ENVIRONMENTAL RESEARCH
LETTERS

Dryland belt of Northern Eurasia: contemporary environmental changes and their consequences

To cite this article: Pavel Groisman *et al* 2018 *Environ. Res. Lett.* **13** 115008

IOP Publishing Environ. Res. Lett. 13 (2018) 115008 https://doi.org/10.1088/1748-9326/aae43c

Environmental Research Letters

OPEN ACCESS

RECEIVED
13 July 2018

REVISED
6 September 2018

ACCEPTED FOR PUBLICATION
26 September 2018

PUBLISHED
15 November 2018

LETTER

Dryland belt of Northern Eurasia: contemporary environmental changes and their consequences

Pavel Groisman[1,2,3], Olga Bulygina[4,15], Geoffrey Henebry[5], Nina Speranskaya[6], Alexander Shiklomanov[7], Yizhao Chen[8], Nadezhda Tchebakova[9], Elena Parfenova[9], Natalia Tilinina[2], Olga Zolina[2,10], Ambroise Dufour[10], Jiquan Chen[5], Ranjeet John[11], Peilei Fan[5], Csaba Mátyás[12], Irina Yesserkepova[13] and Ildan Kaipov[14]

[1] North Carolina State University at NOAA Center for Environmental Information, Asheville, North Carolina, United States of America
[2] P. P Shirshov Institute for Oceanology, RAS, Moscow, Russia
[3] Hydrology Science and Services Corp., Asheville, North Carolina, United States of America
[4] Russian Institute for Hydrometeorological Information, Obninsk, Kaluga Area, Russia
[5] Michigan State University, East Lansing, Michigan, United States of America
[6] State Hydrological Institute, St. Petersburg, Russia
[7] Earth Systems Research Center, University of New Hampshire, Durham, New Hampshire, United States of America
[8] Joint Innovation Center for Modern Forestry Studies, College of Biology and the Environment, Nanjing Forestry University, Nanjing, Jiangsu, People's Republic of China
[9] Sukachev Institute of Forest, Krasnoyarsk Federal Research Center, SB RAS, Krasnoyarsk, Russia
[10] Lab. de Glaciologie et Géophysique de l'Environnement, Joseph Fourier Univ., Grenoble, France
[11] Oklahoma State University, Stillwater, Oklahoma, United States of America
[12] University of Sopron, Sopron, Hungary
[13] Joint Stock Company 'Zhasyl Damu' of the Ministry of Energy of the Republic of Kazakhstan, Almaty, Kazakhstan
[14] National Center for Space Research and Technologies, Almaty, Kazakhstan
[15] Deceased on 16 June 2018.

E-mail: groismanp@bellsouth.net

Keywords: Northern Eurasia, climatic and environmental changes, impact and feedbacks of human activity on environment

Supplementary material for this article is available online

Abstract

The dryland belt (DLB) in Northern Eurasia is the largest contiguous dryland on Earth. During the last century, changes here have included land use change (e.g. expansion of croplands and cities), resource extraction (e.g. coal, ores, oil, and gas), rapid institutional shifts (e.g. collapse of the Soviet Union), climatic changes, and natural disturbances (e.g. wildfires, floods, and dust storms). These factors intertwine, overlap, and sometimes mitigate, but can sometimes feedback upon each other to exacerbate their synergistic and cumulative effects. Thus, it is important to properly document each of these external and internal factors and to characterize the structural relationships among them in order to develop better approaches to alleviating negative consequences of these regional environmental changes. This paper addresses the climatic changes observed over the DLB in recent decades and outlines possible links of these changes (both impacts and feedback) with other external and internal factors of contemporary regional environmental changes and human activities within the DLB.

1. Introduction

The Northern Eurasia Earth Science Partnership Initiative (NEESPI, launched in 2003) and its successor the Northern Eurasia Future Initiative (NEFI, launched in 2016) have been internationally supported diversified research programs with the overarching scientific questions 'How do Northern Eurasia's terrestrial ecosystem dynamics interact with and alter the biosphere, atmosphere, and hydrosphere of the Earth?' and 'What dynamic and interactive changes will affect societal activities, human well-being, and health, and what might be the mitigation and adaptation strategies that could support sustainable development and decision-making activities?' respectively. The NEESPI is currently waning through attrition (Soja and Groisman 2018) and the second initiative has just released its programmatic documents and keynote publication

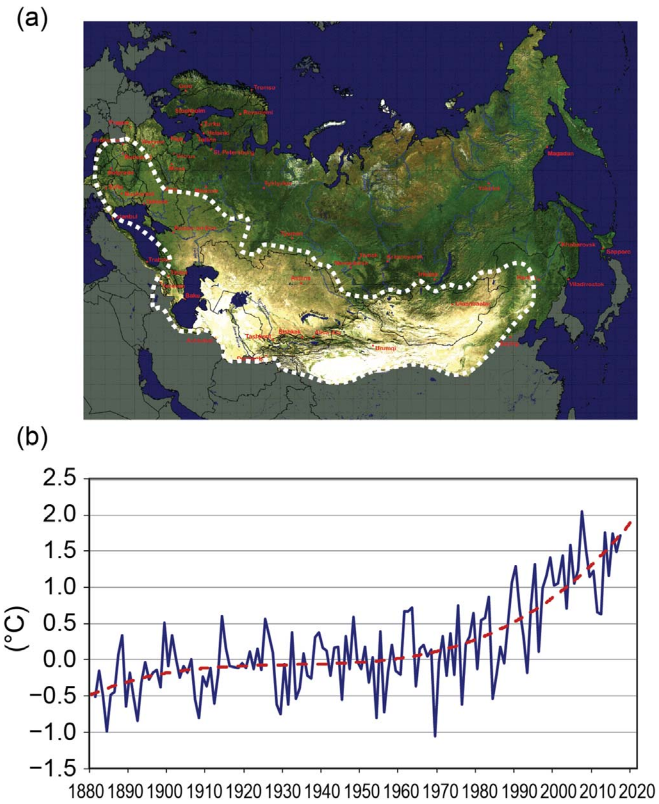

Figure 1. (a) The Northern Eurasia Earth Science Partnership Initiative (NEESPI) research domain map with the dryland belt (DLB) of Northern Eurasia outlined (the dashed contour on the map from Groisman *et al* 2017). (b) Mean annual surface air temperature anomalies (°C) for 1881–2017 area-averaged over the DLB with the polynomial trend shown in the graph describing 60% of the time series variation. Data source is an archive of the monthly surface air temperature by Lugina *et al* (updated 2006). Anomalies were calculated from the mean values for the 1951–1975 period.

(Groisman *et al* 2017). The research domains of the NEESPI and NEFI coincide and are shown in figure 1(a). The southern tier of this domain falls within by the dryland belt (DLB) of Northern Eurasia that occupies the interior of the Earth's largest continent and spans the territory of 16 countries: Armenia, Azerbaijan, China dryland region, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Moldova, Mongolia, Romania, Russia dryland region, Slovakia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan. To delineate the DLB in figure 1, we used the boundaries of deserts, semi-deserts, steppes, and forest-steppes within the NEESPI/NEFI research domain north of 37°N and south of 52° N (figure 1(a)).

The mountain ridges and high plateaus of the central regions of Asia mostly cut off the DLB from water vapor transported from the tropics (figure 1). Some parts of the DLB have fertile land and are quite densely populated. However, there exist strong physical limitations on the production of crops and rangelands. The region has a very limited fresh water supply, which is highly dependent upon irregular extra-tropical cyclones and a shrinking regional cryosphere (Shver 1976, Bliss *et al* 2014). Increases in evapotranspiration (ET) arising from increases in warm season temperatures and expansions of the growing season in the DLB are generally not compensated by precipitation increases (IPCC AR5 WG1 2013). Furthermore, spatio-temporal shifts in the precipitation pattern increase the likelihood that various unusual or extreme events (e.g. heat waves, dzuds, and dust storms) will negatively affect the livelihoods of regional societies and their interactions with the global economy (e.g. Henebry *et al* 2013, Chen *et al* 2015, Yu *et al* 2018). The DLB region is a source of dust storms that can adversely impact the environment, climate, and human well-being over the region and beyond, including densely populated areas of East Asia (Goudie and Middleton 1992, Darmenova *et al* 2009).

Over the past three decades, the DLB went through several major socio-economic changes that drove regional changes in agricultural and pastoral lands. The regional population has increased at a moderate rate similar to the global population trend, and there have been profound institutional shifts in the agricultural sector over the past three decades. Increased global demand for meat and dairy products has produced higher pressure on agro-pastoral lands where fragile developing economies are subject to frequent institutional shifts, water scarcity, and changing climatic conditions that interact to alter the DLB ecosystem services and the societies that rely on them (Groisman *et al* 2017, Qi *et al* 2017; see also supplement 1, available online: stacks.iop.org/ERL/13/115008/mmedia).

Within the transforming socio-economic context of the DLB, our objectives here are threefold:

(1) To document the current tendencies of ongoing climatic changes in the DLB.

(2) To partition, where possible, the natural and regional anthropogenic signals of these changes.

(3) To provide projections, where possible, of the future changes within the region arising from both natural and anthropogenic factors.

2. Current and anticipated climatic changes

2.1. Regional surface air temperature changes

The surface air temperature across the DLB region had been stable from the beginning of the 20th century until the mid-1960s, but has increased rapidly in the past five decades (figure 1(b)). These changes are mostly illustrated by changes during the winter and spring seasons with mean rates of change of 1.8 °C (100yr)$^{-}$1 and 1.6 °C (100yr)$^{-1}$, respectively. In winter, the temperature variability is higher with the 1.8 °C (100yr)$^{-1}$ linear trend explaining 23% of the variation, whereas a slightly smaller warming trend explains 37% of the variation in spring temperatures. For autumn and summer seasons, the warming signals have been much smaller with rates of 0.7 °C (100yr)$^{-1}$ in autumn and 0.4 °C (100yr)$^{-1}$ in summer, with the changes concentrated solely in the past three decades. This warming shifts the temperature seasonal cycle, particularly the earlier dates of snowmelt (Arctic Climate Impact Assessment (ACIA) 2005, Bulygina *et al* 2013, Tomaszewska and Henebry 2018), earlier spring onset in the biosphere, and freshet in river discharge. In summer, the warming causes glacial retreat in Central Asia, the Caucasus, and Southern Siberia (Khromova *et al* 2014) and exacerbates water deficit for the DLB landscapes. In the past three decades, warming in the DLB has spread from Hungary in the West (Mátyás *et al* 2018) to Northeast China in the East (Zhao *et al* 2013) exaggerating dry weather conditions. These and many other negative consequences of the DLB warming could be avoided, were precipitation to increase. Indeed, oceanic warming must result in more evaporation, and the additional atmospheric water vapor could mitigate the water deficits in lands of the continental interior through increased precipitation. However, this water vapor must first be transported to the interior by atmospheric circulation.

