including the areas underlain by permafrost. Hereafter, predictive CMIP5 model runs have been used for the twenty-first century under the high greenhouse gas emission scenarios likely to result from the developing world economy (RCP-8.5) (Riahi, Gruebler, and Nakicenovic 2007). By 2025, the MAAT in most regions of the Russian North is projected to rise by 2–3°C relative to the 1961–1990 norm, and by approximately 4°C through the mid-twenty-first century. Interestingly, except for Western Siberia (region 7), the optimal ensemble predicts higher rates of warming than the average over all models. Although the differences between the ensemble-means are small, the optimal ensemble has an added value in narrowing the range of uncertainty in climate projections by eliminating those based on GCMs with poor regional accuracy.

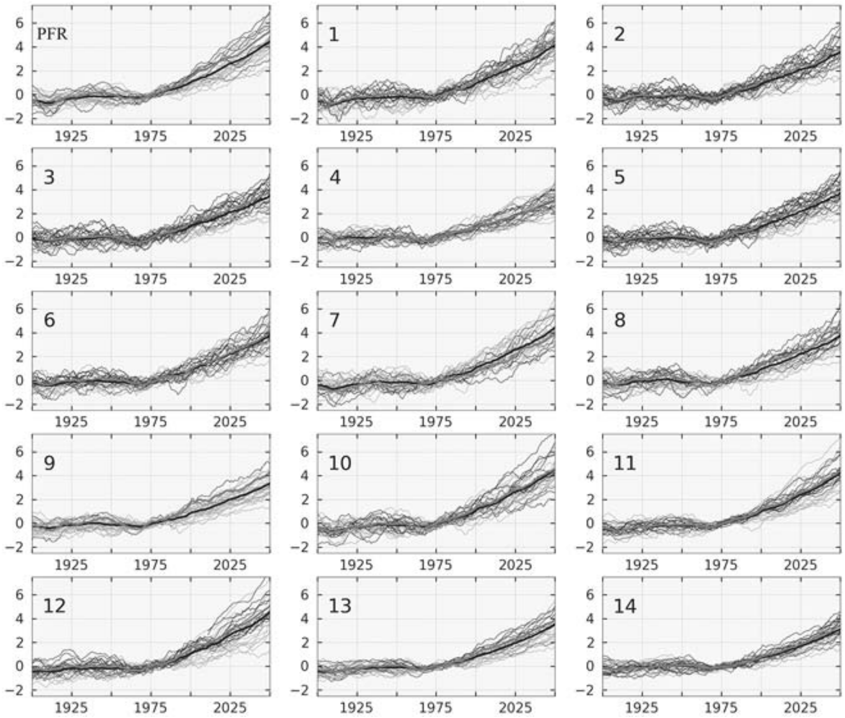


Figure 7.2. | *Regional-Mean MAAT Projections from Individual CMIP5 Models (light grey curves), Ensemble of all 36 Models (dark grey curve), and Optimal Ensemble of Models with the Best Regional Skills (black curve)*

Climate Change and Urban Sustainability in the Russian Arctic

Urban development in the Russian Arctic has been largely driven by the exploration of natural resources, as well as by the need to support marine and river transport operations and maintain defense systems in the coastal zone and northern seas. Of the approximately 370 villages and settlements in the Russian high Arctic (tundra zone), more than 80 percent are located in the coastal zone or in close proximity to large rivers (Anisimov 2010). Unlike other northern countries, the Russian Arctic is characterized by intensive urban developments, and has cities with more than 100,000 population, most of whom are permanently employed and serve the needs of regional industries (Table 7.3).

Table 7.3. | *Russian North City Characteristics*

Region	Cities	Population	Key local industries
North-European Russia (reg.1)	Arkhangelsk	355,800	timber production, river port
	Kholmogory	4,592	timber production
	Severodvinsk	190,083	ship repair
	Shenkursk	5,548	timber production and manufacturing
	Vorkuta	70,548	coal
	Syktyvkar	253,432	forestry, timber
	Ukhta	99,600	coal
	Severomorsk	50,060	ship repair, fisheries
	Apatity	59,672	aluminium
	Zapolarny	15,825	iron
	Kandalaksha	35,654	shipyard
	Kirovsk	28,625	apatite
	Kovdor	18,820	iron
	Monchegorsk	45,361	nickel
	Murmansk	304,508	sea port serving the NSR
	Nikel	12,756	nickel
	Olenegorsk	23,072	nickel
	Naryan-Mar	42,844	river and sea port
	Petrozavodsk	265,263	machinery production, forestry
West Siberia (reg.7)	Nefteyugansk	138,000	oil
	Nizhnevartovsk	262,600	oil
	Nyagan	57,101	oil, forestry
	Surgut	322,900	oil and gas
	Khanty-Mansiysk	85,029	regional administrative center
	Tyumen	609,650	oil and gas
	Nadym	47,360	oil and gas
	Novy Urengoy	112,192	oil and gas
	Noyabrsk	107,210	oil and gas
	Salekhard	46,552	regional administrative center
	Urengoy	10,070	gas

Southern Siberia (reg. 9)	Irkutsk	600,000	energy, coal and lignite, aircraft, heavy engineering
Central Siberia (reg.10)	Norilsk	176,189	nickel, copper, cobalt, non-ferrous metals
	Dudinka	23,923	sea port, part of NSR
Sakha-Yakutia (reg.11)	Lensk	24,373	river and road transportation, port
	Neryungri	62,333	coal
	Yakutsk	267,983	administrative center
	Mirniy	35,994	diamonds
	Aldan	23,371	gold
Chukotka (reg.12)	Anadyr	13,529	gold, coal, non-ferrous metals
	Magadan	95,925	gold, silver, non-ferrous metals
Far East (reg. 13)	Blagoveshchensk	219,861	machinery production, forestry

Source: Anisimov 2010, updated

To the extent that the public focuses on the problem, its perception of climate change's impacts on the urban environment in the Arctic typically focuses on potentially detrimental consequences for the infrastructure built upon thawing permafrost. Numerous examples of climate- and permafrost-related infrastructure failure have been presented in academic and popular publications and are discussed in detail by Dmitry Streletskiy and Nikolay Shiklomanov's Chapter 9 in this volume. Meanwhile, climate impacts are much broader than just those associated with thawing permafrost, and include both challenges and opportunities. Besides thawing permafrost, serious concerns are associated with changes in the freshwater ice and the hydrological regime.

