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CONTENTS

SPECIAL ISSUE: GEOGRAPHICAL PERSPECTIVES ON THE ARCTIC

INTRODUCTION	<i>Lawson W. Brigham and Frederick E. Nelson</i>	3
THE AMERICAN GEOGRAPHICAL SOCIETY'S 1975 MAP OF THE ARCTIC REGION	<i>Miklos Pinther</i>	8
GEOGRAPHY AND JURISDICTION IN THE MARITIME ARCTIC.....	<i>Caitlyn Antrim</i>	24
ORGANIZATION AND MANAGEMENT CHALLENGES OF RUSSIA'S ICEBREAKER FLEET	<i>Arild Moe and Lawson Brigham</i>	48
THE ARCTIC CRYOSPHERE IN THE TWENTY-FIRST CENTURY	<i>Roger G. Barry</i>	69
A DATABASE FOR DEPICTING ARCTIC SEA ICE VARIATIONS BACK TO 1850	<i>John E. Walsh, Florence Fetterer, J. Scott Stewart, and William L. Chapman</i>	89
ARCTIC ECOSYSTEMS AND THEIR SERVICES UNDER CHANGING CLIMATE: PREDICTIVE-MODELING ASSESSMENT . . .	<i>Oleg Anisimov, Vasily Kokorev, and Yelena Zhiltcova</i>	108
CLIMATE CHANGE AND STABILITY OF URBAN INFRASTRUCTURE IN RUSSIAN PERMAFROST REGIONS: PROGNOSTIC ASSESSMENT BASED ON GCM CLIMATE PROJECTIONS.....	<i>Nikolay I. Shiklomanov, Dmitry A. Streletskiy, Timothy B. Swales, and Vasily A. Kokorev</i>	125
TRADITIONAL IÑUPIAT ICE CELLARS (SIĠĽUAQ) IN BARROW, ALASKA: CHARACTERISTICS, TEMPERATURE MONITORING, AND DISTRIBUTION.....	<i>Kelsey E. Nyland, Anna E. Klene, Jerry Brown, Nikolay I. Shiklomanov, Frederick E. Nelson, Dmitry A. Streletskiy, and Kenji Yoshikawa</i>	143
PEOPLE OF THE WHALES: CLIMATE CHANGE AND CULTURAL RESILIENCE AMONG IÑUPIAT OF ARCTIC ALASKA.	<i>Chie Sakakibara</i>	159
INTERPRETING CAPTAIN BOB BARTLETT'S AGS NOTEBOOK CHRONICLING SIGNIFICANT PARTS OF PEARY'S 1908-09 NORTH POLE EXPEDITION.....	<i>Deirdre C. Stam</i>	185
"WE ARE FULLY IN THE EXPEDITION": PHILADELPHIA'S SUPPORT FOR THE NORTH GREENLAND EXPEDITIONS OF ROBERT E. PEARY, 1891-1895.....	<i>Douglas W. Wamsley</i>	207
MESSAGES ON ARCTIC POLICY: EFFECTIVE OCCUPATION IN POSTAGE STAMPS OF THE UNITED STATES, CANADA, AND RUSSIA.....	<i>Corine Wood-Donnelly</i>	236

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ARCTIC ECOSYSTEMS AND THEIR SERVICES UNDER CHANGING CLIMATE: PREDICTIVE-MODELING ASSESSMENT*

OLEG ANISIMOV, VASILY KOKOREV and YELENA ZHILTCOVA

ABSTRACT. There is increasing evidence that permafrost and vegetation have already responded to pronounced warming of the Arctic in the past few decades. In this study we used mathematical models to assess changes of permafrost and Arctic vegetation in the first half of the twenty-first century. We tested the regional performance of the CMIP5 Earth system models and eliminated outliers that have large errors in replicating temperature and precipitation trends in the Arctic over the historical time period. The remaining “best” models were combined into an optimal ensemble and used as climatic forcing in permafrost and vegetation modeling. Probabilistic metrics, such as the number of climate trajectories leading to different levels of impacts on permafrost and vegetation, have been used to evaluate the uncertainties associated with the climate projections. Results under all trajectories predict deeper seasonal thawing of the uppermost soil layer above permafrost, a northward shift of biome ranges, expansion of the boreal forest, and reduction of the tundra area. Such changes will have implications for land use, market and nonmarket economies, infrastructure in the urban and industrially developed regions of the Russian Arctic, indigenous peoples following traditional lifestyles, and wildlife. *Keywords:* climate change, ecosystems, modelling, permafrost, projection, uncertainty.

For centuries, public perception associated Arctic regions with pristine wilderness, exceptionally harsh and inhospitable climatic conditions, sparse small settlements, and nonmarket economies with a significant part of the population following traditional lifestyles. This situation changed dramatically in the 1950s and early 1960s, particularly in the Russian part of the Arctic, with the advent of the new reality of industrial and urban developments (Larsen and Fondahl 2014). Focus was made on the extraction of mineral resources, constructing robust transportation utilities with an emphasis on pipelines and all-season roads, energy and water supply systems to serve the needs of the industry, and rapidly rising population in settlements and newly established Arctic cities.