2.2. Changes in atmospheric circulation

The DLB receives an abundance of heat through insolation, although the drylands do not have sufficient holding capacity to retain heat in soil, biosphere, or hydrological objects. Consequently, day/night temperature differences are very high in comparison to maritime climates. Soil moisture that could mitigate strong diurnal temperature swings is limited in drylands and is often concentrated below the rooting zone. Dryland areas also have limited heat capacity and finite water storage in glaciers, interior lakes, and permafrost accumulated during the past pluvial epochs and/or during cold seasons. The remaining water that the region receives comes from atmospheric precipitation, ground water, and inland lakes. However, precipitation is not necessarily transferred inland via the atmosphere. The role of atmospheric circulation is critical here. There appear two competing major components of the global warming process that are, among others, responsible for water vapor transport into the interior drylands of Northern Eurasia.

Disproportional warming at high latitudes and in the Arctic (Arctic Climate Impact Assessment (ACIA) 2005, Blunden and Arndt 2017) decreases the equator-to-pole temperature differential with the latitudinal temperature gradient instrumental for the westerlies' circulation in the extratropics. In particular, in the Northern Hemisphere westerlies move the water vapor from the North Atlantic Ocean into the Eurasian interior. The weaker the westerlies, the less water vapor penetrates into the northern part of the continent exposed to the Atlantic and Arctic air transfer (i.e. most of Northern Eurasia). Another feature associated with weaker westerlies is the meandering of their flow and more frequent formation of atmospheric blocking (Mokhov *et al* 2013, Lupo *et al* 2014). These changes in atmospheric circulation lead, in the cold season, to a larger variability when unusually cold and warm weather conditions occur over the entire Northern Eurasia (Schubert *et al* 2014). In the warm season, it results in prolonged periods of days with and/or without precipitation (Groisman and Soja 2009, Zolina *et al* 2013, Lupo *et al* 2014).

In summer, the land warms more strongly than the ocean, which is projected to strengthen the monsoon circulation with global warming (IPCC 2013). The southern edge of the DLB is mostly blocked from the warm Indian Ocean, but its eastern edge is exposed to the Pacific Ocean and warm humid air from the Pacific penetrates northwestward. Thus, with the stronger monsoons, a more humid climate would occur on the eastern edge of the DLB and will be expected to continue in the future with continued global warming (Collins *et al* 2013). However, the observations in Northeast China (Guo *et al* 2013) and analysis of the eastern edge of the DLB do not support these expectations (figure 2).

Figure 2 and table 1 show major statistics of cyclone characteristics for the four regions of the Asian

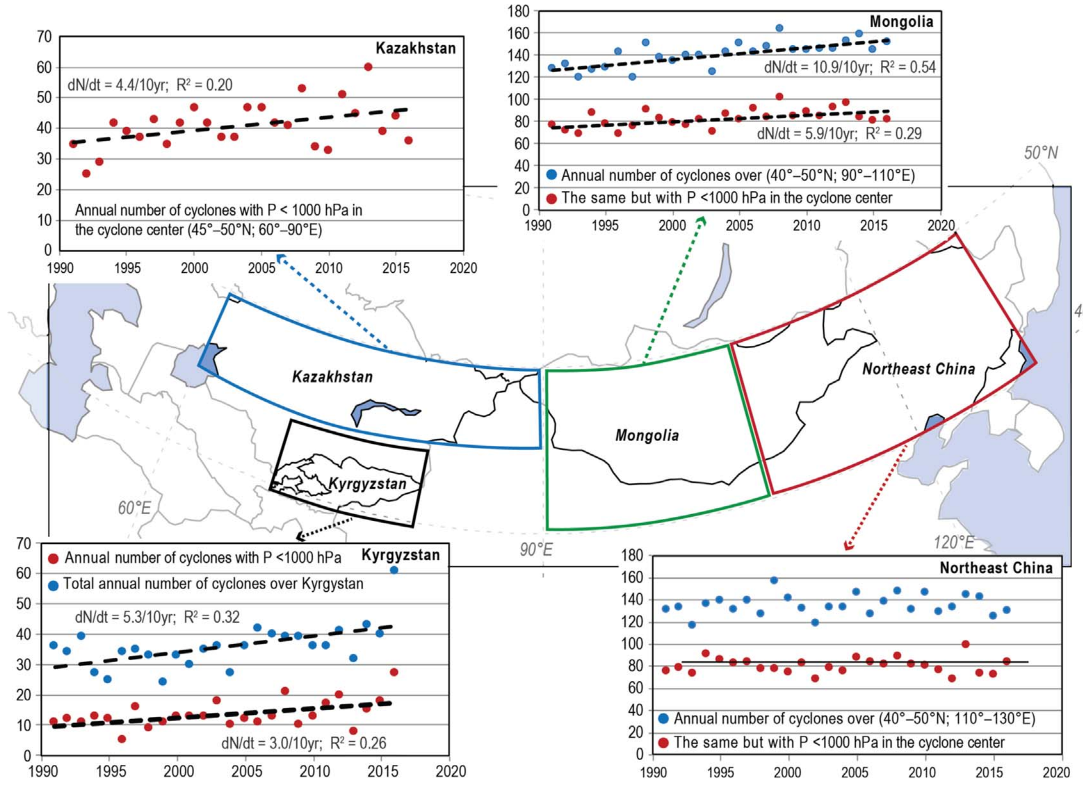

Figure 2. Annual number of atmospheric cyclones area-averaged of the four regions in the Asian part of the DLB. Definition of individual cyclones and the follow up counting were made by Tilinina *et al* (updated 2013) within the IMILAST project (Neu *et al* 2013) activity and applied to the ERA-Interim reanalysis data for the post-USSR period.

Table 1. Long-term mean number of cyclones by season with atmospheric pressure at its center less than 1,000 hPa in four regions during 1979–2016 (see figure 2). JFM: January–February–March; AMJ: April–May–June; JAS: July–August–September, and OND: October–November–December.

Region	JFM	AMJ	JAS	OND	Annual
Kazakhstan	3	17	18	2	40
Kyrgyzstan	1	6	7	0	14
Central Mongolia	4	38	37	4	83
Northeastern China	8	35	29	8	80

Table 2. Southward and eastward water vapor transport into Central Asia across 50°N latitude in Northern Asia from 60°E to 110°E and across 50°E from 40°N to 50°N during the post-USSR period (1990–2017).

Period/Water Vapor Flux	Southward annual flux through 50°N, kg (m×s)$^{-1}$	Eastward annual flux through 50°E, kg (m×s)$^{-1}$
1990–1999	0.14	46.4
2000–2009	−0.48	43.4
2010–2017	1.11	39.6

part of the DLB. In figure 2, these regions are identified with four figure inserts that visualize the time series of the annual count of individual cyclones that crossed the regions. Tilinina *et al* (2013) showed that the total cyclone count is dependent of the spatial resolution of the post-USSR period tracks. Here we use the ERA-Interim reanalysis (Dee *et al* 2011) that has a spatial resolution of 1.5° × 1.5°. The climatology of the cyclone counts shown in table 1 depends on this resolution. The Asian DLB includes many mountain and plateau systems. Reanalyses have shown that these areas are very sensitive to the observational network used for their generation. In particular, when these networks have been changing, there can be spurious inhomogeneity in the data (Arsenault and Brissette 2014). Therefore, we used only the post-Soviet Union period (prior to this period the networks were much denser in Central Asia and in the eastern half of the DLB, but these data were less available to the developers of the reanalysis products).

The one central and two western regions of the Asian DLB in figure 2 receive most of their atmospheric water vapor from the West (Shver 1976, Kuznetsova 1983), but the easternmost DLB region—Northeastern China and Western Mongolia—resides in a monsoon climate benefiting from major water transport from the Pacific Ocean. Over the past three decades, we have not seen systematic changes in cyclone counts in this region (figure 2). In contrast, the numbers of cyclones in Central Asia, Northwest China, and Mongolia increased. We cautiously conclude that these increases indicate improvement in the water budgets of these drylands.

Water vapor transport into these regions during recent decades can provide an estimate of integral precipitation changes related to atmospheric circulation.

Table 2 reports the results of processing of the ERA-Interim reanalysis data for the post-USSR period. It demonstrates that most of water vapor integrated over the atmospheric column comes from the West, while the southward water vapor transfer is substantially less. Moreover, the dramatic reduction of the eastward water vapor transport into Central Asia (~15% during the last three decades) is not only the result of weakening of the westerlies but may be related to the simultaneous retreat of the Aral Sea (the 60°E longitude crosses its remnants). The Aral Sea has been shrinking since the 1960s with the largest decrease in the past two decades (Zavialov 2007, Gaybullaev *et al* 2012). In addition, large-scale climate oscillations can affect precipitation patterns in Central Asia (de Beurs *et al* 2018). Whatever the cause of the water vapor transport decline, it contributed to drier weather conditions in Central Asia (see section 2.5).