Human settlements in the Russian Arctic, including cities with a population of over 50,000, are often located in close proximity to rivers, which serve as essential transportation routes linking them with other parts of the country. A particular concern with riparian settlements is the risk of floods caused by ice jams, which occur in all Arctic and sub-Arctic regions. Jams develop abruptly, lead to much higher water levels than freshets caused by thermal-driven snow melt, and may have potentially catastrophic consequences. Although not discussed here, floods have many positive ecological impacts, such as the replenishment of riparian ecosystems in the flood plain with water and nutrients (AMAP 2011). The mechanism of ice jam floods is well understood, and besides numerous scientific publications, has been detailed in the SWIPA assessment report (AMAP 2011). The uneven onset of ice break-up in spring leads to ice aggregation at certain locations followed by elevated water levels and flooding in the upstream segment of the river. The subsequent release of ice jams is a related concern, associated with a steep water wave characterized by high flow velocity and significant destructive potential (Beltaos and Burrell 2008). This phenomenon is exemplified by the catastrophic flood of the city Lensk on the Lena River in May 2001, which is detailed in the case study further in this section.

Despite its risks, not all impacts of climate change in the Arctic are negative. A less severe climate will reduce the demand for heating energy, and current observations and model-based projections suggest that hydropower generation would benefit from reduced ice periods and increased runoff in winter, when energy demand is at its annual maximum (AMAP 2011). The duration of the ice period on rivers in the circumpolar North has been decreasing since the 1970s on average by 12 days/100 years with up to 4 times greater rates in the high Arctic. Statistically, an increase in autumn and/or spring air temperature of 2 to 3°C leads to a 10- to 15-day shift in freeze-up and/or break-up of the river ice in the Arctic (AMAP 2011). Lengthening of the ice-free period on rivers and in the northern seas opens new opportunities for transportation over water. In the period 1980–1999 the entire NSR was open for navigation up to 45 days per year. With the current dramatic decline of sea ice extents in the Arctic Ocean, navigation has become more feasible. According to model projections, by the mid-twenty-first century, there will be up to three months per year suitable for navigation along the NSR. (See Scott Stephenson's Chapter 8 in this volume for a detailed discussion of transportation in the Arctic.)

The potential benefits for water transportation are in part balanced by the reduced usability of ice roads currently serving the supply needs of remote settlements in the Arctic, which would otherwise remain isolated in winter. In the coming decades many of the ice roads and river crossings may become economically unfeasible necessitating significant investments into the development of all-weather roads (AMAP 2011) (see Chapter 9). Climate change will also have some positive implications for the health of Arctic residents, such as a decrease of injuries, cold-related diseases, and mortality associated with extreme cold temperatures (ACIA 2005).

Snow

In thinking about the implications for urban sustainability, the role of snow is threefold. First, it has direct implications for city maintenance costs given the substantial resources required for regular snow cleaning of highways, streets, airport runways, and roofs. Snow affects the performance of the engineered systems of buildings in permafrost areas by blocking the ventilation spaces designed to prevent northern buildings from warming (and thus deforming) underlying permafrost. Buildings are heated throughout the winter, and special care is needed to minimize the warming effect on permafrost and keep the temperature of the frozen ground below the threshold incorporated in the design of the foundation, achieved through constructing open basements surrounded by fences with ventilation windows, and by means of passive ground coolers. Obligatory maintenance operations in northern city management include regular snow removal around the buildings to allow the circulation of cold air in the basement through the ventilation windows.

Second, snow acts as a thermal insulator, and as such is an important factor governing the ground thermal regime and the state of permafrost. Ground temperature under snow cover is several degrees higher than it would be if the surface were exposed to the atmosphere. Lastly, the amount of snow accumulated over the cold season and the spring temperatures are two main factors governing the severity (peak water level rise) and duration of annual freshets, as opposed to floods due to ice jams.

In summation, a longer snow period and deeper snow cover are associated with increased operational expenses in the urban environment, leading to the warming of permafrost through higher thermal insulation during the cold period, enhanced risks for infrastructure on pile foundations, and increased peak water levels during spring freshets. Decreasing snow depth and duration are thus favorable for urban Arctic regions.

Shmakin (2010) analyzed observed changes in regional snow characteristics and calculated the sums of solid precipitation over the cold period, which is defined in his paper as that with daily average air temperatures below 1°C. In the Arctic, this period lasts from mid-fall to late spring. Results indicate up to a 30 percent increase in the cumulative amount of snowfall in Chukotka between the 1951–1980 and 1989–2006 timeframes, mostly due to spring snowfall, which outweighed a decline in winter precipitation over the same time period. In West Siberia and in the northeast of the European part of Russia, cumulative snowfall increased by 10 percent–20 percent, whereas in eastern Siberia, snowfall decreased up to 20 percent (Shmakin 2010).