As a result of these developments, the Arctic’s share of the world economy increased multifold. According to (Huskey and others 2014), in 2010 the Gross Regional Product (GRP) of the circumpolar Arctic was \$442.8 billion, or 0.6 percent of world GDP, which is four times more than its share of the world population (0.15 percent). Per capita GRP was \$45,360, which is greater

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than in the European countries and is comparable to the United States. As of 2010, the bulk of the Arctic GRP is produced in Russia (71.1 percent). Other contributors are the United States (10.8 percent), Sweden, Finland, and Norway (each contributing 4.2 percent to 4.6 percent). A significant part of the Arctic GRP comes from oil, gas, and mining, which serve an international market. In this study, we focus on renewable ecosystems resources, which support different types of economic activities exemplified by forestry, fisheries, herding, and a few other industries, and serve both international and local markets. While accurate differentiation of their share of the GRP is not possible due to lack of published data, it is apparently small in comparison to extractive industries. However, in the longer prospective, renewable ecosystem resources are likely to play an increasingly larger role in the Arctic due to their sustainable nature.

Consideration of environmental sustainability was given little attention in the early stages of industrial exploration of the Arctic, although pragmatic reasoning stimulated efforts to adjust the construction methods and technological solutions to the severe climatic conditions, and to harmonize land use and demographic, social, and cultural societal developments with the characteristics of the ecosystems and their services. These services included provisioning of water, food, timber, recreational benefits, habitat for traditional activities, local agriculture, and other essential functions for the Arctic population, which currently totals more than 4 million people (Heleniak and Bogoyavlensky 2014). From the perspective of modern environmentalism, ecosystems and their services are particularly important in the Arctic due to many region-specific constraints, such as limited capacities for adaptation to current and ongoing climatic changes, high vulnerability to anthropogenic disturbances in combination with low recovery rates, and the absence of alternative resources. This is exemplified by the case study of Yamal in Western Siberia. Yamal is the world's largest area of reindeer herding (Forbes and Kumpula 2009), and also a region of extensive oil and gas development. Several studies have demonstrated that reindeer husbandry and overgrazing, in combination with land fragmentation due to construction of pipelines, has put increasing pressure on ecosystems in recent decades, at rates exceeding their recovery rates and ultimately reducing the availability of pasturelands (Degteva and Nellemann 2013; Forbes 2013).

In this study we use mathematical modeling to explore the effects of the changing climate on ecosystem services. We follow the methodological approach used earlier for northern Eurasia and extend it over the terrestrial circumpolar Arctic (Anisimov and others 2011). Terrestrial systems include the biotic communities of living organisms, conventionally termed "ecosystems" and exemplified by vegetation biomes, and their nonliving environments, such as permafrost, hydrological, and other abiotic systems. The latter are relevant to our study as long as they interact with the ecosystems and/or humans and

provide services. From this standpoint, permafrost is an important system that possesses several unique properties and provides at least two essential services. The first is the ability of the frozen ground to support buildings and other infrastructure. This has direct implication for cold-regions engineering, particularly now, when changing climate and thawing permafrost put much of the existing infrastructure at risk (Streletskiy and others 2014). This aspect of permafrost changes is detailed in the paper by Nikolai Shiklomanov and others in this volume, and we do not address it here. The second is the ability of permafrost to provide habitat to the roots of plants in the uppermost layer of the seasonally thawing soil, and to support different types of above-ground vegetation. This ecosystem-related aspect is explored further in the paper through predictive modeling of permafrost and vegetation. Inland hydrological, coastal, and marine systems in the Arctic deserve close study, and despite their importance are not considered here. The ultimate goal of our study is threefold: to evaluate changes in the state of permafrost and the distribution of vegetation under the climatic conditions projected for the future; to compare the services these systems could provide under current and future conditions, and to identify regions in the circumpolar Arctic where climate-induced changes of permafrost and vegetation in the twenty-first century are likely to affect land use, economic activities, and human well-being.

To accomplish these tasks we constructed a detailed digital vegetation map for the circumpolar Arctic; developed and validated a statistical vegetation model specifically adjusted for the cold-climate biomes; tested the regional performance of 46 CMIP5 Earth system models (ESMs) in the Arctic and constructed the optimal climate projection using top-ranked twenty-nine models; performed predictive calculations for the mid-twenty-first century using coupled permafrost-vegetation models; and evaluated the uncertainties associated with the climate projections.

DATA AND METHODS

Following the work of myself and my colleagues, we distinguish between the gradual ecosystem changes in response to climate variations, and threshold-based changes associated with tipping points (2011). The latter are of the greatest interest as they lead to new long-term patterns of services. Once the system crosses a tipping point, structural changes evolve further, causing cascading environmental impacts until a new equilibrium state is achieved. Such threshold-driven changes under sustained climatic warming are exemplified by a northward shift of the tree line, displacement of biome boundaries, and thawing of near-surface permafrost beneath the base of the active layer. In contrast, gradual changes, such as interannual climate-driven variations of permafrost temperature and depth of seasonal thawing, or variations in biological productivity, have only local effects in time and over space, and are excluded from our analysis.

The distribution and state of permafrost under current climatic conditions are relatively well studied. According to the classical definition, permafrost is any subsurface material that remains below 0°C for two or more consecutive years (Washburn 1979). Depending on the fraction of land underlain by frozen ground in the near-surface soil layer, permafrost is divided into continuous (>90 percent), discontinuous (50 percent to 90 percent) and sporadic (<50 percent) zones. According to the most recent estimates, frozen ground occurs in 9 percent–12 percent of all continents (13.2–18.0 million km²), whereas the total area of all permafrost zones underlies 23 percent to 25 percent of the land surface (Gruber 2012). The state of permafrost is best characterized by the mean annual ground temperature in the top near-surface layer, and by the depth of seasonal thawing, which is often called the active-layer thickness (ALT). Temperature is the major factor governing the bearing capacity of frozen ground—for example, the ability to support structures and pile foundations (Streletskiy 2012).

