

ACCEPTED MANUSCRIPT • OPEN ACCESS

Dry land belt of Northern Eurasia: contemporary environmental changes and their consequences

To cite this article before publication: Pavel Ya Groisman *et al* 2018 *Environ. Res. Lett.* in press <https://doi.org/10.1088/1748-9326/aae43c>

Manuscript version: Accepted Manuscript

Accepted Manuscript is “the version of the article accepted for publication including all changes made as a result of the peer review process, and which may also include the addition to the article by IOP Publishing of a header, an article ID, a cover sheet and/or an ‘Accepted Manuscript’ watermark, but excluding any other editing, typesetting or other changes made by IOP Publishing and/or its licensors”

This Accepted Manuscript is © 2018 The Author(s). Published by IOP Publishing Ltd.

As the Version of Record of this article is going to be / has been published on a gold open access basis under a CC BY 3.0 licence, this Accepted Manuscript is available for reuse under a CC BY 3.0 licence immediately.

Everyone is permitted to use all or part of the original content in this article, provided that they adhere to all the terms of the licence <https://creativecommons.org/licenses/by/3.0>

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permissions may be required. All third party content is fully copyright protected and is not published on a gold open access basis under a CC BY licence, unless that is specifically stated in the figure caption in the Version of Record.

View the [article online](#) for updates and enhancements.

Dry Land Belt of Northern Eurasia: Contemporary Environmental Changes and Their Consequences

Pavel Groisman^{1,2,3}, Olga Bulygina^{*,4}, Geoffrey Henebry⁵, Nina Speranskaya⁶, Alexander Shiklomanov⁷,
Yizhao Chen⁸, Nadezhda Tchepakova⁹, Elena Parfenova⁹, Natalia Tilinina², Olga Zolina^{2,10}, Ambroise
Dufour¹⁰, Jiquan Chen⁵, Ranjeet John¹¹, Peilei Fan⁵, Csaba Mátyás¹², Irina Yesserkepova¹³, and Ildan
Kaipov¹⁴

¹ North Carolina State University at NOAA Center for Environmental Information, Asheville, North
Carolina, USA

² P. P Shirshov Institute for Oceanology, RAS, Moscow, Russia

³ Hydrology Science and Services Corp., Asheville, North Carolina, USA

⁴ Russian Institute for Hydrometeorological Information, Obninsk, Kaluga Area, Russia

⁵ Michigan State University, East Lansing, Michigan, USA

⁶ State Hydrological Institute, St. Petersburg, Russia

⁷ Earth Systems Research Center, University of New Hampshire, Durham, New Hampshire, USA

⁸ Joint Innovation Center for Modern Forestry Studies, College of Biology and the Environment, Nanjing
Forestry University, Nanjing, Jiangsu, 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, USA

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

* deceased on June 16th, 2018

Abstract.

The Dry Land 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 feedbacks) with other external and internal factors of contemporary regional environmental changes and human activities within the DLB.

Social Media Abstract.

Brief overview of recent climatic and environmental changes over the Dry Lands of Northern Eurasia

1
2
3 **1. Introduction**
4

5 Northern Eurasia Earth Science Partnership Initiative (NEESPI, launched in 2003) and its successor
6 Northern Eurasia Future Initiative (NEFI, launched in 2016) have been internationally supported
7 diversified research programs with overarching Science questions “How do Northern Eurasia’s terrestrial
8 ecosystem dynamics interact with and alter the biosphere, atmosphere, and hydrosphere of the Earth?”
9 and “What dynamic and interactive changes will affect societal activities, human well-being, and health,
10 and what might be the mitigation and adaptation strategies that could support sustainable development
11 and decision-making activities?” respectively. The NEESPI is currently waning through attrition (Soja and
12 Groisman 2018) and the second Initiative has just released its programmatic documents and keynote
13 publication (Groisman *et al* 2017). Research domains of NEESPI and NEFI coincide and are shown in Figure
14 1a. The southern tier of this domain falls within by the Dry Land Belt (DLB) of Northern Eurasia that
15 occupies the interior of the Earth’s largest continent and spans the territory of 16 countries: Armenia,
16 Azerbaijan, China Dry Land Region, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Moldova, Mongolia,
17 Romania, Russia Dry Land Region, Slovakia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan. To
18 delineate the DLB in Figure 1, we used boundaries of deserts, semi-deserts, steppes, and forest-steppes
19 within the NEESPI/NEFI research domain north of 37°N and south of 52°N (Figure 1a).
20
21 The DLB occupies the interior of the Earth’s largest continent and spans the territory of 16 countries.
22 Mountain ridges and high plateaus of the central regions of Asia mostly cut off the DLB from water vapor
23 transported from the tropics (Figure 1). Some parts of the DLB have fertile land and are quite densely
24 populated. However, there exist strong physical limitations on the production of crops and rangelands.
25 The region has a very limited fresh water supply, which is highly dependent upon irregular extra-tropical
26 cyclones and a shrinking regional cryosphere (Shver 1976, Bliss *et al* 2014). Increases in evapotranspiration
27 (ET) arising from increases in warm season temperatures and expansions of the growing season in the DLB
28 are generally not compensated by precipitation increases (IPCC AR5 WG1 2013). Furthermore, spatio-
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