2.3. Changes in atmospheric precipitation

Atmospheric precipitation, its amount (total), form (frozen, mixed, or liquid), intensity (for rainfall), intraseasonal distribution, and the systematic changes (trends) remain the most variable characteristics of the DLB climate. Past studies have documented an earlier onset of spring across the entire Northern Hemisphere (Schwartz *et al* 2006), increases in daily rainfall intensity during the heavy rain events that may coincide with prolonged no-rain periods (Zolina *et al* 2010, Groisman *et al* 2013, Zolina *et al* 2013), and uncertainties in quantifying the changes in precipitation. The uncertainty emerges in this part of the globe both from the relatively sparse observational networks and from time-dependent systematic biases in precipitation records (Groisman and Legates 1995). Groisman *et al* (2014) quantified these biases for Russia, while Ding *et al* (2007) did the same for China. They showed how each improvement in rain gauge instrumentation, wind shielding of gauges, and observing routines resulted in increases of ‘observed’ precipitation while the actual ‘ground-true’ precipitation was quite different and had different decadal trends. As a result, the latest Second National Climate Change Assessment for the Russian Federation contains two estimates of the past precipitation changes over the nation rather than just one (Second National Climate Change Assessment for the Russian Federation 2014). The first set of estimates is based on high-quality observations from the national meteorological network and the second set of estimates is based on the same observations but corrected for the time-dependent biases that provide the real ground-true precipitation values. The first set of estimates reports nationwide increase of annual precipitation; whereas, the second set reports moderate multi-directional changes. For the Russian part of the DLB (steppes in the south of West Siberia and the Trans-Baikal region), the assessment reports a long-term decrease in precipitation. Using bias-corrected precipitation time series, Akhmadiyeva and Groisman (2008) reported only a 4% increase in annual precipitation over Kazakhstan during the 1990–2006 period compared to previous three decades (1960–1989). Furthermore, significant discrepancies between a global precipitation reanalysis and a fuller representation of regional precipitation stations was documented for Kazakhstan (Wright *et al* 2009).

Difficulties with the reporting of precipitation trends in other parts of the former USSR as well as in Mongolia are the same and, therefore, alternative approaches based on remote sensing land surface products were used (see Lioubimtseva and Henebry 2009, de Beurs *et al* 2015). In Kazakhstan in the 1990s, precipitation deficit growth was reported using normalized difference vegetation index (NDVI) analyses. Farther southward, Wang and Zhou (2005) and Ding and Chan (2005) reported an increase in precipitation in the northwest of Xinjiang province in China. Ding *et al* (2007) showed the importance of bias corrections for precipitation reports in China and addressed the possible time dependence of biases in these reports. The biases can be caused by changes in observations, but they can be also introduced by changes in other ‘natural’ factors that affect precipitation measurements. In particular, systematic continent-wide reduction in the near-surface wind speeds (see Ding *et al* 2007, Bulygina *et al* 2013) may ‘increase’ the observed cold season precipitation while the ground-true precipitation is unchanged or even decreased. Figure 3(a) shows that during most of the year (autumn, winter, and spring), there were no significant changes in the total precipitation over the DLB (a region-wide increase by 16 mm per 8 months).

Liquid precipitation observations are less prone to biases than those for frozen precipitation; thus, changes in liquid precipitation can be presented in absolute numbers (in mm instead of percent). In figure 3(b), we show the latest changes in summer rainfall totals over the DLB during the past 13 years compared to the previous 25 years estimated from the MERRA-2 reanalysis output. These changes are mainly negative illustrating the Northern Eurasian heat waves and droughts described by Schubert *et al* (2014). These waves over the western part of the DLB (Hungary, the Ukraine, and European Russia) manifested themselves by several severe droughts (including the extreme drought of 2010). Over the eastern part of the DLB (the Baikal Lake Basin, Trans-Baikal area, and Northeastern China) the waves were responsible for increasing water deficit and severe forest fires centered in the Trans-Baikal area (Loboda and Chen 2017).

2.4. Changes in the cryosphere

All components of the cryosphere in the DLB have been changing in recent decades, with most of these

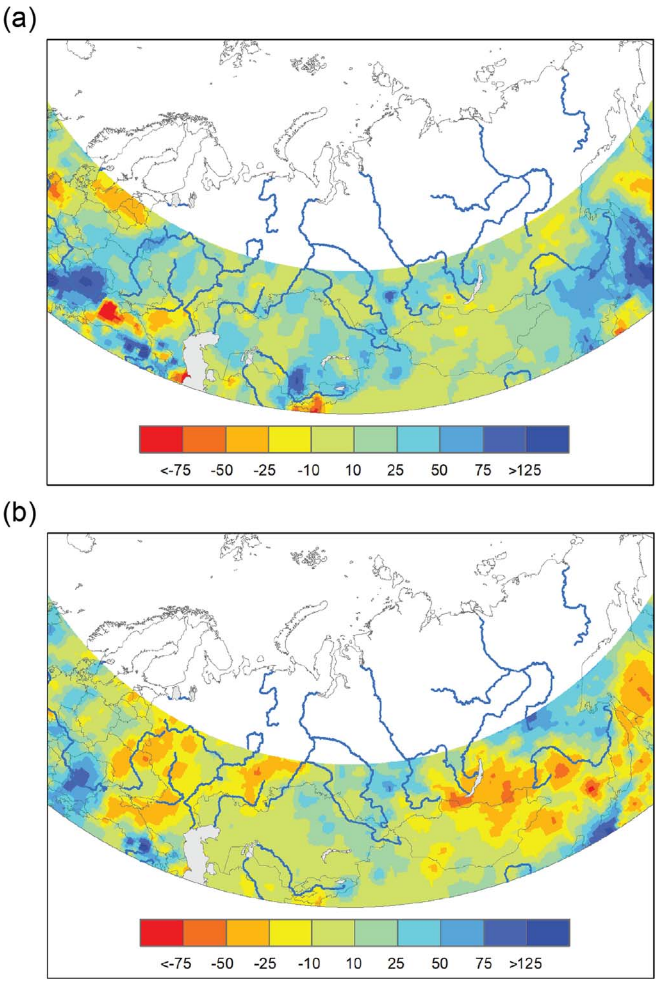

Figure 3. Deviations of mean seasonal precipitation totals (mm) across the DLB from 2005–2017 from a baseline average over the 1980–2004 period. (a) October through May. (b) June, July, August, and September. Estimates are based on the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2 reanalysis; Gelaro *et al* 2017) that has a cubed-sphere horizontal discretization at an approximate resolution of 0.5° × 0.625° and allows relatively uniform grid spacing at all latitudes.

changes showing stable decreases (AMAP Arctic Monitoring and Assessment Programme 2011, 2017):

- Duration of seasonal spring snow cover has been steadily decreasing, making the onset of spring (e.g. the start of vegetation growth and spring freshet on rivers) earlier by several days (Bulygina *et al* 2011, Second National Climate Change Assessment for the Russian Federation 2014).
- Period with stable snow cover over Europe has become shorter and/or disappears causing river ice break-up, and increases in winter runoff (see section 2.5).
- Permafrost at the edge of the permafrost zone, especially in the areas of discontinuous permafrost, has begun to thaw (Romanovsky *et al* 2017).
- The depth of seasonal frozen ground thawing has increased from the Arctic to the mountains of Central Asia affecting infrastructure, such as roads and buildings (Shiklomanov *et al* 2017).
- The area and volume of land ice (i.e. glaciers) has been decreasing across the entire Northern Eurasia including the montane areas of the DLB (Shahgedanova *et al* 2010, Khromova *et al* 2014, Shahgedanova *et al* 2014, Kotlyakov *et al* 2015, Syromyatina *et al* 2015).

Ice storage on and below the ground is an important source of the water supply for the DLB. For centuries (or millennia) water was transported to the remote mountains of the Eurasian continent and, instead of entering the global water cycle via runoff, was fixed and stored there in frozen form. This storage served as a cushion for the water balance of the DLB regions located at the foothills of high mountains. Currently, this storage is being gradually depleted.

Ongoing global warming is more prominent at higher elevations than in lowlands (Barry 2008). The temperature increases, particularly during the warm season, escalating glacial melt and the thawing of subsurface ice. Although the abundant summer streamflow promises a strong future water supply in the drylands, the storage of water in glaciers is limited. As

River Basin	Level of glaciation	Discharge tendency
Kaskelen	Low glaciation	Decrease
Malaya Almaatinka	Moderate glaciation	Moderate increase
Bolshaya Almaatinka	Extensive glaciation and buried ice	Very strong increase

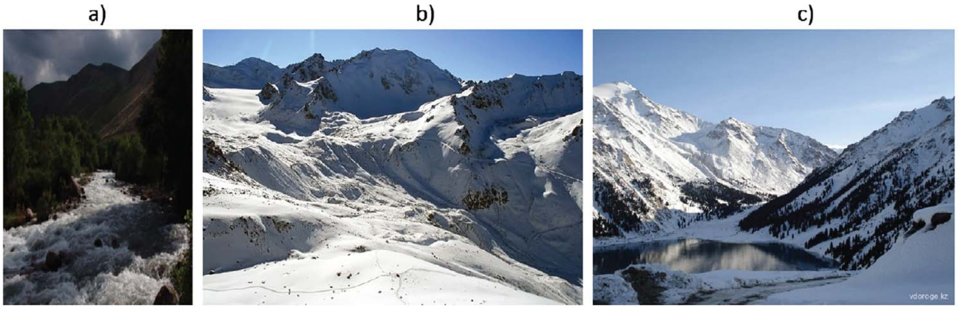

Figure 4. River discharge tendencies within three neighboring valleys in the Tian Shan mountains (Zailijskiy Alatau; archive of Groisman *et al* 2017).

illustrated in figure 4, three rivers in neighboring valleys have distinctively different tendencies of their discharge depending upon the glaciation level at their higher elevations. Snow-free high dry plains and disappearing lakes in Northwest China (e.g. in Qinghai province) and West Kazakhstan are good examples.

2.5. Changes in water supply and availability

Runoff data for the Russian Federation as well as for most of the Central Asian countries show an increase in river discharge. However, it is not clear how persistent these increases will be in the future once several factors that are currently favorable for these increases change (supplement 2).