Analysis of observations presented in David Vaughan and others (2013) indicated a discernable increase of permafrost temperatures during the past three decades, by 0.6–3°C in northern Alaska, 1–2°C in northern Canada, 0.3–2°C in northern Eurasia, and circumpolar-scale thickening of ALT. Such changes have direct implications for vegetation. Depending on its thickness, the active layer could support a wide range of vegetation species along the north-south environmental gradient (Tchebakova and others 2010). In this study we consider a higher organizational level that aggregates individual species into biomes, such as distinct combinations of indicative species sharing common habitat under a specific range of climatic conditions. Although some types of economic activities, such as timber production, are targeted at specific tree species, biomes are more representative units than individual species, and characterize the broader range of potential ecosystem services under given climatic and environmental conditions.

Until recently, Arctic vegetation studies were complicated by the absence of internationally standardized classifications of the circumpolar tundra and boreal biomes. North American classifications are based on biogeochemical parameters of soil and consider two compositionally distinct tundra vegetation types: moist acidic tundra (soil pH 3–4), and moist nonacidic tundra (soil pH 6–7). Nonacidic tundra has higher graminoid (grasses and grasslike plants) and forb (flowering plants) abundance, whereas acidic tundra has higher woody-shrub abundance (Hobbie and Gough 2004). In contrast, conventional European and Russian classifications are based on a combination of the dominant indicative species and prevailing climate conditions (Yurtsev 1994). The conflict between the North American and European terminology and classifications was partly resolved with the appearance of the Circumpolar Arctic Vegetation Map (CAVM), which established the correspondence between the five physiognomic units with distinct vegetation types and bioclimatic subzones (2003).

Multiple lines of evidence indicate that the productivity and distribution of biomes in the circumpolar Arctic respond to climate variations and change. Field observations and satellite Normalized Difference Vegetation Index (NDVI) data demonstrate strong correlation between the greenness, which is a metric of the photosynthetic activity for any given biome, and growing season temperature sums (summer warmth index) throughout the circumpolar Arctic in the period 1982–2014 with noticeable regional variations (Myers-Smith and others 2015). The most pronounced changes have been observed in the southern tundra. They were manifested in the increased abundance of shrubs and northward advancement of their ranges in North America (Fraser and others 2014) and Eurasia (Frost and Epstein 2014). Long-term observations at sites with sustained experimental warming have demonstrated that such changes could be attributed to an increase in the summer warmth index (Zamin and others 2014; Hollister and others 2015). European sites in the southern tundra demonstrate higher sensitivity of shrub growth to summer warmth than North American sites. Recently, satellite data indicate a decline of the tundra greenness following nearly three decades of continuous rise, which is also coherent with the changes of the summer warmth (Bhatt and others 2013). Xu and his colleagues demonstrated that only 37 percent of Arctic vegetation had greened over the period 1982–2012 (2013).

While the distribution of biomes, state of permafrost, and their dynamics are driven by the interplay of many factors, in this study we assess only the climate-related component of such changes. This implies that our analysis lacks synergism, such as the potential exacerbation of vulnerabilities to the cumulative effect of the multiple climatic and nonclimatic forcing (Hovelsrud and Smit 2010; Bjerke and others 2014). In this study, climate is viewed as an inexhaustible resource that supports Arctic ecosystems as global change proceeds. Apparently, warmth and moisture conditions largely govern the state of ecosystems.

From the perspective of the ecosystem services, the ecological role of permafrost is to provide root habitat for Arctic plants. We used a permafrost model of intermediate complexity, which is best known as Kudryavtcev's model (Kudryavtcev and others 1974), to predict the state of the frozen ground under projected future climatic conditions. A conventional mathematical formalism of this model is detailed in Tatiana Sazonova and Vladimir Romanovsky (2003). The model has low input data requirements and demonstrated high efficiency in predicting the distribution of permafrost, ground temperature, and ALT over a wide range of geographical scales. We consecutively ran the model at the nodes of a $0.5^\circ \times 0.5^\circ$ latitude/longitude circumpolar grid spanning the permafrost region using mean monthly temperature and precipitation data as climate forcing.

Following Sazonova and others (2004) and Shiklomanov and others (2007), we prescribe standardized zone-specific properties to the uppermost organic layer (includes lower above-ground vegetation such as moss, lichens and grass,

and organic soil), and underlying mineral soil. While the organic and mineral soil layers have distinctly different thermal properties, the conventional algorithm of Kudryavtcev's model does not differentiate them and operates with the volumetric soil thermal conductivity, which is averaged over both layers. Such an approach does not allow accurate evaluation of the effect that changes in the organic layer have on ALT. We modified the model to explicitly take into account the thermal properties of each soil layer.

Another feature of our study is interactive coupling of the permafrost model with the statistical model of biome distribution described in the next section. Unlike the situation with stand-alone permafrost and vegetation modeling, interactively coupled models simulate feedbacks and threshold-based changes in the permafrost-vegetation system under climatic forcing.

RESULTS

We developed a new circumpolar map of extratropical vegetation zones with an optimal number of biomes spanning the boreal and tundra zones. This task was accomplished by combining the generalized variant of CAVM, which covers the circumpolar tundra vegetation zone, with the Russian map of boreal and alpine vegetation (Stolbovoi and McCallum 2002), and applying the later vegetation classification to the North American continent. The resulting Arctic vegetation map contains the following eleven biome categories: barrens, northern tundra, typical tundra, southern tundra, forest tundra (roughly approximates the location of the tree line), northern taiga, middle taiga, southern taiga, mountain taiga, subalpine sparse forest, and alpine tundra.