temporal shifts in precipitation pattern increase the likelihood that various unusual or extreme events (e.g., heatwaves, 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 socioeconomic 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 have 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 DLB ecosystem services and the societies that rely on them (Groisman *et al* 2017, Qi *et al* 2017; see also Suppl. 1).

{insert Figure 1 here}

Within the transforming socioeconomic 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; and
- (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

Surface air temperature across the DLB region had been stable from the beginning of the 20th century until mid-1960s, but has increased rapidly in the past five decades (Figure 1b). 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 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 (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 the glacial retreat in Central Asia, 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 (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 (Lupo *et al* 2014, Mokhov *et al* 2013). 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 (Zolina *et al* 2013, Groisman and Soja 2009, 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 for the eastern edge of the DLB do not support these expectations (Figure 2).

{insert Figure 2 here}

{insert Table 1 here}

Figure 2 and Table 1 show major statistics of cyclone characteristics for the four regions of the Asian part of the DLB. In Figure 2, these regions are identified with four figure inserts that visualize the time series of 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 spatial resolution of $1.5^{\circ} \times 1.5^{\circ}$. 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 the 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 (Kuznetsova 1983, Shver 1976), 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 do not see systematic changes in cyclone counts in this region (Figure 2). In contrast, the numbers of cyclones in Central Asia, Northwest China, and Mongolia increase. 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, a dramatic reduction of the eastward water vapor transport into the 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 extent of the Aral Sea had been shrinking since 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 was the cause of the water vapor transport decline, it contributed to drier weather conditions in the Central Asia (see Section 2.5).

{insert Table 2 here}

2.3 Changes in atmospheric precipitation

Atmospheric precipitation, its amount (totals), form (frozen, mixed or liquid), intensity (for rainfall), intraseasonal distribution, and their systematic changes (trends) remain the most variable characteristics of the DLB climate. Past studies documented 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 (Groisman *et al* 2013, Zolina *et al* 2010, 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 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, Akhmediyeva 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 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 (*cf.* 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 of China. Ding *et al* (2007) show an 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 (*cf.*, Bulygina *et al* 2013, Ding *et al* 2007) may “increase” the observed cold season precipitation while the ground-true precipitation is unchanged or even decreased. Figure 3a shows that during the 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).

{insert Figure 3 here}

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 3b, 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 MERRA2 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, European Russia), manifested themselves by several severe droughts (including extreme drought of 2010). Over the eastern part of the DLB (the Baikal Lake Basin, Trans-Baikal area, and northeastern China, the waves are 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 changes showing stable decreases (AMAP 2011, AMAP 2017):

- Duration of seasonal spring snow cover has been steadily decreasing making the earlier 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 2014);
- Period with stable snow cover over Europe has become shorter and/or disappears causing river ice break-up, and increases in winter runoff (*cf.*, 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 mountains of the Central Asia affecting infrastructure, such as roads and buildings; (Shiklomanov *et al* 2017); and
- 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, Shahgedanova *et al* 2014, Syromyatina *et al* 2015, Khromova *et al* 2014, Kotlyakov *et al* 2015).

{insert Figure 4}

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, escalate glacial melt and 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 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 into the future once several factors that are currently favorable for these increases change (Suppl. 2).

We have a complete set of socio-economic and meteorological data for the Central Asia nations, and our analysis of climate change impacts on different aspects of water availability here was made using combination of economic census data with hydrological modeling (Suppl. 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, Suppl. 3) using country-based statistical socio-economic information along with spatially distributed population density. 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).