We have a complete set of socio-economic and meteorological data for the Central Asian nations, and our analysis of climate change impacts on different aspects of water availability here was made using a combination of economic census data with hydrological modeling (supplement 3). The dynamics of water use for domestic, industrial, and livestock needs have been simulated using the University of New Hampshire water balance model (WBM, supplement 3) using country-based statistical socio-economic information along with spatially distributed population density. The water scarcity index (WSI; Damkjaer and Taylor 2017) and water availability indexes (WAI; Schyns *et al* 2015) for the Central Asian countries were estimated with WBM simulations using only locally generated water resources (figure 5, left panels) and total available water resources (including inflow) (figure 5, right panels).

The WSI is the ratio of annual freshwater abstractions (i.e. system losses due to water consumption, ET, and deep drainage) to the annual water availability. This information was aggregated over administrative units and adjusted using census data. Water stress is classified from high water stress (red in figure 5) to water abundance (blue in figure 5). The WSI neglects temporal and spatial variations as well as water quality data. There was a general and substantial decline in available water between the 1990s and 2014 (figure 5). The water security situation across the region is more stressful despite significant political and socio-economic transformations during the 1990s, which led to decreased water use and increases in river runoff in some montane areas, as mentioned above. The current trend toward increasing water stress results primarily from changing climatic conditions coupled with fast population growth (https://www.populationpyramid.net/central-asia/2017/).

2.6. Land use and land cover change and some of their consequences

One of the biggest episodes of land cover change over the steppes of the DLB was the so-called 'Virgin Lands' development during 1954–1964, when the area of arable land in Kazakhstan was expanded from 7–8 to 21–23 million hectares. These changes were also spread across the steppe zone of Western Siberia and Southern Russia but were centered over Northern Kazakhstan (Jackson 1962). This massive conversion of grassland to cropland resulted in statistically significant increases of monthly surface air temperatures by 0.3° to 0.5 °C during the spring, summer, and autumn seasons and significant changes in ET (Yesserkepova 1988). Even within the interdecadal variability of the near-surface temperature and humidity in this part of the world, the impacts of large-scale virgin land development are evident in figure 6.

The latest land cover types and their changes within the Asian part of the DLB were examined using

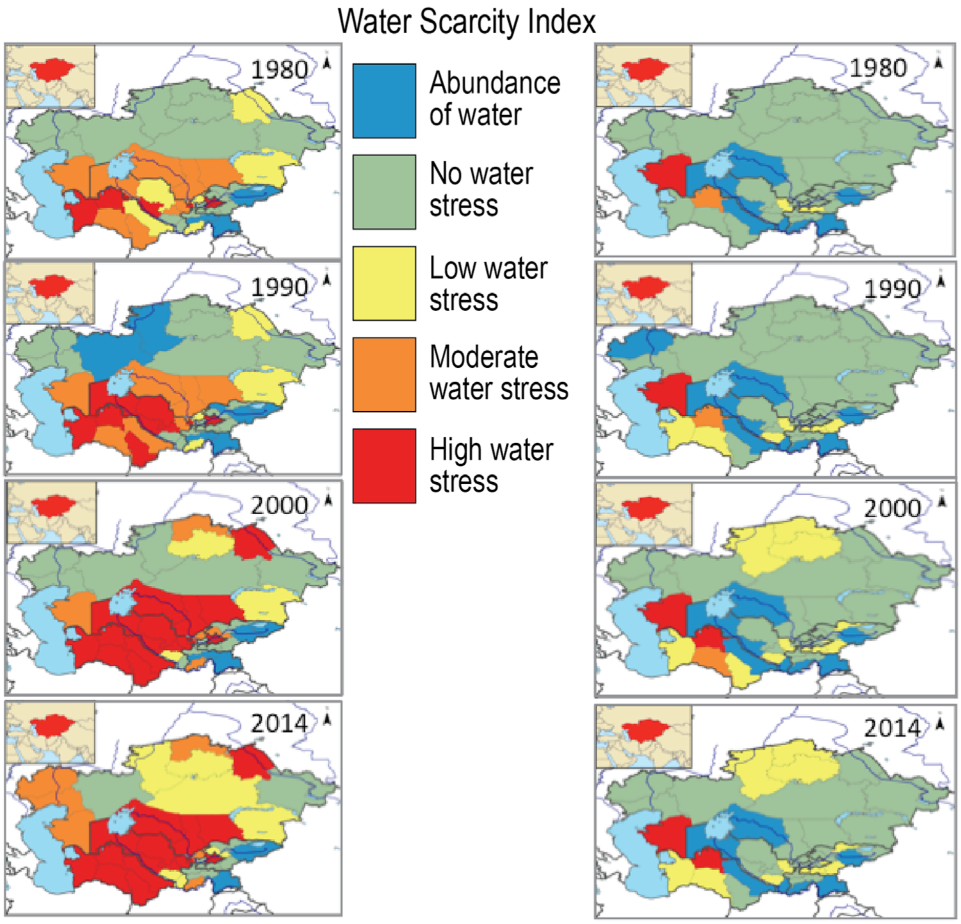

Figure 5. Evaluation of the water scarcity index (WSI) for Central Asia based on a combination of socio-economic data for administrative units with hydrological simulations on the hydrological model taking into account various natural and anthropogenic processes. Maps on left show the WSI based only on available local water resources. The right maps account for both local water resources and river inflow from other territories.

the MODIS land cover product (MCD12Q1V6; https://earthdata.nasa.gov/) through re-grouping the International Geosphere-Biosphere Program (IGBP) classification cover types between 2001–2016. This product provides global land cover types at yearly intervals (2001 to date) at 500 m spatial resolution and is a combined product derived from Terra and Aqua reflectance data. Version 6 of the MCD12Q1V6 data product was derived from different classification schemes, of which we used the IGBP classification scheme validated to stage 2 maturity level (Friedl and Sulla–Menashe 2015). Because land cover changes within a short time period (i.e. <3 years) are likely minimal and difficult to detect with MODIS imagery, we compared the difference between 2001–2014, 2002–2015, and 2003–2016 to ensure that the three differences are consistent and, hence, representative of the actual land cover changes during the 15-year study period.

We used the tabulate area function in ArcGIS to categorize area by cover type and their relative proportions by the 10 administrative units in the Asian part of the DLB (8,779,162 km^2). We created a triad of image difference datasets, namely 2001–2014, 2002–2015, and 2003–2016, to compare change across six years, thereby making the findings robust (three years in the early period of observations and three in the last three years). We then labeled and visualized the pixels with consistent change (red), some change (blue, when one of the three triads shows a different change) and no change (light gray) with 5.58%, 0.18%, and 94.24% of the area respectively. The pixels with 'some change' are labeled with blue dots. They are nearly invisible in figure 7(b). The small number of such dots indicates that the post-classification land cover changes due to uncertainties in the land cover labels for any one year and do not seriously impact our conclusions about the regional land cover change.

The DLB is dominated by arid barrens and temperate grasslands that accounted for 56.85% and 31.36% of the total land area (total = 88.21%), respectively, during 2001–2016 (figure 7(a)). The arid barrens are the largest on the Earth's surface and stretch from the Gobi Desert in Southwest Mongolia to the Western portion of Central Asia (Mildrexler *et al* 2006, Chen *et al* 2014). The grasslands included those on the

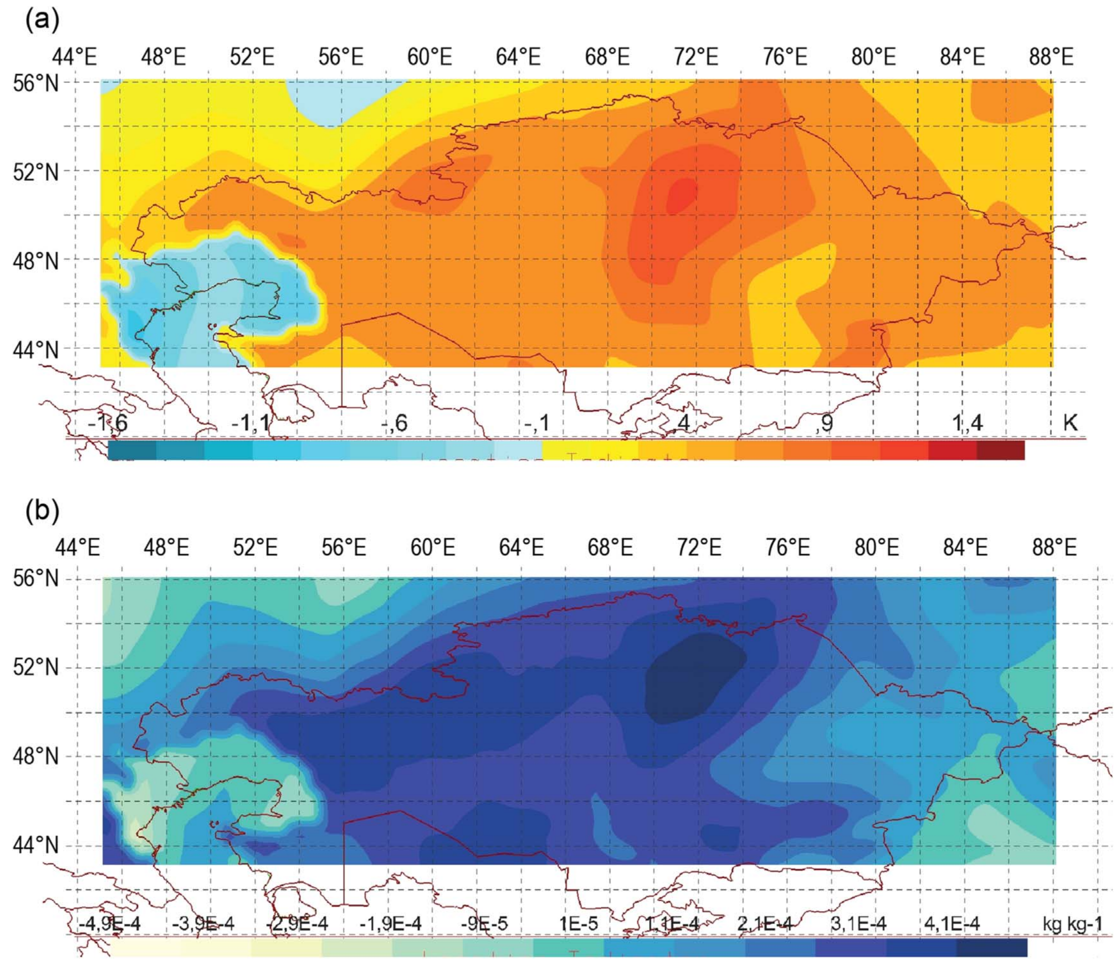

Figure 6. Differences in averaged near-surface temperature (a) and near-surface specific air humidity fields (b) between the years 1961–1970 and 1951–1960. These maps were constructed using the Global Meteorological Forcing Dataset prepared at Princeton University (MFD; Sheffield *et al* 2006). The MFD is available globally for the 1948–2016 period at 0.25 degrees of spatial and 3-hourly temporal resolutions. It was constructed by combining a suite of global observation-based datasets with the NCEP/NCAR reanalysis.