Vegetation models of different complexity have been developed to study changes in the distribution and productivity of Arctic biomes under current and projected climatic conditions. The most comprehensive are the dynamic global vegetation models (DGVMs) (Bachelet and others 2003; Sitch and others 2003; Prentice and others 2007). They are based on physiological mechanisms or relationships between ambient parameters (for example temperature, precipitation, solar radiation, and soil fertility) and plant functional types. DGVMs have potentially high predictive power in estimating the distribution of vegetation and associated fluxes of carbon, nutrients, and water, as demonstrated in several recent studies (Sitch and others 2008; Forkel and others 2016). Such models have high input data requirements and hundreds of output variables. However, their application in the Arctic was so far limited due to the absence of the full set of required input data, and also because DGVMs do not differentiate relatively low-productive biomes located northward of the tree line, combining them into a single class of tundra vegetation. For the purpose of this study we developed a much simpler statistical vegetation model, which is less sensitive to input data limitations. Such models are also called ecological niche models (Goberville and others 2015). They are receiving increased attention in studies of climate change impacts on vegetation (Anisimov and others 2015;

Tchebakova and others 2010; Peterson 2006; Raybaud and others 2013). However, none of these studies addressed Arctic vegetation at sufficient levels of regional detail.

Two such studies are relevant to the scope of our paper. Eric Goberville and others (2015) developed an ecological niche model for two European species indicative of the deciduous forest in southern and central Europe (sweet chestnut) and Scandinavian cold-climate vegetation (dwarf birch). They demonstrated that appropriate selection of ecologically relevant descriptors, for example predictive climate indexes, is a prerequisite to model the ecological niche of a species. Analysis of nineteen tested descriptors indicated that the following four indexes have the highest predictive power for the selected species: the temperature annual range, annual mean temperature, annual precipitation and precipitation of the warmest quarter (for sweet chestnut). Another study by Nadezda Tchebakova and others (2010) was focused on Siberian larch forest. This study demonstrated the importance of incorporating the extreme low winter temperatures into the vegetation models because they impose physiological limitations for survival of species in the cold climates. We applied the methodology and results of these studies to specific conditions of the Arctic, and developed a statistical vegetation model based on the following three predictive climate indexes:

- Summer warmth index, for example air temperature sums above 5°C, ($\Sigma T_{>5}$, °C9days);
- Air temperature sums below 0°C, ($\Sigma T_{<0}$, °C9days);
- dryness index, (D , °C9days/mm), which is defined as the ratio of $\Sigma T_{>5}$ to the annual sum of precipitation (in mm).

Following Tchebakova and her associates, we constructed a statistical vegetation model through ordination of biomes along three selected indexes (2010). They are closely related to the physiological limitations of biomes, and could be used as predictors of their distribution in cold climate regions. In permafrost regions we also took into account ALT as an auxiliary predictor, as described below. We used monthly temperature and precipitation data from the CRU TS3.10 gridded dataset with 0.5° × 0.5° latitude/longitude resolution (Harris and others 2014), calculated the average values of the climate indexes for the 1901–1980 period, compared them with the vegetation map, and calibrated the statistical vegetation model by identifying the climatic limits for each biome—for example, the lower and the upper values of the predictors. An intrinsic limitation of the statistical vegetation model is that it does not account for the transient effects of environmental changes and characterizes the state of the system, which is adjusted to long-term climatic conditions. Given that vegetation succession in the Arctic is slow, with a typical time scale of many decades, we calibrated the model using climatic data averaged over the century-scale period. We also eliminated the recent few decades of pronounced warming of the Arctic, when transient effects have dominated. The selected calibration period 1901–1980 is long enough to minimize the transient effects

associated with the short-term climate variations (for example, warming of the Eurasian Arctic in the 1930s), on one hand, and to allow sufficient time for the vegetation to reach dynamic equilibrium with the climatic conditions of the twentieth century on the other. To account for the large-scale, region-specific physiological adjustment of biomes to local environmental conditions, model calibration was performed individually in the five sectors in Alaska, northern Canada, northern Europe, Siberia, and the Russian Far East. Results are presented in Table 1. Ranges between the lower and upper limits for each biome characterize the spatial variability. They have been calculated as minimum and maximum across the five sectors in the circumpolar Arctic. Exceptions are three alpine biomes, for which the intersectoral distinctions are small and the circumpolar mean values have been indicated instead of the ranges.

The data in Table 1 were used to construct model-based maps of biomes under the current and projected climatic conditions. Changes of the climate indexes in the twenty-first century were evaluated using results from CMIP5 ESMs under the RCP8.5 greenhouse gas emission scenario. Emission scenarios—or representative climate pathways (RCPs), as they are called in the recent studies—and CMIP5 projections are detailed in William Collins and others (2013). We intentionally limited our analysis to only one extreme RCP8.5; the rationale behind it is given further in the discussion section. CMIP5 computations were made with more than forty-five models, including different experiments with the same ESMs. All experiments include historical (for the period 1850–2005) and predictive (for the period 2006–2100) runs. Unlike weather-forecast models, which are designed to predict real-time dynamic changes of all climatic parameters from the present state ahead over the period of few days, ESMs generate century-scale “projections,” which simulate the statistics of climatic conditions rather than particular weather patterns (Flato and others

TABLE 1—CLIMATIC LIMITS OF THE NORTHERN BIOMES: 1 – BARRENS; 2 - NORTHERN TUNDRA; 3 –TYPICAL TUNDRA; 4 – SOUTHERN TUNDRA; 5 – FOREST-TUNDRA; 6 – NORTHERN TAIGA; 7 – MIDDLE TAIGA; 8 – SOUTHERN TAIGA; 9 – MOUNTAIN TAIGA; 10 – SUBGOLETS SPARSE FOREST; 11 – ALPINE TUNDRA.