{insert Figure 5}

The WSI is the ratio of annual freshwater abstractions (*i.e.*, system losses due to water consumption, evapotranspiration, 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 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 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.

{insert Figure 6 here}

The latest land cover types and their changes within the Asian part of DLB were examined using the MODIS land cover product (MCD12Q1V6; <https://earthdata.nasa.gov/>) through re-grouping IGBP classification cover types between 2001 and 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 MCD12Q1V6 data product was derived from different classification schemes, of which we used the International Geosphere-Biosphere Programme (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 and 2014, 2002 and 2015, and 2003 and 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 km²). 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 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 grey) 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 7b. 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 7a). The arid barrens are the largest on the Earth's surface and stretch from the Gobi Desert in the southwest Mongolia to the Western portion of Central Asia (Chen *et al* 2014, Mildrexler *et al* 2006). The grasslands included those on the 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 (Tian *et al* 2018, John *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%) than those in Central Asia (45.50%). Kazakhstan has the highest grassland cover (85.2%) among all administrative units (Figure 7a). Overall croplands in East and Central Asian countries occupy 4.13% and 7.60%, respectively. Forests were found in northeast Inner Mongolia, and on northern aspects slopes in the Tian Shan Mountains of Central Asia.

{insert Figure 7 here}

Land use was also very extensive and intensive across the DLB, with 5.58% of the land experiencing consistent cover change from 2001 to 2016 (Figure 7b). 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 the results of major policy shifts by the individual countries and, to a lesser degree, due to 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.

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 Suppl. 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 RCP 2.6 and RCP 8.5 scenarios, while drylands extent changed minimally. A 6% increase in drylands was projected under RCP 8.5 scenario for the 20 GCM ensemble (Table 3, Figure 8c). According to the ensemble of the five driest GCMs under RCP 8.5, drylands would cover 63% of the study area with 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., $\pm 1.5\text{-}2\%$), because the forest would shift into the current tundra distribution and tundra would nearly vanish. Only in a dry climate its coverage would decrease by about 12.5%.

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 a shorter life cycle, a stronger adaptability to less precipitation and droughts, and capabilities to recover due to allocation of perennating plant parts belowground (Tchebakova *et al* 2009). Generally, the projected warmer and drier climates will promote dry lands 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 highlands on mountains and in the RCP8.5 scenario it vanishes completely.

{insert Table 3 here}

To minimize the negative consequences and to enhance the benefit from climate change in Siberian forests and drylands, adaptive measures need to be implemented, including forest restoration on failed forest 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 of inventory data of livestock. The carbon ingested by livestock (C_{graze}) was calculated using the pasture system simulator in boreal ecosystem productivity simulator (BEPS; Chen *et al* 2017). These distribution and C_{graze} are tightly controlled by sub-regional socioeconomic 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 unit per km^2 and $30 \text{ gC m}^{-2} \text{ yr}$, 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 unit per km^2 and Northeastern Inner Mongolia (Hulunbuir City), where density is higher than 200 sheep unit 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 unit per km^2 and $12 \text{ gC m}^{-2} \text{ yr}$ for the two countries (Figure 9), while livestock density is generally lower than 40 sheep unit per km^2 over the steppe of Kazakhstan.

Concern over increasing demands for animal products and preservation of grassland resources led to the launch of regional conservation programs in Inner Mongolia since late 1990s, including the Grain to Green Program (GTGP; Liu *et al* 2008) and the Grazing Withdrawal Program (GWP; 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.

Figure 9.

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 cotton and meat). As a result, the reduction of livestock numbers during the 1990s was mainly induced by the institutional changes, loss of access to markets, and agricultural reforms following dissolution of the USSR (de Beurs and Henebry 2004, Ojiima and Chulun 2008, Wright *et al* 2012, de Beurs *et al* 2015, John *et al* 2016). Clearly, the situation in 1980s for 1990s cannot be considered as baseline for future projections because of very different governance and socio-economic systems.