This study uses the same method described by Shmakin (2010), and applies it to CMIP5 model results to construct projections of snow period length and cumulative amount of snowfall (in water equivalent) over a period with daily average temperatures below 1°C. This study also uses projections of the cumulative precipitation sums for the fixed cold period from October to May to characterize the intensity of seasonal precipitation. Results for each of the study regions in the Russian North are presented in Figure 7.3. Snow accumulation depends on the seasonal precipitation intensity and duration of the snow period. The total amounts of precipitation in the period from October to May (Figure 7.3A) are projected to increase with a rate varying from 0.82 mm/y in Central Siberia (region 10) to 1.62 mm/y in North-European Russia (region 1). The proportion of liquid precipitation (rain) in this period will progressively increase with time due to warming. Depending on the interplay between the increasing total precipitation and fraction of it falling as rain, maximum snow depth is projected to decrease in some regions (12 and 13), and increase in the others (Figure 7.3B). The duration of the snow period (not shown here) is projected to shorten everywhere at a rate varying from −0.70 d/y and −0.61 d/y in North-European Russia and West Siberia (regions 1 and 7), to less than −0.43 d/y in Yakutia and Southern Siberia (regions 11 and 9).

Changes in Air Temperature

There are many ways by which air temperature affects cities in the Russian Arctic. Cumulative degree-days of thawing (ddT—the total number of days with temperatures above 0°C) govern the state of permafrost and its ability to support structures built upon it. The temperature regime directly affects the budget expenditures on heating over the winter period, measured as the duration of the heating period (dH), which is defined as the period when daily air temperature is below 8°C, and heating degree-days (Hdd), defined as the cumulative sum of the daily differences between the physiological comfort temperature (prescribed at 18.3°C) and ambient air temperatures over the heating period. Such temperature limits are set in Russian Federal regulations for heating standards (Construction code, 2003), and they generally align with the principles of heating regulation used in other countries (e.g. Day et al. 2003; Isaac and Vuuren 2009).

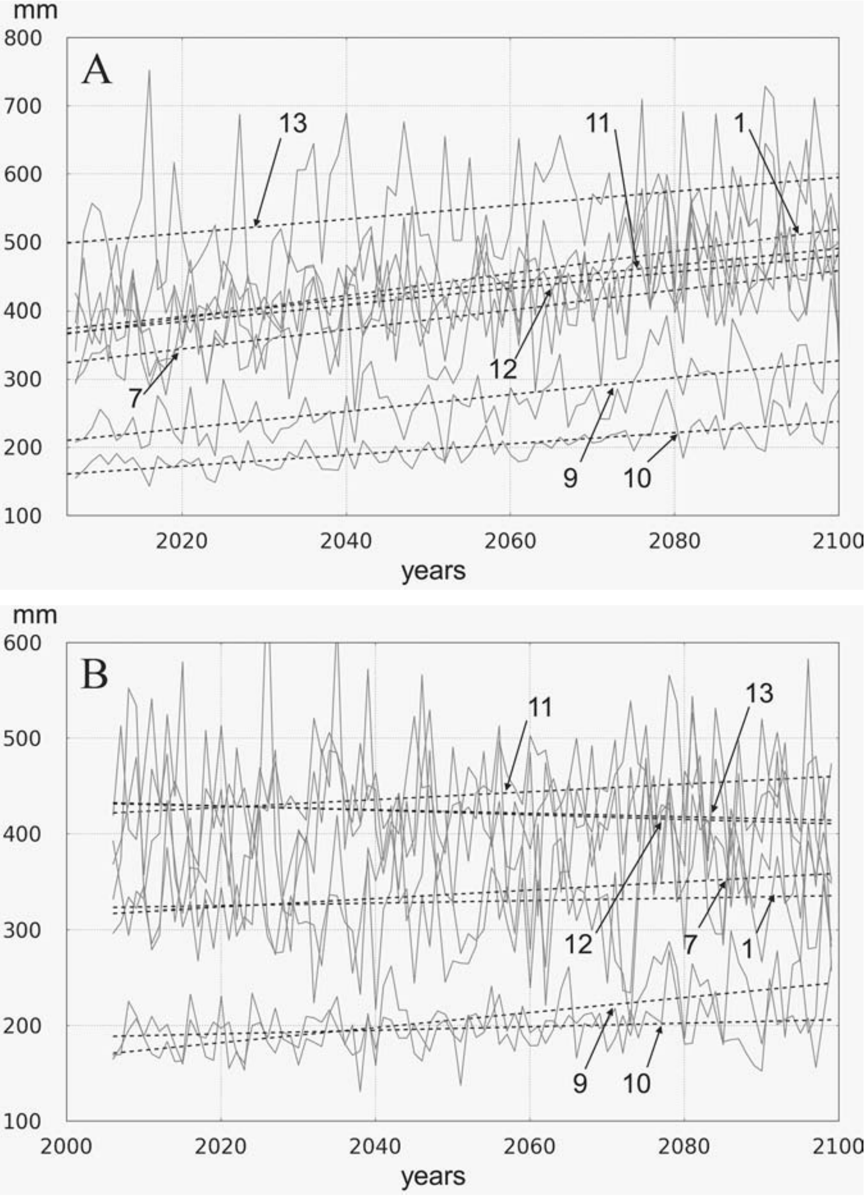


Figure 7.3. | *Projected Regional Changes in the Cumulative Amounts of Precipitation in the Period October–May (A), and in the Snowfall Period with Temperatures Below 1°C (B)*

Note: Calculations are based on CMIP5 ensemble climate projection under the RCP-8.5 emission scenario.

Projected changes in the degree-days of thawing are presented in Figure 7.4. According to these data, the expected rate of ddT rise (trend) decreases from west to east in the Russian Arctic, varying between 16.5 degree-days per year (°C d/y) in North-European Russia (region 1) and 15.7°C d/y in West Siberia (region 7), to 11–12°C d/y in the Central Siberia, Yakutia, and Chukotka (regions 10 through 12 in Figure 7.4). By 2050, the Russian Arctic will be accumulating much more heat during the summer. Except for Chukotka (region 12) all regions will be characterized by ddT rates higher than those of present-day North European Russia (region 1), where permafrost is relatively warm. By the end of the century the regional-mean ddT everywhere in the Russian North is projected to rise well above the current ddT level in the warmest of all permafrost regions.