BIOME	$\Sigma T_{>5}, \text{ }^{\circ}\text{C}\text{9DAYS}$		$\Sigma T_{<0}, \text{ }^{\circ}\text{C}\text{9DAYS}$				$D, \text{ }^{\circ}\text{C}\text{9DAYS/MM}$	
	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER
1	0	50–110	–9000	–6000	–4000	0.0	1.1–1.7	
2	0–90	400–1000	–8000	–5500	–5500	–1100	0.0	2.1–6.1
3	50–250	800–1250	–7500	–4400	–4500	–1090	0.0–0.2	2.5–7.5
4	200–800	1100–1600	–7000	–3400	–3000	–1050	0.5–1.7	3.1–7.6
5	500–1000	1200–1500	–6800	–2900	–4500	–1020	0.8–2.3	1.8–7.2
6	650–1100	1700–1950	–6000	–2500	–3400	–1000	0.8–2.1	3.5–7.9
7	1200–1550	2000–2300	–5400	–2300	–3300	–700	0.9–2.7	4.0–8.5
8	1500–1800	2200–2700	–3800	–1800	–2000	–400	1.1–3.4	4.3–8.7
9	700	2500–3000	–6000	0.0			0.6	10.0
10	200	1500	–8000		–1500		0.0	5.0–7.0
11	0	1200	–9000		–2500		0.0	3.9–5.0

2013). This implies that ESM's results may not be used to predict future temperature and precipitation patterns for specific years and locations. Instead, they should be smoothed in time and over space (Raisanen and Ylhaisi 2011). Conventionally, they are averaged over thirty-year periods, which can be compared with each other to identify changes. We considered two thirty-year-long time slices, the baseline period 1961–1990, and the mid-twenty-first century period 2036–2065. Here, we follow the World Meteorological Organization's conventional use of the 1961–1990 period for calculating climatic norms.

Modern climatic projections are constructed using the ensemble approach—that is, results from several (often all available). ESMs are combined and averaged to minimize the effect of individual model's errors. We followed the approach suggested by Reto Knutti (2010) to narrow the range of uncertainties in the ensemble climate projections by testing forty-six ESMs and evaluating their performance in each of the five Arctic sectors. We compared calculated trends of climatic indexes over the period 1981–2005 with observations and eliminated outliers, for example, models with errors above the average level. The remaining twenty-nine “best” models were combined into an “optimal ensemble.” Results of ESM evaluation in the Eurasian Arctic are available through the data portal <http://permafrost.su/gcm.html>.

With rare exceptions, climate-impact studies use the ensemble-mean as the only driver of projected changes. A more sophisticated approach considers results from individual models in the optimal ensemble as a unique and equally probable future climate pathway. The intermodel spread, or envelope of climate pathways in the optimal ensemble, characterizes the uncertainty of the projected climate. This is illustrated in Figure 1, which shows—averaged over each of the five Arctic sectors—changes of the three climate indexes ($\Sigma T_{>5}$, $\Sigma T_{<0}$, and D). Medians of the twenty-nine best ESMs are indicated by black solid curves. Gray curves show results from individual models.

Most of the tested CMIP5 ESMs have large biases in replicating climatic changes in the Arctic. Thus, the ensemble projections based on all models have to be considered critically and with caution. According to our results, all-model ensembles underestimate the projected temperature changes in the Arctic compared to the optimal ensemble. Depending on the region, elimination of the outliers narrows the uncertainty of climate projection—for example, the difference between the end-member climate pathways, by 5–20 percent. To further reduce the uncertainty, we eliminated the biases of individual models by combining their results with observations. We used each of the ESM results to calculate differences between the climatic indexes averaged over the 2036–2065 and 1961–1990 periods, and overlaid these differences with the baseline (1961–1990 mean) values calculated from the CRU TS3.10 gridded dataset.

We used permafrost and vegetation models to construct maps of ALT and biome distribution in the circumpolar Arctic under different climate conditions. Predictive calculations have been made using the ensemble-mean climate