Future projections show that, with 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 (CAFOs). In order to meet the increasing demand, pasture land would need to be expanded by ~8%, and feed efficiency to be 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 (Chen *et al* 2014, John *et al* 2009, John *et al* 2018, Miao *et al* 2009, Yusupov 2003). 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 surface air temperature, 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 of northern Asia vegetation: biomes shifts northwards, coniferous forests decrease, light-neededled coniferous and broadleaved softwood forests and forest steppe dominant, and steppes expands in the south. From 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, the human activity has already interacted with climatic variation and extremes to impact both 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 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, 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 become a major factor responsible for environmental health and human well-being.

Acknowledgements: P. Groisman and G. Henebry were supported in part by NASA grant NNX15AP81G. N. Tchebakova acknowledges the Russian Foundation for Basic Research grant 16-05-00496. O. Zolina, A. Dufour, and P. Groisman 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). Y. Chen 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. Work of A. Shiklomanov was partially supported by U.S. 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 P. Groisman, N. Tilinina, A. Shiklomanov, O. Bulygina, and O. Zolina for their work conducted at the P.P. Shirshov Institute of Oceanology. Support for work of I. Yesserkepova and I. Kaipov is provided by Grant AP05135848 of the Ministry of Education and Sciences of the Republic of Kazakhstan. J. Chen and R. John 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). The synthesis workshop (Ulaan Baatar, June 2-5, 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).

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 [Available at <http://amap.no/swipa/>] AMAP Oslo Norway
- AMAP (Arctic Monitoring and Assessment Programme) 2017 *Snow, Water, Ice, Permafrost in the Arctic (SWIPA). Update*. <http://www.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** 517-526
- Arctic Climate Impact Assessment (ACIA) 2005 Scientific Report Chapter 2 “Arctic Climate: Past and Present” Cambridge University Press
- Barry R G 2008 *Mountain Weather and Climate Third Edition*. Cambridge Univ. Press. 506
- Bennett K E, Cannon A J and Hinzman L 2015 Historical trends and extremes in boreal Alaska river basins *J Hydrol* **527** 590-607 <http://dx.doi.org/10.1016/j.jhydrol.2015.04.065>
- Blench R and Sommer F 1999 *Understanding Rangeland Biodiversity* Overseas Development Institute London
- Blunden J and Arndt D S Eds 2017 State of the Climate in 2016 *Bull Amer Meteor Soc* **98** Si-S277 [doi:10.1175/2017BAMSStateoftheClimate.1](https://doi.org/10.1175/2017BAMSStateoftheClimate.1)
- Bliss A, Hock R and Radić V 2014 Regional estimates of glacier runoff for the twenty-first century *J Geophys Res Earth Surface* **119** doi: 10.1002/2013JF002931

- Bring A, Fedorova I, Dibike Y, Hinzman L, Mård J, Mernild S H, Prowse T D, Semenova O, Stuefer S and M-K Woo 2016 Arctic terrestrial hydrology: A synthesis of processes, regional effects and research challenges *J Geophys Res Biogeosci* **121** 621–649 doi:10.1002/2015JG003131
- Bruinsma J 2003 World agriculture: towards 2015/2030: *an FAO perspective Earthscan*
- Bulygina O N, Groisman P Y, Razuvaev V N, Korshunova N N 2011 Changes in snow cover characteristics over Northern Eurasia since 1966 *Environ Res Lett* **6**:045204. doi: 10.1088/1748–9326/6/4/045204
- Bulygina O N, Korshunova N N, 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 Laforteza 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, Kappas M 2014 *Dryland East Asia: Land Dynamics Amid Social and Climate Change* Walter de Gruyter 467 p
- 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
- Chevallier P, Pouyaud B, Mojaïsky M, Bolgov M, Olsson O, Bauer M and Froebrich, J 2014 River flow regime and snow cover of the Pamir Alay (Central Asia) in a changing climate. *Hydrol Sci J* **59** 1491–1506 <http://dx.doi.org/10.1080/02626667.2013.838004>
- Collins M and Coauthors 2013 Long-term climate change: Projections, commitments and irreversibility *Climate Change 2013: The Physical Science Basis* Stocker T F et al eds Cambridge University Press 1029–113 <https://doi.org/10.1017/CBO9781107415324.024>