Khlebnikova, Sall, and Shkolnik (2012) used observational data and calculated changes in the demand for heating energy between the two periods of 2001–2010 and 1981–2000. According to results of this study, Hdd dropped by 200–300°C d (about 5–8 percent) in North-European Russia, by less than 200°C d (0–2 percent) in West Siberia, and by 200–500°C d (2–5 percent) elsewhere in the Russian North. Projected changes in the heating regime have been addressed by several Russian publications, some of which have been summa-

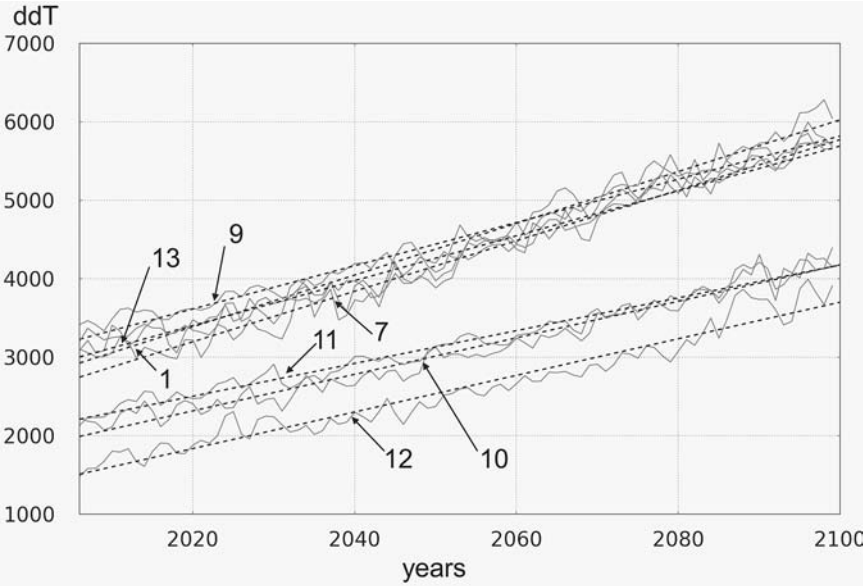


Figure 7.4. | *Projected Changes of Thawing Degree-Days (ddT), °C d*
Note: Calculations are based on CMIP5 ensemble climate projections under the RCP-8.5 emission scenario.

rized in English by Anisimov and Vaughan (2007). According to these results, demand for heating energy in the Russian Arctic is expected to decrease up to 15 percent under projected mid-twenty-first century climate conditions, whereas the duration of the period when heating in the northern cities is needed will decline by up to one month.

These findings have been updated with the most recent CMIP5 climate projections, and scaled down to selected regions in the Russian North. Projected characteristics of the heating regime for specific regions are presented in Figure 7.5. The rate at which the demand for heating energy is decreasing in the Russian Arctic (Hdd trend, Figure 7.5B) varies from −21.8°C d/y in North-European Russia (region 1) to −27°C d/y in West Siberia (region 7) and −30.2 to 31.7 in Yakutia and Central Siberia (regions 11 and 10) due to the cumulative effect of less severe winters and the shortening of the heating period (dH, Figure 7.5A).

River Floods

Climatic warming will lead to changes in the frequency, duration, and severity (peak water levels) of floods on northern rivers. The current situation, available data, and trends in the frequency and severity of ice jams on northern Russian rivers have been analyzed in papers by Buzin (2007) and Buzin and Kopaliani (2007, 2008). A summary of their findings in English is given in the SWIPA assessment report (AMAP 2011).

In 2007 Buzin and Kopaliani predicted in the near-term period of 2010–2015 that ice-jam floods on major Siberian rivers would affect larger proportions of the total channel length, become more frequent, and have much higher peak water levels than in the baseline period before 1977 (Map 7.2). One of the driving factors governing such changes is the delay of ice break-up at latitudes 58° to 60°N due to distinct temperature gradients that often occur in this zone in spring. Particular concerns were associated with the Severnaya Dvina, Sukhona, Vug, and Pechora Rivers that traverse urbanized areas in north-European Russia. Many cities located along these rivers, including Shenkursk, Kholmogory, Arkhangelsk, Naryan-Mar, and Veliky Ustug, were likely to be affected by an increased frequency and severity of ice-jam floods, although projected near-term changes were smaller than in Yakutia and Chukotka. The frequency of floods in North-European Russia was projected to increase by 20 percent at most, while peak water levels were expected to increase by 35–50 percent. Our analysis suggests reasons why these explanations were not correct.