Mongolia Plateau, which are experiencing higher warming trends than the global average due to a combination of high latitude, high elevation, and a continental climate (John *et al* 2018, Tian *et al* 2018). The croplands (4.80%), shrublands (1.48%), and forests (1.14%) are the next three major cover types in the region. However, the distributions of these cover types varied substantially by country. East Asian countries have a similar proportion of grasslands (45.86%) to those in Central Asia (45.50%). Kazakhstan has the highest grassland cover (85.2%) among all administrative units (figure 7(a)). Overall croplands in Eastern and Central Asian countries occupy 4.13% and 7.60%, respectively. Forests were found in Northeast Inner Mongolia, and on northern aspect slopes in the Tian Shan mountains of Central Asia.

Land use was also very extensive and intensive across the DLB, with 5.58% of the land experiencing consistent cover change from 2001–2016 (figure 7(b)). Overall, it appeared that countries in Central Asia experienced more cover changes than those in East Asia. Several visual hotspots included land cover changes that are apparent around the Caspian Sea in Turkmenistan, Uzbekistan, and Southwest Kazakhstan (**I**) and around the edges of the East Asian drylands of Western Xinjiang–Inner Mongolia–Mongolia (**III** and **V**). Other major hotspots of land cover change were found in the Yellow River Delta or Hetao region (**IV**), forested regions of Northeast Inner Mongolia (**VII**), Northern Mongolia (**VI**), and Northwestern Kazakhstan (**II**). These hotspots have been widely reported as being the results of major policy shifts by the individual countries and, to a lesser degree, the changing temperature and ET (i.e. water loss) (Jung *et al* 2011, Liu *et al* 2013, Chen *et al* 2014, Groisman *et al* 2017, Qi *et al* 2017, John *et al* 2018). For example, the large increases in forest cover in the Yellow River Delta and Northeast Inner Mongolia are likely due to afforestation/reforestation program of China's Green for Grain Program (Liu *et al* 2014), whereas hotspots in Western Xinjiang are due to the rapid expansion of agricultural lands. Meanwhile, hotspots in Central Asia may have been the direct results of elevated ET loss, salinization of soils, or new agricultural enterprises.

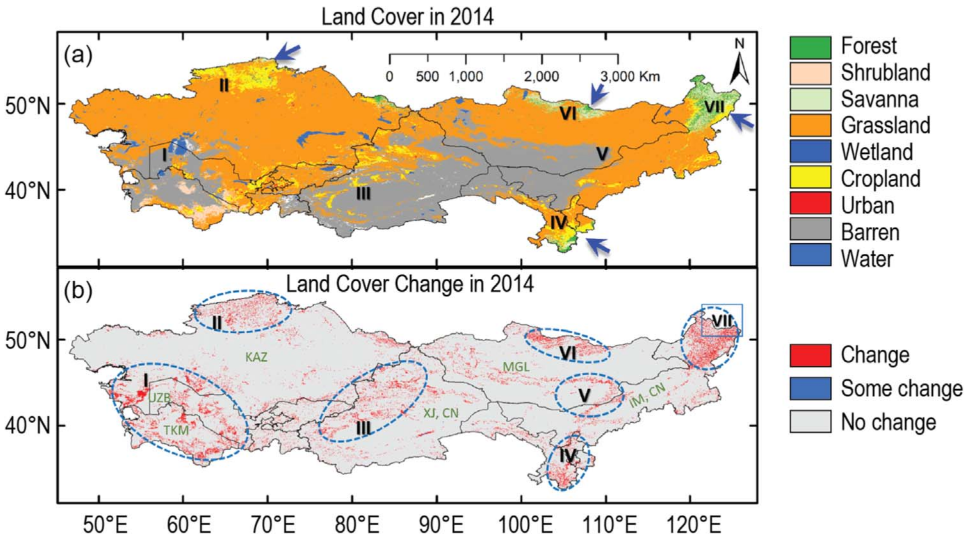

Figure 7. (a) Land cover in 2014 and (b) land cover change from 2001–2016 in the DLB. The cover types are re-grouped from the IGBP classification scheme based on the land cover product of MODIS (MCD12Q1V6). (b) Land cover change represents type shift from 2001–2016. The areas encircled by the blue lines are hotspots for the cover change across the DLB, which are mostly associated with agricultural development, shrubland encroachment, desertification, and afforestation.

Table 3. Biome distribution (%) over the Siberian window (60–140° E and 40–60° N), predicted by selected CMIP5 GCM ensembles for the 2080s.

		20 GCM ensemble		5 driest GCM ensemble
Vegetation type	Baseline climate	RCP 2.6 scenario	RCP 8.5 scenario	RCP 8.5 scenario
Tundra	3.0	1.2	0.0	0.0
Forest	49.9	51.3	47.2	37.4
Drylands:				
Steppe	23.6	25.4	29.6	36.6
Semi-desert and desert	23.5	22.1	23.2	26.0

3. Projections to the nearest decades of environmental changes

3.1. Land cover transitions and potential climate-driven land cover transitions over northern Asia in the 21st century

Biosphere modeling employed for this projection is described in supplement 3. Here we present and discuss the biosphere modeling output. In the baseline climate, drylands were projected to cover about 50% of the Siberian window that was allocated equally between steppe and semi-desert/desert. Simulations indicated that Siberian vegetation would be altered by the 2080s over the study area. Almost no change in the forest distribution was projected in the 20 GCM ensemble under both the RCP 2.6 and RCP 8.5 scenarios, while the extent of the drylands changed minimally. A 6% increase in drylands was projected under the RCP 8.5 scenario for the 20 GCM ensemble (table 3, figure 8(c)). According to the ensemble of the five driest GCMs under RCP 8.5, drylands would cover 63% of the study area with a 10% predominance of steppe. The semi-desert/desert area would increase only slightly compared to its current extent. Forest coverage would remain similar to the current conditions (i.e. ± 1.5%–2%), because the forest would shift into the current tundra distribution and the tundra would nearly vanish. Only in a dry climate would its coverage decrease by about 12.5%.

The ecological consequences for forestry and agriculture in the rapidly changing environment of Southern Siberia will require adaptive management to adjust agricultural and mixed agro-forestry practices to the newly emerging forest steppe and steppe habitats of the late 21st century.

Increased tree mortality in a drier climate along the southern Taiga border would lead to accumulation of woody debris, which in turn, paired with increased 'fire' weather, could result in destructive fires and shift forests northward to wetter habitats. Grasslands that follow in the wake of the forest are better adapted to frequent fire events because of their shorter life cycle, a stronger adaptability to less precipitation and droughts, and their capability to recover due to the allocation of perennating plant parts below ground (Tchebakova *et al* 2009). Generally, the projected warmer and drier climates will promote drylands to extend over southern Siberia (Tchebakova *et al* 2010, Tchebakova *et al* 2011a) and the steppe area would increase by 50%. South of 60°N, tundra is observed only in the highlands on mountains and in the RCP 8.5 scenario it vanishes completely.

To minimize the negative consequences and to enhance the benefit of climate change in Siberian forests and drylands, adaptive measures need to be implemented, including forest restoration on failed forest

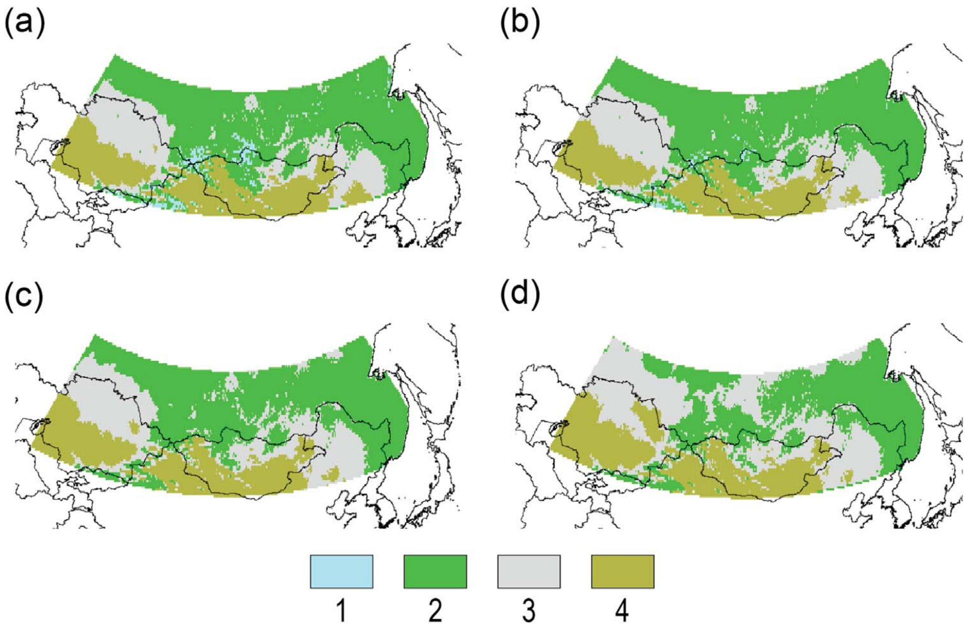

Figure 8. The biome and dryland (steppe, semi-desert/desert) distributions over Siberia and adjacent DLB regions predicted (a) for the baseline climate of 1960–1990, (b) for the future climate in the 2080s by an ensemble of 20 GCMs under RCP 2.6, (c) by an ensemble of 20 GCMs under RCP 8.5, and (d) the ensemble of the five driest GCMs under RCP 8.5. Tundra (1) is cyan, practically absent in these figures; forest (2) is green; steppe (3) is gray; and semi-desert/desert (4) is brown.

lands and planting different crops suitable for the new climates. Due to recent and predicted climatic changes, concerns about food security increase. However, in the cold climates of Siberia, agriculture would benefit from climatic warming, only when and where appropriate infrastructure development and population growth permit.