- Damkjaer S and Taylor R 2017 The measurement of water scarcity: Defining a meaningful indicator *Ambio* **46** 513-531 <https://doi.org/10.1007/s13280-017-0912-z>
- 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 doi 10.1029/2008JD011236
- 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 Sensing of Environment* **89** 497-509 <https://doi.org/10.1016/j.rse.2003.11.006>
- 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 Sensing of Environment* **170** 48-61 <https://doi.org/10.1016/j.rse.2015.08.018>
- 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. Res. Lett.* **13** 065018 <https://doi.org/10.1088/1748-9326/aac4d0>
- Dee D P, and Coauthors 2011 The ERA-Interim reanalysis: Configuration and performance of the data assimilation system *Quart J Roy Meteorol Soc* **137** 553-597
- Ding Y and Chan J C L 2005 The East Asian summer monsoon: an overview *Meteorol Atmos Phy* **89** 117-142 <https://doi.org/10.1007/s00703-005-0125-z>
- Ding Y, Yang D, Ye B and Wang N 2007 Effects of bias correction on precipitation trend over China *J Geophys Res* **112** D13116. doi:10.1029/2006JD007938
- 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. *FAO*

- Frauenfeld O W and Zhang T 2011 An observational 71-year history of seasonally frozen ground changes in the Eurasian high latitudes *Environ Res Lett* **6** 044024, DOI:10.1088/1748-9326/6/4/044024
- 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. doi: 10.5067/MODIS/MCD12Q1.006
- Gaybullayev B, Chen S C and Gaybullayev D. 2012 *Appl Water Sci* **2** 285 <https://doi.org/10.1007/s13201-012-0048-z>
- Gelaro R, McCarty W, Max J, Suárez M J, et al. 2017 The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) *J Clim* doi: 10.1175/JCLI-D-16-0758.1
- Georgievsky V Yu, Georgievsky M V, Golovanov O F and Shalygin A L 2014 Land Water Systems, Chapter: 4.1 in *Second Assessment Report of Roshydromet on Climate Change and its Consequences for Territory of the Russian Federation* Moscow 350-361 http://downloads.igce.ru/publications/OD_2_2014/v2014/htm/1.htm
- Goudie A S and Middleton N J 1992 The changing frequency of dust storms through time. *Climatic Change* **20** 197–225 doi: 10.1007/BF00139839
- Groisman P Y and Legates D R 1995 Documenting and detecting long-term precipitation trends: where we are and what should be done. *Climatic Change* **31** 601-622
- Groisman P Y and Soja A J 2009 Ongoing climatic change in Northern Eurasia: justification for expedient research *Environ Res Lett* **4** 045002. doi: 10.1088/1748-9326/4/4/045002
- Groisman P Y, Knight R W and Zolina O G 2013 Recent trends in regional and global extreme precipitation patterns. Chapter 5.03 (pages 25-55). In Pielke, R Sr and Hossain F (eds) *Climate Vulnerability: Understanding and Addressing Threats to Essential Resources Volume 5 Vulnerability of Water Resources to Climate* Elsevier Publishing House ISBN 978-0-12-384703-4 1440 p

- 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* No. 2 (126) 29-43
- Groisman P Y, Shugart H H, Kicklighter D *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**. doi 10.1186/s40645-017-0154-5.
- 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(2)** doi: 10.3724/SP.J.1248.2013.073
- Gurevich E 2009 Influence of air temperature on the river runoff in winter (the Aldan river catchment case study) *Russ Meteorol Hydrol* **34** 628-633 DOI: 10.3103/S1068373909090088
- Henebry G M, de Beurs K M, Wright C K, John R, and Lioubimtseva E 2013 Dryland East Asia in Hemispheric Context. In: (J Chen, S Wan, G Henebry, J Qi, G Gutman, G Sun, M Kappas, eds) *Dryland East Asia: Land Dynamics Amid Social and Climate Change* HEP/De Gruyter. Chapter 2 pp 23-44
- Holmes R M, Shiklomanov A I, Tank S E, McClelland J W and Tretiakov M 2016 River Discharge. In State of the Climate in 2015. *Bull Amer Meteorol Soc* **97** S147–S149
- IPCC AR5 WG1 2013, Stocker T F, *et al* eds *Climate Change 2013: The Physical Science Basis*. Working Group 1 (WG1) Contribution to the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5), 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, Chen J, Kim Y, Ouyang Z, Park H, Xiao J, Shao C, Amarjargal A, Zhang Y, Bakshishig O and Qi J 2016 Differentiating anthropogenic modification and precipitation-driven change on vegetation productivity on the Mongolian Plateau *Landscape Ecology* **31** 547-566. doi: 10.1007/s10980-015-0261-x.s