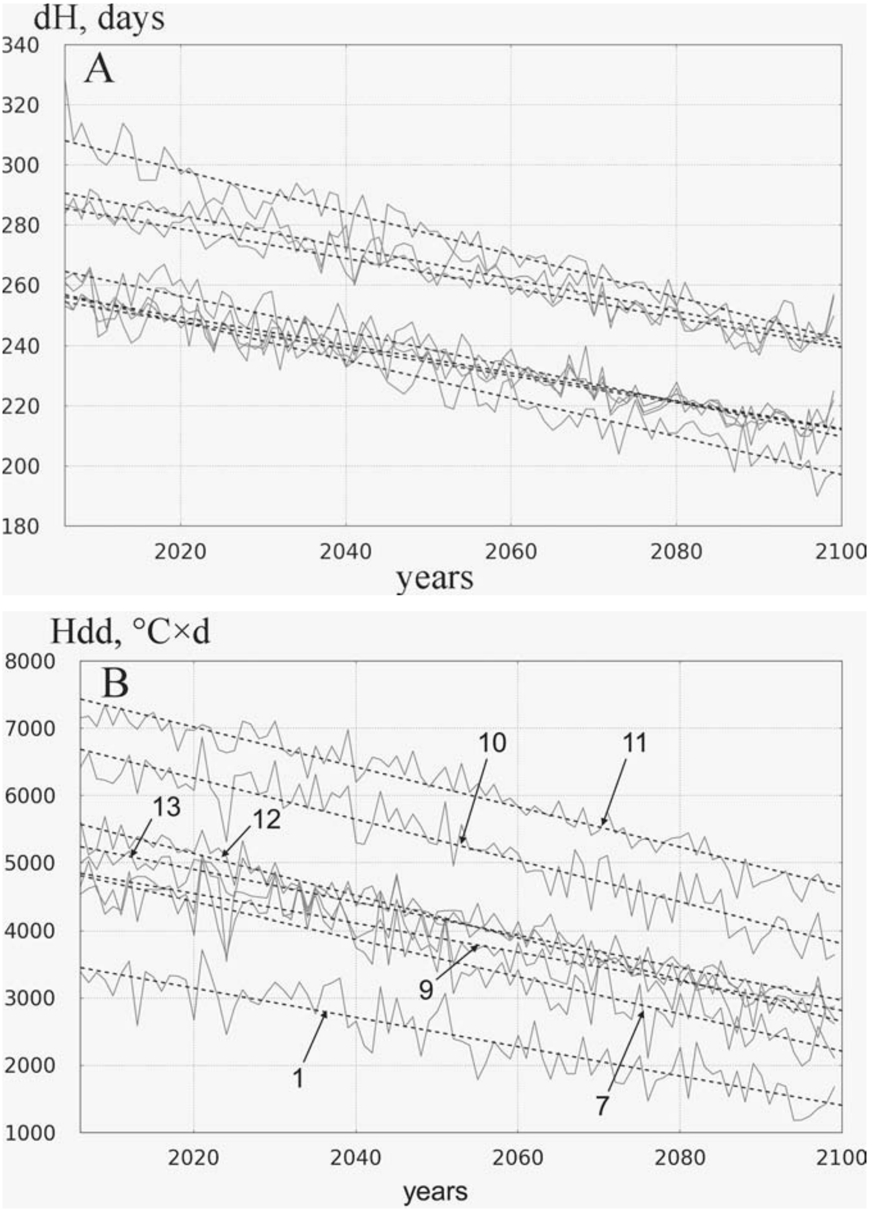
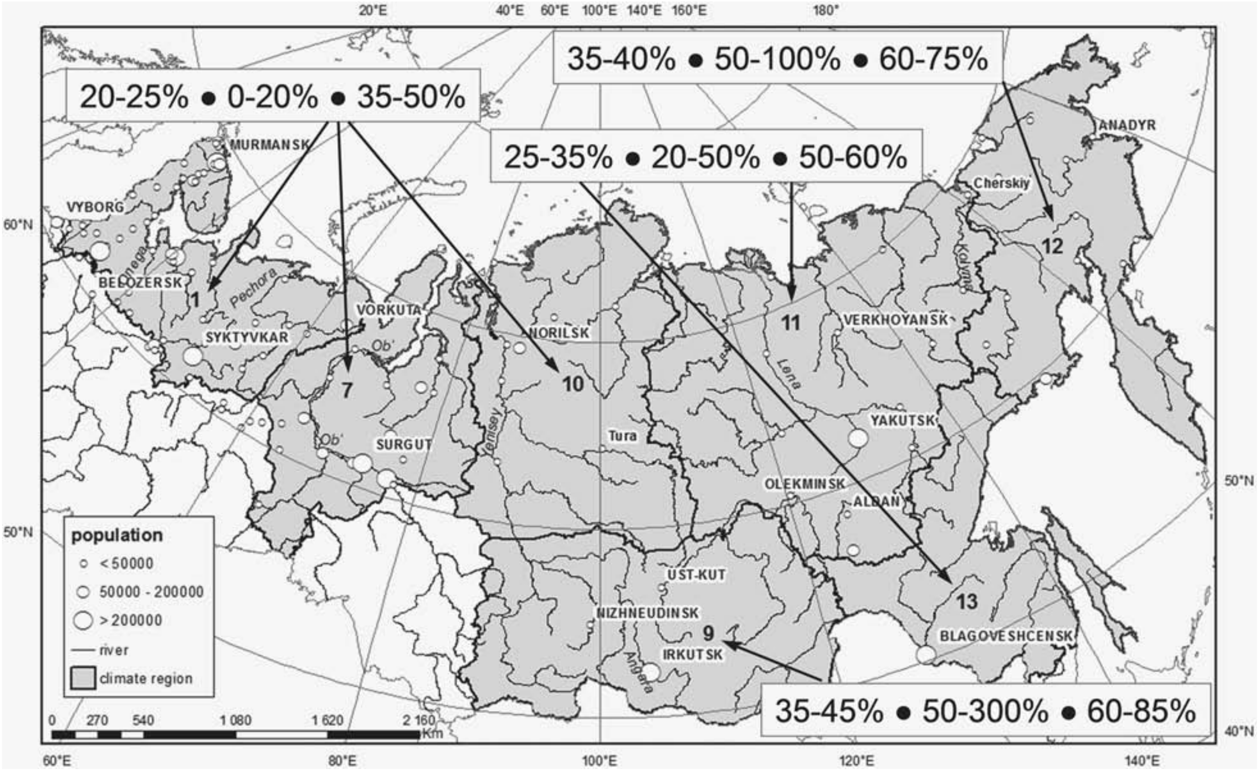


Figure 7.5. | *Projected Regional-Mean Changes in the Characteristics of the Heating Regime*

Note: A—heating period length. B—heating degree-days. Calculations are based on CMIP5 ensemble climate projection under the RCP-8.5 emission scenario.