3.2. Current livestock distribution, *C* consumption by grazing and their projections

Spatial distribution of livestock density on temperate Eurasian steppe in 2006 was estimated based on province/prefecture-level inventory data of livestock. The carbon ingested by livestock (C_{graze}) was calculated using the pasture system simulator in a boreal ecosystem productivity simulator (BEPS; Chen *et al* 2017). The distribution and C_{graze} are tightly controlled by sub-regional socio-economic conditions (Chen *et al* 2014). Spatial heterogeneity exists across and within different administrative divisions (figure 9). In the Mongol steppe, major consumption by livestock was concentrated in China, particularly in Inner Mongolia. The most extensively grazed grasslands were located in traditional natural pastures with relatively high productivity, such as the XilinGol Prairie in mid-Inner Mongolia, and in some areas of desert steppe in Southwestern Inner Mongolia. Livestock density and C_{graze} in those areas exceeded 800 sheep units per km2 and 30 gC m^{-2} yr, respectively. In contrast, the livestock density and C_{graze} in Mongolia were much lower (John *et al* 2016). This contrast can be seen in the bordering areas of Eastern Mongolia (Dornod province), where livestock density is lower than 40 sheep units per km2 and Northeastern Inner Mongolia (Hulunbuir City), where density is higher than 200 sheep units per km^2.

In the Kazakh steppe, C_{graze} was highly concentrated in the South, especially in the desert countries of Turkmenistan and Uzbekistan. These two countries contain huge numbers of livestock within limited pasture ecosystems. Livestock density and C_{graze} are generally higher than 500 sheep units per km2 and 12 gC m^{-2} yr for the two countries (figure 9), while livestock density is generally lower than 40 sheep units per km^2 over the steppe of Kazakhstan.

Concern over increasing demands for animal products and preservation of grassland resources has led to the launch of regional conservation programs in Inner Mongolia since the late 1990s, including the Grain to Green Program (Liu *et al* 2008) and the Grazing Withdrawal Program (Chen *et al* 2017). As a result, improvements to livestock habitat and ecosystem service functions have been observed in recent years (Li *et al* 2012, Mu *et al* 2013). In contrast, the excessive stocking rates in the southern Kazakh steppe have not received enough attention from the scientific community or from governments (Blench and Sommer 1999, Mirzabaev *et al* 2016). Field investigations, large-scale assessments, and specific rehabilitation programs are urgently needed in this area.

Prior to 1990, the Central Asian economies were not economically independent. Most agricultural and livestock production was focused on meeting demands dictated by the central planners of the USSR (e.g. production of cotton and meat). As a result, the reduction of livestock numbers during the 1990s was

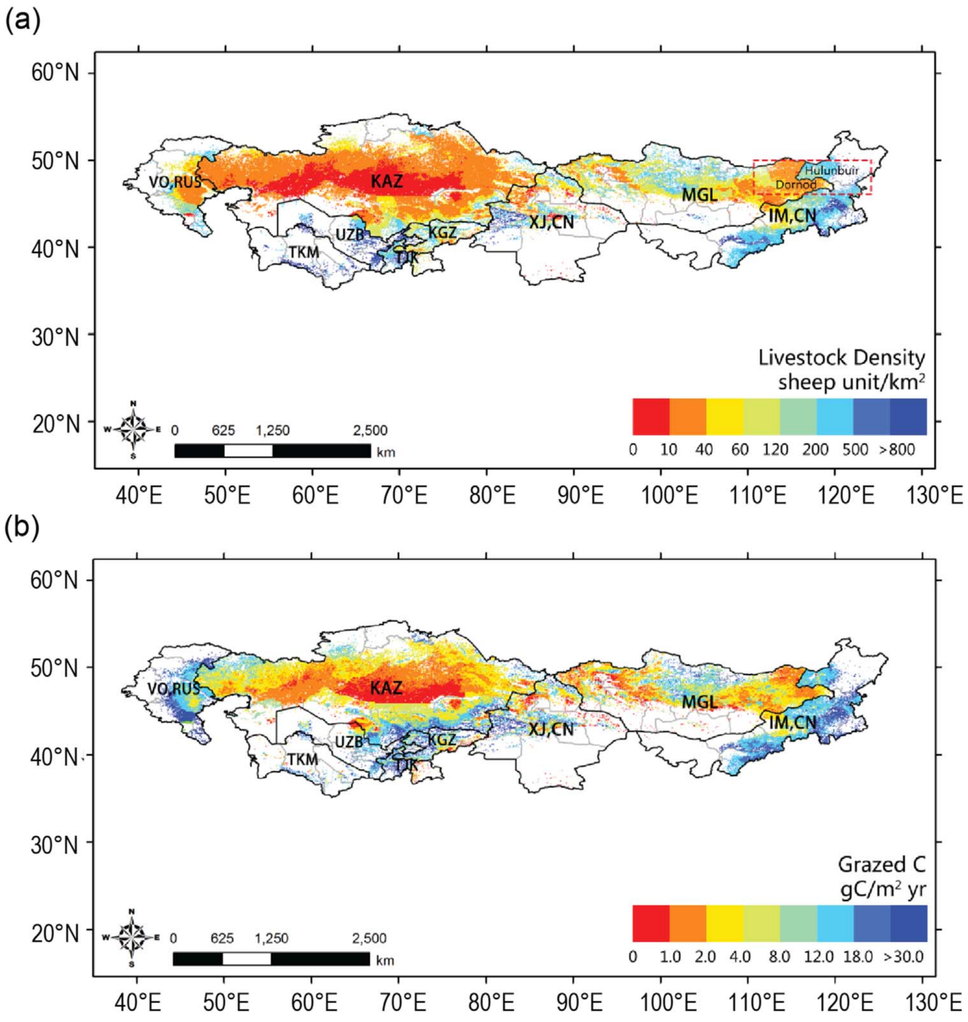

Figure 9. Spatial distributions of (a) livestock density and (b) carbon ingested by grazing (C_{graze}) in the temperate Eurasian steppe.

mainly induced by institutional changes, loss of access to markets, and agricultural reforms following the dissolution of the USSR (de Beurs and Henebry 2004, Ojima and Chuluun 2008, Wright *et al* 2012, de Beurs *et al* 2015, John *et al* 2016). Clearly, the situation in the 1980s or 1990s cannot be considered as the baseline for future projections because of the very different governance and socio-economic systems.

Future projections show that, with the rapid population growth and dietary transitions associated with economic development, the demand for animal products will continue to increase. For example, global meat demand is projected to double by 2050 (Flammini *et al* 2017). This new demand level will lead to continuously increasing production of meat and milk from East and Central Asia (Bruinsma 2003).

This situation would require future expansion of the scale of pasture systems and/or enhanced feed efficiency, such as through concentrated animal feeding operations. In order to meet the increasing demand, pasture land would need to be expanded by ~8%, and feed efficiency enhanced by ~30%, compared to the 1990s level in East and Central Asia (Wirsenius *et al* 2010). However, both arable land and water resources limit further feed production expansion in many areas of the DLB (Qi *et al* 2012, Qi *et al* 2017).

Meanwhile, large-scale unregulated grazing patterns have caused large reductions in biodiversity and productivity, and led to degradation and desertification, even in historically productive and stable pasture systems (Yusupov 2003, John *et al* 2009, Miao *et al* 2009, Chen *et al* 2014, John *et al* 2018). Therefore, addressing the question of how to enhance feed efficiency in a sustainable way is urgently needed to meet the challenges from both human activities and climatic changes to the pasture systems of the DLB.

4. Summary

Section 2 as well as previous findings (e.g. those provided in the overview by Groisman *et al* 2017) report indisputable increases in the surface air temperature, a retreating cryosphere, and uncertainties in precipitation changes that have led to a generalized depletion of available water resources over most of the DLB.

In the northern part of the DLB, which is presently occupied by forest, the large warming projected by general circulation models for the end of the century is expected to impact vegetation significantly and shift biomes northwards (figure 8, table 3). In particular, ecological bioclimatic modeling of climate warming consequences for terrestrial ecosystems demonstrates a structural change in Northern Asian vegetation: biomes shift northwards, coniferous forests decrease, light-needled coniferous and broadleaved softwood forests and forest steppe dominate, and steppes expand in the South. From the modeling results, the risk zone of forest loss in Siberia would expand in favor of the steppe vegetation with some limited desertification.

In the southern DLB, presently occupied by steppe and semi-deserts, human activity has already interacted with climatic variation and extremes to impact both the environment and livelihood dependent on livestock (figures 7–9; see also Qi *et al* 2012, Qi *et al* 2017).

To minimize negative consequences and benefit from climate change in the Siberian forest and drylands, the following adaptive measures could be pursued: forest restoration on failed forest lands by assisting seed transfer of appropriate species and phenotypes to their climatic optima in the new climates or using those lands for agriculture by planting crops suitable for the new climates (Tchebakova *et al* 2010, 2011b). Current and projected environmental changes (higher temperature, more droughts, and more fires) raise concerns about future food security. However, in the cold climate of the northern DLB agriculture may benefit from climatic warming only after the necessary infrastructure could be developed and a larger rural population could be encouraged to move northward to this frontier.

It is expected that increasing global and regional populations and a growing demand for land use and water resources will remain the major challenges for sustainable development in the DLB of Northern Eurasia. Therefore, in this part of the world, the role of conscientious human activity in land use, water management, construction, and consumption habits becomes a major factor responsible for environmental health and human well-being.