- John R, Chen J, Giannico V, Park H, Xiao J, Shirkey G, Ouyang Z, Shao C, Laforzezza R, and Qi J 2018 Grassland canopy cover and aboveground biomass in Mongolia and Inner Mongolia: spatio-temporal estimates and controlling factors *Remote Sensing of Environment* **213** 34-48
- Jung M, Reichstein M, Cescatti A *et al* 2011 Global patterns of land biosphere - atmosphere fluxes derived from upscaling FLUXNET observations *J Geophys Res - Biogeosci* **116** doi:10.1029/2010JG001566
- Kalyuzhny I and Lavrov A 2012 Basic physical processes and regularities of winter and spring river flow formation under the climate warming. *Russ Meteorol Hydrol* 68-81 doi: 10.3103/S1068373912010074
- 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 288 p
- Kuznetsova L P 1983 *Atmospheric water exchange over the USSR territory* Moscow Nauka 173 p (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** 807-819
- Lioubimtseva E and Henebry G M 2009 Climate and environmental change in arid Central Asia: impacts, vulnerability, and adaptations *J Arid Environ* **73** 963–977
- 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** 9477-9482 <https://doi.org/10.1073/pnas.0706436105>
- Liu, Y L, Zhuang Q, Chen M, Pan Z, Tchebakova N, Sokolov A, Kicklighter D, Melillo J, Sirin A, Zhou G, He Y, Chen J and Bowling L 2013 Response of evapotranspiration and water availability to changing climate

- and land cover on the Mongolian Plateau during the 21st century. *Global and Planetary Change* **108** 88-95
- Liu D, Chen Y, Cai W, Dong W, Xiao J, 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** 1675–1688
- Loboda T V and Chen D 2017 Spatial distribution of young forests and carbon fluxes within recent disturbances in Russia *Global Change Biology* **23** (1) 138-153 doi: 10.1111/gcb.13349
- 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* Carbon Dioxide Information Analysis Center Oak Ridge National Laboratory U.S. Department of Energy Oak Ridge Tennessee USA Doi: 10.3334/CDIAC/cli.003
- 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* 942027
- Markov M L 2003 Spatial-temporal dynamic of surface and ground water interaction *Proc. of State Hydrol Inst Hydrometeoizdat* **25** 90-104, (in Russian)
- Mátyás C, Berki I, Bidló A *et al* 2018 Sustainability of forest cover under climate change on the temperate-continental xeric limits *Forests in review*
- 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** 1810-1819
- Miao C, Duan Q, Sun Q *et al* 2014 Assessment of CMIP5 climate models and projected temperature changes over Northern Eurasia *Environ. Res. Lett* **9** 055007 doi:10.1088/1748-9326/9/5/055007
- Mildrexler D J, Zhao M and Running S W 2006 Where are the hottest spots on Earth? *Eos Trans. AGU* **87**(43) 461–467 doi: 10.1029/2006EO430002

- 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** 430–433
- 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 *Global and Planetary Change* **108** 29-41
- Neu U and Co-Authors 2013 IMILAST: A Community Effort to Intercompare Extratropical Cyclone Detection and Tracking Algorithms *Bull Amer Meteorol Soc* **94** 529-547 <https://doi.org/10.1175/BAMS-D-11-00154.1>
- Ojima D and Chuluun T 2008 Policy changes in Mongolia: Implications for land use and landscapes In: Galvin K, Reid R, Behnke R and Hobb N (eds) *Fragmentation in Semi-Arid and Arid Landscape: Consequences for Human and Natural Systems* Springer 179-193
- Parfenova E I, Tchebakova N M, and Soja A J 2018 The ecological potential for human life and well-being across Asian Russia in a warming climate of the XX1 century. *Environ Res Lett* (in review)
- Peterson B J, Holmes R M, McClelland J W, Vorosmarty C J, Lammers R B, Shiklomanov A I, Shiklomanov I A and Rahmstorf S 2002 Increasing river discharge to the Arctic Ocean *Science* **298** 2171-2173
- Portmann F T, Siebert S, et al 2010 MIRCA2000-Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling *Global Biogeochemical Cycles* **24**
- Qi J, Chen J, Wan S, 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**(1) 22.
- Romanovsky V E, Smith S I, Shiklomanov N I and Marchenko S S 2017 Terrestrial Permafrost *Bull Amer Meteorol Soc* **98**(8) 147–149
- Schubert S, Wang H, Koster R, Suarez M and Groisman P 2014 Northern Eurasian Heat Waves and Droughts *J Climate* **27** 3169–3207 doi: 10.1175/JCLI-D-13-00360.1
- Schwartz M D, Ahas R and Aasa A 2006 *Global Change Biol* **12** 343–351 doi: 10.1111/j.1365-2486.2005.01097.x
- 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 doi: 10.1029/2009JD012976
- 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** 2367–2379 doi: 10.5194/tc-8-2367-2014.
- 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** 3088–3111
- Shiklomanov A I, Lammers R B, Rawlins M A, Smith L S and Pavelsky T M 2007 Temporal and spatial variations in maximum river discharge from a new Russian data set *J Geophys Res Biogeosci* **112** G04S53 doi: 10.1029/2006JG000352
- Shiklomanov A I and Lammers R B 2009 Record Russian river discharge in 2007 and the limits of analysis *Environ Res Lett* **4** 045015 doi: 10.1088/1748-9326/4/4/045015.