Map 7.2. *Projected 2010–2015 Changes in the Characteristics of Ice-Jam Floods Relative to the Baseline Period 1946–1977*

Note: Numbers indicate projected relative changes in the following parameters: flooded fraction of the channel length, frequency of flooding, and maximum water level.
Source: Modified from Buzin (2007) and Buzin and Kopaliani (2007, 2008)

Ice dynamics are largely governed by the thermal gradients along rivers (AMAP, 2011). For northward-flowing rivers, such as those in the Russian Arctic, the onset of warm temperatures and ice break-up come earlier upstream, ultimately leading to ice jams downstream. Climatic warming could change the situation to the better by lowering the thermal gradient along rivers in spring, if the rate of warming in the downstream segments exceeds those upstream. Alternatively, if climatic warming leads to the enhancement of the thermal gradients along rivers, there is a potential for the increased frequency and severity of ice jam floods.

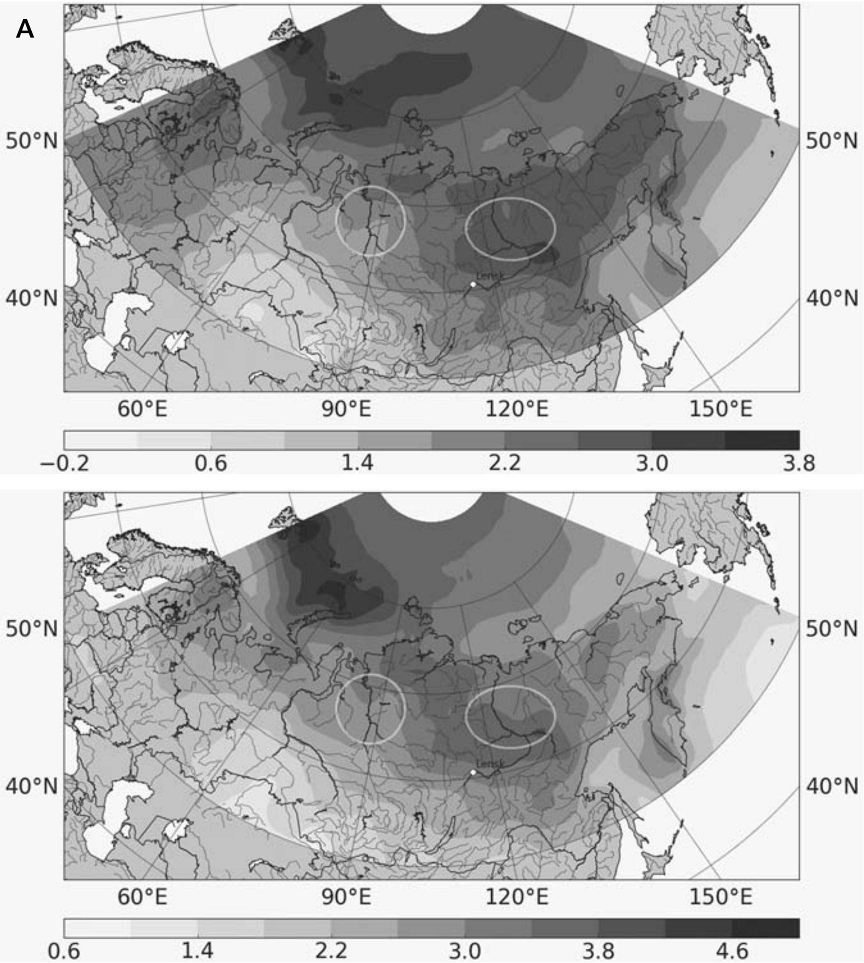
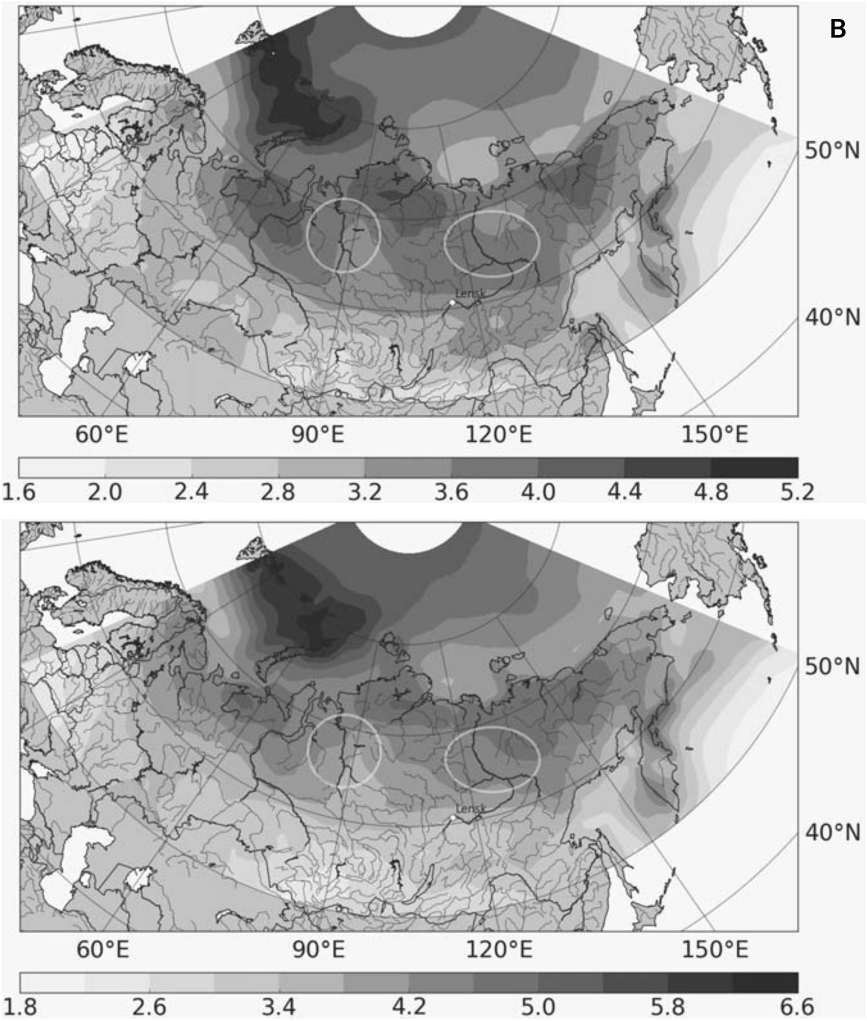