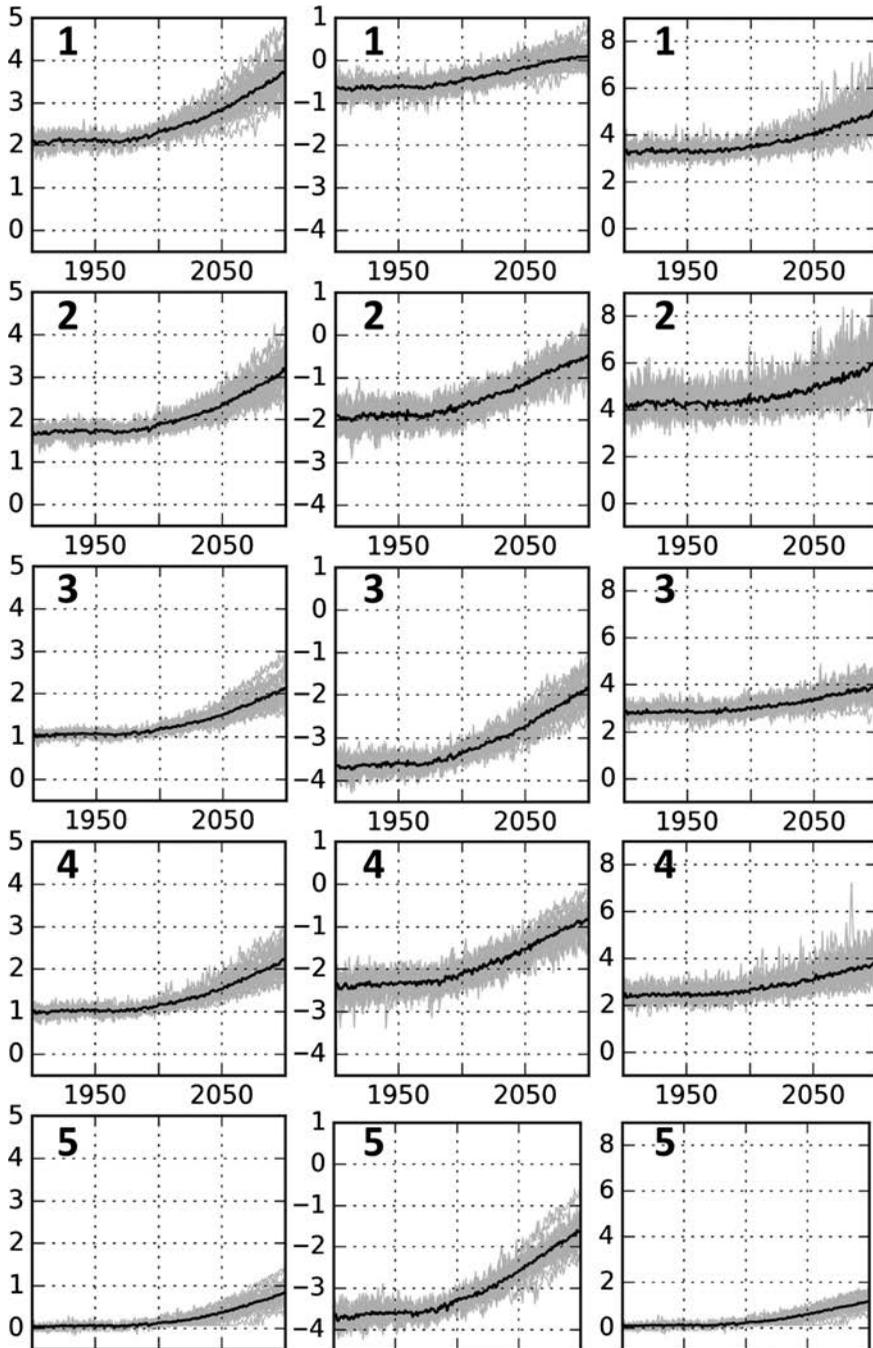


FIG. 1.—Changes of the summer warmth index (left column), air temperature sums below 0°C (middle column), and dryness index (right column) in the period 1960-2080 simulated by 29 ESMs. Black curves show medians of all ESMs, grey curves show results from individual models. Numbers on panels designate five five sectors in Alaska (1), northern Canada (2), northern Europe (3), Siberia (4), and the Russian Far East (5).

projection for mid-twenty-first century. The permafrost model is sensitive to soil properties, and we made several calculations for sand, silt, and loam with 5 and 10 cm thick organic layers atop the soil column. ALT maps in Figures 2a and 2b correspond to silt with a 5 cm organic layer, which is representative for many locations in the continuous and discontinuous permafrost zones.

The maps in Figure 3 illustrate the model-based distribution of biomes in the Arctic under the baseline (A) and projected for the mid-twenty-first century (B) climatic conditions. The dotted background on the map in Figure 3b designates areas where the model predicts replacement of the current vegetation by the new forest and steppe biomes, which are not present in the Arctic under the baseline climatic conditions.

The predictive maps in Figures 2 and 3 were constructed using the ensemble-mean climate data, and as such represent the environmental conditions under the “average” climatic projection. This approach underestimates the uncertainty associated with the envelope of climate projections in the optimal ensemble (Goberville and others 2015). The effect of the intermodel spread on the permafrost and vegetation projections can be assessed using a probabilistic metric. Results from individual models within the optimal ensemble, such as those illustrated in Figure 1, may be considered as independent and equally

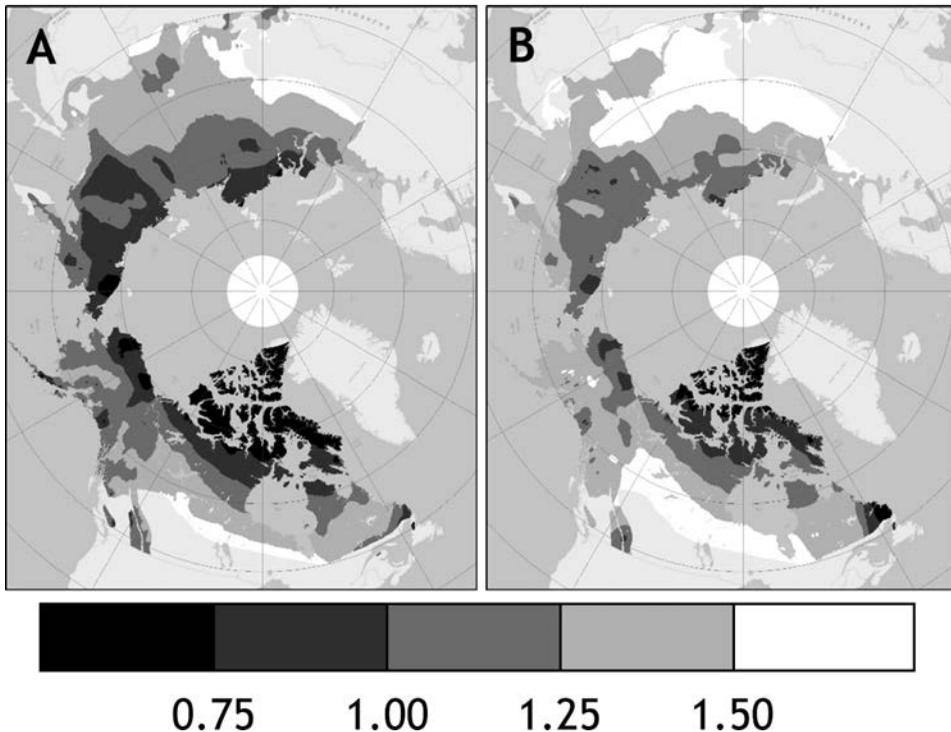


FIG. 2.—Model-based circumpolar active-layer thickness (m) under the baseline (A) and projected for the mid-21st century (B) climatic conditions.