Acknowledgments

PG and GH were supported in part by NASA grant NNX15AP81G. NT acknowledges the Russian Foundation for Basic Research grant 16-05-00496. OZ, AD, and PG were partially supported through 'ARCTIC-ERA: ARCTIC climate change and its impact on environment, infrastructures, and resource availability' sponsored by ANR (France), RFBR (Russia), and US NSF (grants 1717770 and 1558389). YC was supported by National Youth Science Fund of China grant 41701227 and by the Priority Academic Program Development of Jiangsu Higher Education Institutions in China. The work of AS was partially supported by US NSF grant 1602879 and Russian RFFI grant 18-05-60240. Grant 14.B25.31.0026 of the Ministry of Education and Science of the Russian Federation provided support to PG, NT, AS, OB, and OZ for their work conducted at the P P Shirshov Institute of Oceanology. Support for the work of IY and IK was provided by grant AP05135848 of the Ministry of Education and Sciences of the Republic of Kazakhstan. JC and RJ were supported by the Dynamics of Coupled Natural and Human Systems (CNH) Program of the NSF (grant 1313761) and the LCLUC program of NASA (grant NNX14AD85G). Grant 1717770 by the US National Science Foundation to George Washington University provided support to PG for his work at the Hydrology Science and Services Corporation via Sub-Recipient Agreement Number 17-S03R. The synthesis workshop (Ulaanbaatar, 2–5 June 2017) was partially sponsored by the 'Dynamics of Coupled Natural and Human Systems' program of the NSF (grant 1313761) and the LCLUC program of NASA (grant NNX15AD10G).

ORCID iDs

Pavel Groisman https://orcid.org/0000-0001-6255-324X
Geoffrey Henebry https://orcid.org/0000-0002-8999-2709
Yizhao Chen https://orcid.org/0000-0002-9218-6679
Peilei Fan https://orcid.org/0000-0003-4448-4281

References

Akhmadiyeva V K and Groisman P Y 2008 General estimate of climatic change over Kazakhstan since 1990 *Hydrometeorol and Ecol* **2-3** 46–54 (in Russian)

AMAP (Arctic Monitoring and Assessment Programme) 2011 Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere *Report to the Arctic Council* AMAP (Oslo, Norway)(http://amap.no/swipa/)

AMAP (Arctic Monitoring and Assessment Programme) 2017 Snow, Water, Ice, Permafrost in the Arctic (SWIPA) (update) (http://amap.no/swipa2017)

Arsenault R and Brissette F 2014 Determining the optimal spatial distribution of weather station networks for hydrological modeling purposes using RCM datasets: an experimental approach *J Hydrometeorol* **15** 517–26

Arctic Climate Impact Assessment (ACIA) 2005 Scientific report *Arctic Climate: Past and Present* (Cambridge: Cambridge University Press) ch 2

Barry R G 2008 *Mountain Weather and Climate* 3rd edn (Cambridge: Cambridge University Press) p 506

Blench R and Sommer F 1999 *Understanding Rangeland Biodiversity* (London: Overseas Development Institute)

Blunden J and Arndt D S (ed) 2017 State of the climate *2016 Bull Amer Meteor Soc* **98** Si–S277

Bliss A, Hock R and Radić V 2014 Global response of glacier runoff to twenty-first century climate change *J Geophys Res Earth Surface* **119** 717–30

Bruinsma J 2003 *World Agriculture: Towards 2015/2030: an FAO Perspective Earthscan* ed J Bruinsma (London: Publication Ltd)

Bulygina O N, Groisman P Y, Razuvaev V N and Korshunova N N 2011 Changes in snow cover characteristics over Northern Eurasia since 1966 *Environ. Res. Lett.* **6** 045204

Bulygina O N, Korshunova N N and Razuvaev V N 2013 Change of the near-surface winds over Russia during the past decades *Transact Voeikov Main Geophys Observ* **568** 156–72 (in Russian)

Chen J, John R, Shao C, Fan Y, Zhang Y, Amarjargal A, Brown D G, Qi J, Han J and Lafortezza R 2015 Policy shifts influence the functional changes of the CNH systems on the Mongolian plateau *Environ. Res. Lett.* **10** 085003

Chen J, Wan S, Henebry G, Qi J, Gutman G, Sun G and Kappas M 2014 *Dryland East Asia: Land Dynamics Amid Social and Climate Change* Walter de Gruyter p 467

Chen Y, Ju W, Groisman P, Li J, Propastin P, Xu X, Zhou W and Ruan H 2017 Quantitative assessment of carbon sequestration reduction induced by disturbances in temperate Eurasian steppe *Environ. Res. Lett.* **12** 115005

Collins M *et al* 2013 Long-term climate change: Projections, commitments and irreversibility *Climate Change 2013: The Physical Science Basis* ed T F Stocker *et al* (Cambridge: Cambridge University Press) pp 1029–113

Damkjaer S and Taylor R 2017 The measurement of water scarcity: Defining a meaningful indicator *Ambio* **46** 513–31

Darmenova K, Sokolik I N, Shao Y, Marticorena B and Bergametti G 2009 Development of a physically-based dust emission module within the Weather Research and Forecasting (WRF) model: assessment of dust emission parameterizations and input parameters for source regions in Central and East Asia *J. Geophys. Res.* **114** D14201

de Beurs K M and Henebry G M 2004 Land surface phenology, climatic variation, and institutional change: analyzing agricultural land cover change in Kazakhstan *Remote Sens. Environ.* **89** 497–509

de Beurs K M, Henebry G M, Owsley B C and Sokolik I 2015 Using multiple remote sensing perspectives to identify and attribute land surface dynamics in Central Asia 2001–2013 *Remote Sens. Environ.* **170** 48–61

de Beurs K M, Henebry G M, Owsley B and Sokolik I 2018 Large scale climate oscillation impacts on temperature, precipitation, and land surface phenology in Central Asia *Environ. l Res. Lett.* **13** 065018

Dee D P *et al* 2011 The ERA-Interim reanalysis: Configuration and performance of the data assimilation system *Quart J Roy Meteorol Soc* **137** 553–97

Ding Y and Chan J C L 2005 The East Asian summer monsoon: an overview *Meteorol Atmos Phy* **89** 117–42

Ding Y, Yang D, Ye B and Wang N 2007 Effects of bias correction on precipitation trend over China *J. Geophys. Res.* **112** D13116

Flammini A, Puri M, Pluschke L and Dubois O 2017 Walking the nexus talk: assessing the water-energy-food nexus in the context of the sustainable energy for all initiative (Environment and Natural Resources Management) (Working Paper (FAO) eng no. 58)

Friedl M and Sulla-Menashe D 2015 MCD12Q1 MODIS/Terra +Aqua Land Cover Type Yearly L3 Global 500m SIN Grid V006 (Data set) NASA EOSDIS Land Processes DAAC

Gaybullaev B, Chen S C and Gaybullaev D 2012 *Appl Water Sci* **2** 285

Gelaro R *et al* 2017 The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) *J. Clim.* **30** 5419–54

Goudie A S and Middleton N J 1992 The changing frequency of dust storms through time *Clim. Change* **20** 197–225

Groisman P Y and Legates D R 1995 Documenting and detecting long-term precipitation trends: where we are and what should be done *Clim. Change* **31** 601–22

Groisman P Y and Soja A J 2009 Ongoing climatic change in Northern Eurasia: justification for expedient research *Environ. Res. Lett.* **4** 045002

Groisman P Y, Knight R W and Zolina O G 2013 Recent trends in regional and global extreme precipitation patterns *Climate Vulnerability: Understanding and Addressing Threats to Essential Resources Volume 5 Vulnerability of Water Resources to Climate* ed R Sr Pielke and F Hossain (Amsterdam: Elsevier) ch 5.03, pp 25–55

Groisman P Y, Bogdanova E G, Alexeev V A, Cherry J E and Bulygina O N 2014 Impact of snowfall measurement deficiencies on quantification of precipitation and its trends over Northern Eurasia *Ice and Snow* **126** 29–43

Groisman P Y *et al* 2017 Northern Eurasia Future Initiative (NEFI): facing the challenges and pathways of global change in the twenty-first century *Progress in Earth and Planet Sci* **4** 41

Guo W L, Shi H B, Ma J J, Zhang Y J, Wang J, Shu W J and Zhang Z Y 2013 Basic features of climate change in North China during 1961–2010 *Adv Clim Change Res* **4** 73–83

Henebry G M, de Beurs K M, Wright C K, John R and Lioubimtseva E 2013 Dryland East Asia in hemispheric context *Dryland East Asia: Land Dynamics Amid Social and Climate Change* ed J Chen *et al* (Berlin: de Gruyter & Co) ch 2, pp 23–44

IPCC AR5 WG1 2013 *Climate Change 2013: The Physical Science Basis* ed T F Stocker (Cambridge: Cambridge University Press) (archived: 16 July 2014)

Jackson W D 1962 The virgin and idle lands program reappraised *Annals Assoc Amer Geograph* **52** 69–79

John R, Chen J, Lu N and Wilske B 2009 Land cover/land use change in semi-arid Inner Mongolia: 1992–2004 *Environ. Res. Lett.* **4** 045010

John R *et al* 2016 Differentiating anthropogenic modification and precipitation-driven change on vegetation productivity on the Mongolian Plateau *Landscape Ecology* **31** 547–66

John R, Chen J, Giannico V, Park H, Xiao J, Shirkey G, Ouyang Z, Shao C, Lafortezza R and Qi J 2018 Grassland canopy cover and aboveground biomass in Mongolia and Inner Mongolia: spatio-temporal estimates and controlling factors *Remote Sens. Environ.* **213** 34–48

Jung M *et al* 2011 Global patterns of land biosphere - atmosphere fluxes derived from upscaling FLUXNET observations *J Geophys Res—Biogeosci* **116** G00J07

Khromova T, Nosenko G, Kutuzov S, Muraviev A and Chernova L 2014 Glacier area changes in Northern Eurasia *Environ. Res. Lett.* **9** 015003