Figure 7.6. | *Projected Air Temperature Changes for the Spring Break-up Period (May) Relative to the 1961–1990 Norm*

Note: Figure A—2006–2015, Figure B—2016–2025

Projected spring temperature changes are an important spatial feature, especially those in May, which is the most common month for ice-jam floods to occur in the Russian North. The maps in Figure 7.6 illustrate the projected May temperature changes relative to the 1961–1990 norm. Results for several decadal time samples (only two of which are shown in Figure 7.6) consistently show a tendency toward greater warming in the downstream channel segments on all northern rivers. This will lead to a reduction in the current temperature gradient so that ice breakup will be increasingly driven by thermal factors rather than mechanical ice action. Such changes are likely



to reduce the probability of ice jams nearly everywhere in the Russian North, except for a few locations indicated by circles on the maps, including the segment of the Lena River in the vicinity of Yakutsk and a small segment of the Yenisei River. This result does not support the conclusion of Buzin (2007) and Buzin and Kopaliani (2007, 2008) regarding the increased frequency of ice-jam floods on larger proportions of river channels in the next several years.

Case Study: 2001 Flood in Lensk

The history of Lensk[4] is illustrative of man's failure to plan for natural risks in the construction of cities in the North. Lensk existed for many years in harmony with nature; however, planning decisions made in the 1950s placed a new part of the city on a flood plain. In 2001, this decision led to disaster when the Lena River flooded and destroyed much of this construction. Unfortunately, the authorities did not learn from this mistake: after a visit from President Vladimir Putin, the city was quickly rebuilt in the same location.

Existing records show that Lensk was founded no later than 1663. The settlement's original name was Mukhtuia, which means "Big Water" in the Evenk language. In the 1730s, during Vitus Bering's second expedition to Kamchatka, a post office was established in Mukhtuia on the road linking the cities of Irkutsk and Yakutsk. In the nineteenth century and the early part of the twentieth century, the village received political prisoners exiled from European Russia. The population of no more than 500 people worked at the post office and in maintaining the road, in agriculture (raising cattle and cultivating potatoes and vegetables), and trapping fur. In the 1930s, the local economy expanded to include timber production and inland river transportation.

Everything changed in 1956, when the village became the headquarters for the construction of the new city of Mirnyi, set up to mine the diamonds found in a volcanic kimberlite pipe 231 km inland (by air) from Mukhtuia. The village benefitted from its proximity to the river Lena and soon became a base in the supply system that was vital to develop the lucrative diamond industry. Within one year, the population increased from 2,000 to nearly 8,000 people, and peaked at 30,900 people in 1992. Most of the population served the various needs of the diamond industry and its mining operations in Mirnyi.

In 1963 Lensk met the requirements to achieve official designation as a city. By that time it had a well-developed urban infrastructure, with multistory buildings, river links, an airport, and a 280-km all-weather road connecting it to the recently built diamond-producing center of Mirnyi.[5] Proceeds from the diamond industry financed the development of the city, but the builders put little thought into the kind of urban planning required to protect the new structures from natural disasters, particularly floods. Due to this inappropriate planning, in 1956 construction of the new part of the city took place on a flood plain.

In May 1998 the abrupt onset of warm weather caused rapid snowmelt and led to severe flooding of the Lena River. On 17 May, the water level peaked at 17 meters above the norm, damaging many structures. The estimated economic loss in Lensk and smaller towns on the banks of the Lena totaled 872.5 million rubles (equivalent to approximately US$148 million at the 1998 exchange rate).

The next year, the river flooded again, nearly reaching the height of the flood in 1998. It should have been possible to learn lessons from the experiences of 1998 and later years and, if it were not possible to protect the city from the rising waters, to at least minimize any unavoidable losses. Yet to prevent flooding in 2001, the Yakutian authorities considered it sufficient to spend only 15 million rubles (approximately US$530,000), or 0.05 percent of the republic's budget. Unfortunately, the flooding in May 2001 turned out to be much worse than in previous years. As a result, the federal government had to pay 6 billion rubles (US$214 million) to repair the damage caused by the waters and rebuild the almost completely destroyed city. Given the extent of the damage, the republic's government was unable to pay for the losses, so the federal government was required to spend 400 times what had been spent earlier on preventive measures.

Already by March 2001, the Lena basin showed all of the major risk factors for future flooding. The previous winter had been cold and snowy, with snow packs greatly exceeding the norm. The thickness of the ice on the Lena was on average 20–30 cm greater than usual, and in places exceeded the multiyear average by 1.5 to 2 times, reaching 3 meters. In the beginning of May the difference in temperature in the flow of the Lena in Irkutsk Oblast and Sakha (Yakutia) Republic reached 20°C, making possible the accumulation of a large quantity of water in the upper reaches of the Lena River and its tributaries and an earlier ice melt in this area (with a normal river flow, the ice melt would start later). The water began to flow with unusual speed: in the course of a day, the ice "jumped" 250 kilometers and tumbled onto Batami Island, located 40 km downstream from Lensk, where an 80km ice jam formed.