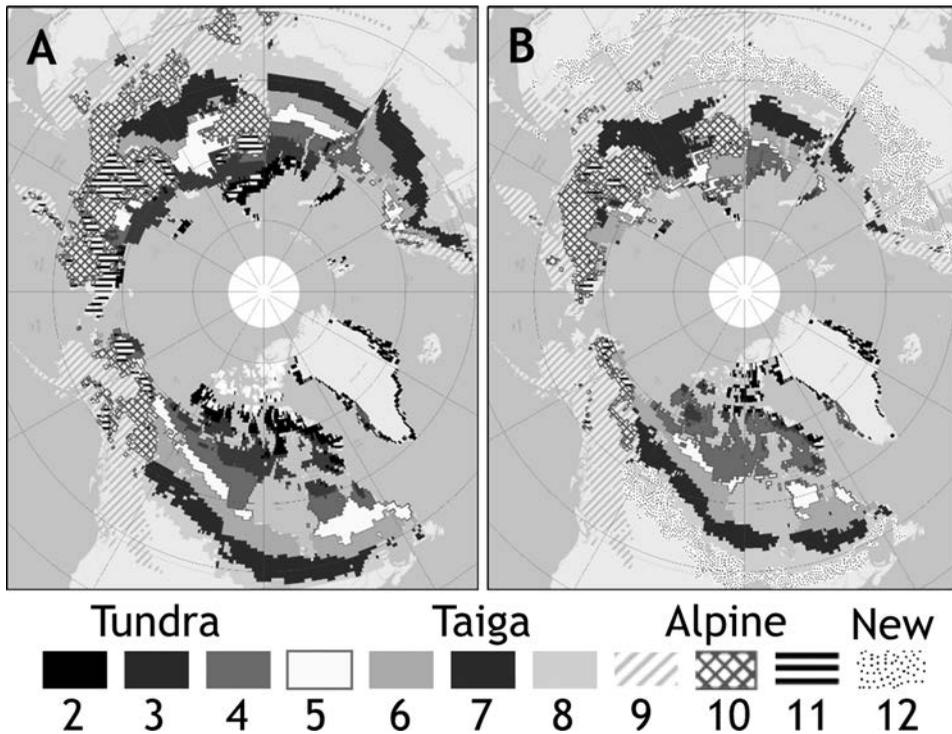


FIG. 3—Model-based distribution of Arctic biomes under the baseline (A) and projected for the mid-21st century (B) climatic conditions. 2 - northern tundra; 3 - typical tundra; 4 - southern tundra; 5 - forest-tundra; 6 - northern taiga; 7 - middle taiga; 8 - southern taiga; 9 - mountain taiga; 10 - subgolets sparse forest; 11 - alpine tundra; 12 - new forest and steppe biomes (in fig. B) advancing from regions outside the Arctic.

probable projections leading to different environmental changes. Following this approach, we made multiple runs of the permafrost and vegetation models with the climatic forcing from each of the twenty-nine “best” ESMs, and evaluated the variability in projected distribution of biomes and ALT.

There are many ways to illustrate the results of probabilistic permafrost and vegetation modelling, one of which is to count the number of climate projections leading to the crossing of a tipping point. As follows from the comparison of maps in Figures 2a and 3a, the divide between the tundra and forest vegetation (forest-tundra zone) outside the mountain regions is roughly approximated by the 1.25 m ALT isoline. This is a physiologically important threshold, and further in the text we designate it as the “permafrost-constrained tree line.” In the context of this study, the importance of this threshold is dictated by differences in the potential services tundra and forest biomes could provide. Results from probabilistic vegetation modelling are best characterized by the number of pathways, which predict changes of the biome type in the given node of the circumpolar grid. The maps in Figure 4 illustrate probabilistic permafrost and vegetation projections with the likelihood