Kotlyakov V M, Khromova T Y, Nosenko G A, Popova V V, Chernova L P, Muraviev A Y, Rototaeva O V, Nikitin S A and Zverkova N M 2015 *Recent Glacier Changes in Mountain Regions of Russia* (Moscow: KMK Scientific Press) p 288

Kuznetsova L P 1983 *Atmospheric Water Exchange Over the USSR Territory* (Moscow: Nauka) p 173 (in Russian)

Li Y, Zhao X, Chen Y, Luo Y and Wang S 2012 Effects of grazing exclusion on carbon sequestration and the associated vegetation and soil characteristics at a semi-arid desertified sandy site in Inner Mongolia, northern China *Canadian J Soil Sci* **92** 807–19

Lioubimtseva E and Henebry G M 2009 Climate and environmental change in arid Central Asia: impacts, vulnerability, and adaptations *J Arid Environ* **73** 963–77

Liu J, Li S, Ouyang Z, Tam C and Chen X 2008 Ecological and socioeconomic effects of China's policies for ecosystem services *Proc Nat Acad Sci USA* **105** 9477–82

Liu Y L *et al* 2013 Response of evapotranspiration and water availability to changing climate and land cover on the Mongolian Plateau during the 21st century *Glob. Planet. Change* **108** 88–95

Liu D, Chen Y, Cai W, Dong W, XiaoJ, Chen J, Zhang H, Xia J and Yuan W 2014 The contribution of China's Grain for Green Program to carbon sequestration *Landscape Ecology* **29** 1675–88

Loboda T V and Chen D 2017 Spatial distribution of young forests and carbon fluxes within recent disturbances in Russia *Global Change Biology* **23** 138–53

Lugina K M, Groisman P Y, Vinnikov K Y, Koknaeva V V and Speranskaya N A 2006 Monthly surface air temperature time series area-averaged over the 30-degree latitudinal belts of the globe, 1881–2005 *Trends Online: A Compendium of Data on Global Change* (Oak Ridge, TN: Carbon Dioxide Information Analysis Center Oak Ridge National Laboratory US Department of Energy)

Lupo A R, Mokhov I I, Chendev Y G, Lebedeva M G, Akperov M and Hubbarti J A 2014 Studying summer season drought in western Russia *Advances in Meteorology* **2014** 942027

Mátyás C *et al* 2018 Sustainability of forest cover under climate change on the temperate-continental xeric limits *Forests* **9** 489

Miao H, Chen S, Chen J, Zhang W, Zhang P, Wei L, Han X and Lin G 2009 Cultivation and grazing altered evapotranspiration and dynamics in Inner Mongolia steppes *Agricultural and Forest Meteorology* **149** 1810–9

Mildrexler D J, Zhao M and Running S W 2006 Where are the hottest spots on Earth ? *Eos Trans. AGU* **87** 461–7

Mirzabaev A, Ahmed M, Werner J, Pender J and Louhaichi M 2016 Rangelands of Central Asia: challenges and opportunities *Journal of Arid Land* **8** 93–108

Mokhov I I, Akperov M G, Prokofyeva M A, Timazhev A V, Lupo A R and le Treut H 2013 Blockings in the Northern hemisphere and Euro-Atlantic region: estimates of changes from reanalysis data and model simulations *Doklady Earth Sciences* **449** 430–3

Mu S J, Zhou S X, Chen Y Z, Li J L, Ju W M and Odeh I O A 2013 Assessing the impact of restoration-induced land conversion and management alternatives on net primary productivity in Inner Mongolian grassland, China *Glob. Planet. Change* **108** 29–41

Neu U *et al* 2013 IMILAST: a community effort to intercompare extratropical cyclone detection and tracking algorithms *Bull Amer Meteorol Soc* **94** 529–47

Ojima D and Chuluun T 2008 Policy changes in Mongolia: implications for land use and landscapes ed K Galvin, R Reid, R Behnke and N Hobb *Fragmentation in Semi-Arid and Arid Landscape: Consequences for Human and Natural Systems* (Berlin: Springer) pp 179–93

Qi J, Chen J, Wan S and Ai L 2012 Understanding the coupled natural and human systems in Dryland East Asia *Environ. Res. Lett.* **7** 015202

Qi J, Xin X, John R, Groisman P and Chen J 2017 Understanding livestock production and sustainability of grassland ecosystems in the Asian Dryland Belt *Ecol Proces* **6** 22

Romanovsky V E, Smith S l, Shiklomanov N I and Marchenko S S 2017 Terrestrial Permafrost *Bull Amer Meteorol Soc* **98** 147–9

Schubert S, Wang H, Koster R, Suarez M and Groisman P 2014 Northern Eurasian heat waves and droughts *J Climate* **27** 3169–207

Schwartz M D, Ahas R and Aasa A 2006 *Global Change Biol* **12** 343–51

Second National Climate Change Assessment for the Russian Federation 2014 (http://cc.voeikovmgo.ru/ru/publikatsii/2016-03-21-16-23-52) Moscow Roshydromet (in Russian)

Shahgedanova M, Nosenko G, Khromova T and Muravyev A 2010 Glacier shrinkage and climatic change in the Russian Altai from the mid-20th Century: an assessment using remote sensing and PRECIS regional climate model *J Geophys Res—Atmos* **115** D16107

Shahgedanova M, Nosenko G, Kutuzov S, Rototaeva O and Khromova T 2014 Deglaciation of the Caucasus Mountains, Russia/Georgia in the 21st century observed with ASTER satellite imagery and aerial photography *The Cryosphere* **8** 2367–79

Sheffield J, Goteti G and Wood E F 2006 Development of a 50-yr high-resolution global dataset of meteorological forcings for land surface modeling *J Climate* **19** 3088–111

Shiklomanov N I, Streletskiy D A, Swales T B and Kokorev V A 2017 Climate change and stability of urban infrastructure in russian permafrost regions: prognostic assessment based on GCM climate projections *Geograph Rev* **107** 125–42

Shver T A 1976 *Atmospheric Precipitation Over the USSR Territory* (in Russian) (Leningrad: Gidrometeoizdat) p 302

Schyns J F, Hoekstra A Y and Booij M J 2015 Review and classification of indicators of green water availability and scarcity *Hydrol. Earth Syst. Sci.* **19** 4581–608

Soja A and Groisman P Y 2018 Earth Science and the integral climatic and socio-economic drivers of change across northern Eurasia: The NEESPI legacy and future direction *Environ. Res. Lett.* **13** 040401

Syromyatina M V, Kurochkin Y N, Bliakharskii D P and Chistyakov K V 2015 Current dynamics of glaciers in the Tavan Bogd Mountains (Northwest Mongolia) *Environ Earth Sci* **74** 1905–14

Tchebakova N M, Parfenova E I and Soja A J 2009 The effects of climate, permafrost and fire on vegetation change in Siberia in a changing climate *Environ. Res. Lett.* **4** 045013

Tchebakova N M, Rehfeldt G and Parfenova E I 2010 From vegetation zones to climatypes: effects of climate warming on Siberian ecosystems *Permafrost ecosystems. Siberian Larch Forests* ed A Osawa *et al* (Berlin: Springer) ch 22, pp 427–47

Tchebakova N M, Parfenova E and Soja A 2011a Climate change and climate-induced hot spots in forest shifts in central Siberia at the turn of the 21st century *Regional Environ Change* **11** 817–27

Tchebakova N M, Parfenova E I, Lysanova G and Soja A 2011b An agroclimatic potential in southern Siberia in a changing climate during the XXI century 2011 *Environ. Res. Lett.* **6** 045207

Tian L, Gong Q and Chen J 2018 Coupled dynamics of socioeconomic and environmental systems in Tibet *Environ. Res. Lett.* **13** 034001

Tilinina N, Gulev S K, Rudeva I and Koltermann P 2013 Comparing cyclone life cycle characteristics and their interannual variability in different reanalyses *J Climate* **26** 6419–38

Tomaszewska M A and Henebry G M 2018 Changing snow seasonality in the highlands of Kyrgyzstan *Environ. Res. Lett.* **13** 065006

Wang Y and Zhou L 2005 Observed trends in extreme precipitation events in China during 1961–2001 and the associated changes in large-scale circulation *Geophys. Res. Lett.* **32** L09707

Wirsenius S, Azar C and Berndes G 2010 How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030 ? *Agricultural Systems* **103** 621–38

Wright C K, de Beurs K M, Akhmadiyeva Z K, Groisman P Y and Henebry G M 2009 Reanalysis data underestimate significant changes in growing season weather in Kazakhstan *Environ. Res. Lett.* **4** 045020

Wright C K, de Beurs K M and Henebry G M 2012 Combined analysis of land cover change and NDVI trends in the Northern Eurasian grain belt *Frontiers in Earth Science* **6** 177–87

Yesserkepova I 1988 Estimation of air temperature changes in Northern Kazakhstan due to virgin and fallow lands development *Questions of Land Hydrology* Gidrometeoizdat pp 235–9 (in Russian) (http://elib.rshu.ru/files_books/pdf/img-214190446.pdf)

Yu X, Zhao Y, Ma X, Yao J and Li H 2018 Projected changes in the annual cycle of precipitation over central Asia by CMIP5 models *Intern J Climatol* **2018** 1–16

Yusupov S Y 2003 Interaction between livestock and the desert environment in Uzbekistan *Proc. of NATO Advanced Research Workshop* 93–6 ‘Desertification problems in Central Asia and its regional strategic development’ Samarkand Uzbekistan NATO pp

Zavialov P O 2007 *Physical Oceanography of the Dying Aral Sea* (Berlin: Springer) p 153

Zhao C Y *et al* 2013 Changes in climatic factors and extreme climate events in Northeast China during 1961–2010 *Adv Clim Change Res* **4** 92–102

Zolina O G, Simmer C, Belyaev K, Gulev S K and Koltermann P 2013 Changes in the duration of European wet and dry spells during the last 60 years *J Climate* **26** 2022–47

Zolina O, Simmer C, Gulev S K and Kollet S 2010 Changing structure of European precipitation: longer wet periods leasing to stronger extremes *Geophys. Res. Lett.* **37** L06704