The water began to rise at the speed of 35–40 cm/hour. On 17 May, it reached a critical point, and the dike protecting Lensk gave way, allowing water to flow directly onto the city's streets. By noon on 18 May, the level of the water in the city had risen by more than 20 meters. All of the ships that had been in the river were crushed by the ice and sunk. At 4:55 pm, the ice logjam was broken and ice began to flow on all parts of the Lena River. As a result, the level of water began to drop with a speed of 1.5–2.5 cm/minute. In Lensk and the surrounding area (Batamai, Saldykel', Nyuya, Natora, and Turukta), 3,331 homes were completely destroyed and 1,831 required extensive reconstruction. In addition, 396 km of electrical lines, 164 substation transformers, 470 km of communication wires, and 5 radio transmission stations were damaged. It was necessary to restore 184 km of roads, 2 bridges, 7 healthcare centers (clinics, hospitals, natal care centers), and 26 schools and child care facilities. Approximately 31,000 people lived in the affected area; of these, 8 people died and more than 20,000 suffered property damage. The furnaces were destroyed in the houses that were flooded (with a cost of tens of thousands of rubles each) and often all that was left were bits of clay. The Lena River turned into a carpet of floating firewood heading for the Laptev Sea. During winter, every Yakutian resident needs 30–40 cubic meters of wood for heating; with the loss of the old wood to the flood, the locals had to gather new wood to replace it. The residents' ice-cellars also flooded, ruining the food supply of frozen fish kept there. After the flood, it was typical to find huge chunks of ice on the streets of the city. Many small homes were destroyed or completely torn from their foundations.

Could this disaster have been avoided? Many scientists suggest that one problem was that the authorities did not carry out the annual dredging that had been conducted in previous years. Before regular dredging began along the Lena, the water rose above the critical level near the city of Yakutsk once every 7–12 years (1917, 1924, 1933, 1946, 1958, and 1966). But when the dredging was regularly performed (1970–1990) and the river was at least 3 meters deep near Yakutsk, rising waters were not a problem. During those years, just in the part of the river lying below Yakutsk, dredgers removed 5–5.5 million cubic meters of soil just to clear one navigation route. With the end of the dredging work and the gradual transition to the natural state of the river, there began to be a series of spring floods (1998, 1999, and 2001). Consequently, it can be concluded that human inaction, in addition to the natural tendencies of the river, was a cause of the 2001 flood in Lensk.

The subsequent development of events was even more interesting. On 24 May, Russian President Vladimir Putin arrived in Lensk and held a meeting with officials to discuss how to deal with the consequences of the flood, stating at the session opening, “First of all, I want to know what was and was not done to prevent the tragedy, and if something was not done, why not?” (Gafutulin 2001). The Russian leader described the situation in the affected area as difficult and announced that 30,000 had suffered as a result of the flood, adding that the destroyed parts of Lensk would be rebuilt in the same place. On that day, the State Duma adopted a special ruling about Yakutia. Ultimately, Lensk was rebuilt by the deadline established by the Russian president and government—1 October. The decision of the president and government to restore the city on its previous location, apparently adopted to confirm the thesis that Russians are stronger than nature, continues to arouse amazement and questions from specialists, especially given the possibility that the dramatic events of 2001 could be repeated.

Conclusion

The results presented in this chapter illustrate that cities in the Russian North will be facing numerous challenges and opportunities in association with climate change. Data in Table 7.4 summarize the projections of the regional-mean climatic and hydrological characteristics that have been selected for analysis in this chapter due to their potential impacts on the urban environment. While these data draw a general pattern of the rates of regional changes, there are large

Table 7.4. | *Projected Changes in the Regional-Mean Climate Characteristics*

Region	ddT, °C d/10y	Hdd, °C d/10y	Snow period, days/10y	flood frequency, %	water level, %
North-European Russia (reg. 1)	164.9	−218.3	−6.4	0–20	35–50
West Siberia (reg.7)	157.4	−270.9	−5.8	0–20	35–50
Southern Siberia (reg. 9)	131.9	−209.5	−4.5	50–300	60–85
Central Siberia (reg. 10)	119.9	−316.6	−5.3	0–20	35–50
Sakha-Yakutia (reg. 11)	110.5	−302.8	−4.9	20–50	50–60
Chukotka (reg. 12)	118.2	−311.1	−7.0	50–100	60–75
Russian Far East (reg. 13)	135.6	−235.8	−4.6	20–50	50–60

gradients of baseline climatic conditions within each region, and the particular impacts on specific cities depend on local conditions.

Caution should be used, as due to the presence of the south-north gradient within each region, these regional-mean data are not suitable for direct application to specific locations such as individual cities. To get insight into smaller levels of spatial details, one can use city-specific norms calculated through observational data from local weather stations and overlay it with regional trends, such as those in Figure 7.4. The latter are likely to be representative for the entire region since homogeneity with respect to the rate of climatic change has been one of the key considerations behind the regionalization developed in this study (Map 7.1), applicable to nearly all results presented in this section, except for projections of floods, which are specific to river basins.

Overall, this chapter shows that Russia's north can expect extensive changes in its climate and that urban planners will have to take these changes into account. While the changes will differ from place to place, it is clear that there will be, on average, warmer temperatures. Subsequent chapters will examine the consequences of these climate changes for transportation and urban infrastructure.

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Notes

1. This research was supported by the Russian Science Foundation, project 14-17-00037.
2. Available at http://www.iea.ru/article/kioto_order/15.12.2009.pdf.
3. Available at http://pcmdi9.llnl.gov.
4. http://www.gorodlensk.ru.
5. http://www.mojgorod.ru/r_saha/lensk/.

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