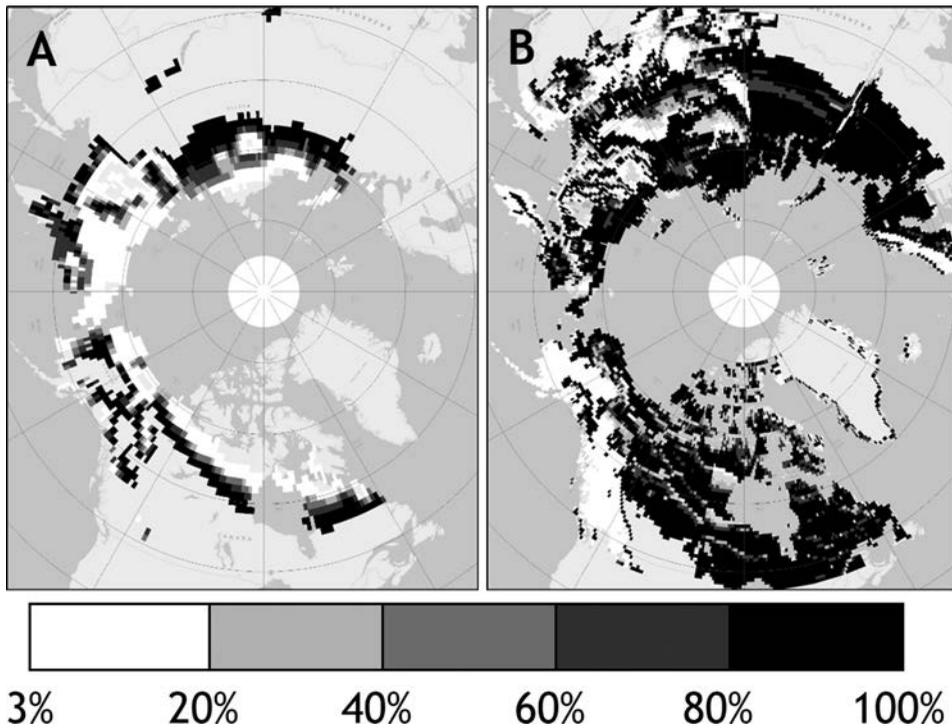


FIG. 4—Percent of climate pathways leading to the shift in the permafrost-constrained tree line (A), and biome change (B) by mid-21st century.

indicated by the differential shading. The scale shows the relative number (percent) of climate pathways that predict indicated changes at given nodes.

DISCUSSION AND CONCLUSIONS

The results of this study provide insight into projected mid-twenty-first century changes of permafrost and vegetation in the circumpolar Arctic. We demonstrated that probabilistic modelling facilitates evaluation of likelihoods of environmental changes under the envelope of climate projections, as well as construction of a new type of predictive maps. Unlike the case with the deterministic maps in Figures 2 and 3, ALT and biome boundaries on probabilistic maps in Figure 4 are fuzzy. By the mid-twenty-first century, the permafrost-constrained tree line is projected to shift poleward from its current position. A prominent feature of Figure 4a is the asymmetry of the projected permafrost changes across the circumpolar Arctic. In North America, the projected changes have a relatively small areal extent. Outside mountainous regions with complex terrain, each category appears on the map as a relatively narrow zone. Most projections predict only a moderate shift of the permafrost-constrained tree line by a few degrees poleward (dark-colored zone in Figure 4a), while the outliers predict that it may advance much further to the north and reach the coastline in Alaska and northwestern Canada (uncolored zone in Figure 4a). In the Eurasian

Arctic, both dark and uncolored zones are much wider, indicating the larger spread of projections and higher uncertainty in the future state of permafrost.

The probabilistic vegetation map delineates areas with sustained biomes under all climate projections (no such areas are predicted under the full range of mid-twenty-first century climate projections), and those where one or more projections lead to the introduction of the new biomes in place of the current ones. Figure 4b shows the percent of projections leading to the biome change in the given node.

The maps in Figures 2 to 4 show a consistent pattern of projected climate-driven changes in the distribution and state of ecosystems, characterized by thickening of the active layer, a northward shift of biome boundaries, expansion of the boreal forest, a reduction of the tundra area, and introduction of new forest and steppelike biomes not present in the Arctic under current climatic conditions. Such changes will have important implications for land use, market and nonmarket economies, infrastructure in the urban and industrially developed regions (particularly in the Russian Arctic), indigenous peoples following traditional lifestyles, and wildlife.

In this study, significant attention has been given to uncertainty of the projected climatic and ecosystem changes. One of its components is associated with future greenhouse gas emissions. The Intergovernmental Panel on Climate Change developed a set of RCPs, which characterize hypothetical global socioeconomic developments and associated emissions of greenhouse gases. Here we used climate projections obtained under the most extreme RCP8.5. The other available scenarios are RCP2.6, RCP4.5, and RCP6.0. Numbers in the designations indicate additional radiative forcing by 2100 (W m^{-2}) attributed to each RCP. Our choice of RCP8.5 was motivated by at least three circumstances, which have to be considered when selecting RCPs for predictive climate impact studies.

First, not all RCPs reflect the realms of modern socioeconomic developments. The least aggressive RCP2.6 has been suggested largely for the research purpose to explore the world with a “green” economy, where all countries significantly reduce their emissions. Up to the present, this has proved to be completely unrealistic. The targets of greenhouse gas emission reductions designated by many countries require distinct and internationally coordinated climate policies, which have yet to be developed, adopted by national governments, and implemented. The world’s largest emissions reduction, by more than 30 percent, involved an enormously high price. It occurred as a side effect of Soviet Russia’s economic collapse in 1990.

Second, in the first decades of the twenty-first century, uncertainty in climate projections associated with the RCPs is half that due to the intermodel differences. By 2030, the range of global temperature projections for any model across all RCPs is less than 0.2°C while the intermodel difference for any given RCP could be as much as 0.4°C (Stocker and others 2013). The further we go into the future, the larger becomes the uncertainty associated with RCPs, and there is no

way by which it can be reduced. This is why in our analysis we did not go beyond the middle of the twenty-first century. We also did not consider different RCPs as equally probable pathways, which could be incorporated into the analysis of the likelihood of future environmental changes. Instead, we used RCP8.5, assuming that patterns of the ecosystem changes obtained under this pathway are inclusive of all potential patterns under less extreme RCPs, whereas timing is different.

Finally, in this study we have strived to achieve better understanding of the changes in ecosystems and their services in the Arctic, which may have potential effect on land use and land use planning. In this context, accounting for the consequences of the extreme and so far realistic RCP8.5 is particularly important.

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