- Shiklomanov A I and Lammers R B 2013 Changing Discharge Patterns of High-Latitude Rivers, in *Climate Vulnerability: Understanding and Addressing Threats to Essential Resources* Elsevier 161-175.
- Shiklomanov A I and Lammers R B 2014 River ice responses to a warming Arctic—recent evidence from Russian rivers. *Environ Res Lett* **9** 035008 doi:10.1088/1748-9326/9/3/035008
- Shiklomanov A, Prusevich A, Gordov E, Okladnikov I and Titov A 2016 Environmental science applications with Rapid Integrated Mapping and analysis System (RIMS) *IOP Conference Series Earth and Environmental Science* **48** 012034 · November 2016 doi: 10.1088/1755-1315/48/1/012034.
- 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** 125–142 doi:10.1111/gere.12214
- Shver Ts A 1976 Atmospheric precipitation over the USSR territory (in Russian) Gidrometeoizdat Leningrad 302 p
- 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** 4581–4608
- Smith L C, Pavelsky T M, MacDonald G M, Shiklomanov A I and Lammers R B 2007 Rising minimum daily flows in northern Eurasian rivers suggest a growing influence of groundwater in the high-latitude water cycle *J Geophys Res - Biogeosciences* **112** G04S47 doi:10.1029/2006JG000327
- Streletskiy D, Tananaev N, Ope, T, Shiklomanov N, Nyland K, Streletskaya I, Tokarev I and Shiklomanov A 2015 Permafrost Hydrology in Changing Climatic Conditions: Seasonal Variability of Stable Isotope Composition in Rivers in Discontinuous Permafrost *Environ Res Lett* **10** 095003 doi:10.1088/1748-9326/10/9/095003
- 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** 1905–1914 doi: 10.1007/s12665-015-4606-1

- 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 doi:10.1088/1748-9326/4/4/045013
- Tchebakova N M, Rehfeldt G and Parfenova E I 2010 From vegetation zones to climatypes: effects of climate warming on Siberian ecosystems *In: Permafrost ecosystems. Siberian Larch Forests* Springer Verlag Eds A.Osawa *et al* Chapter 22 427-447 p
- 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* doi: 10.1007/s 10113-011-0210-4
- 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 doi: 10.1088/1748-9326/6/4/045207
- Tian L, Gong Q and Chen J 2018 Coupled dynamics of socioeconomic and environmental systems in Tibet *Environ Res Lett* **13** 034001 <https://doi.org/10.1088/1748-9326/aaa64e>
- 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** 6419–6438
- Tomaszewska M A and Henebry G M 2018 Changing snow seasonality in the highlands of Kyrgyzstan *Environ Res Lett* **13** 065006 <https://doi.org/10.1088/1748-9326/aabd6f>
- Troy T J, Sheffield J and Wood E F 2012 The role of winter precipitation and temperature on northern Eurasian streamflow trends *J Geophys Res – Atmos* **117** D5 doi: 10.1029/2011JD016208
- 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 doi: 10.1029/2005GL022574
- Wisser D, Frohling S, Hagen S and Bierkens M F P 2013 Beyond peak reservoir storage? A global estimate of declining water storage capacity in large reservoirs *Water Resources Res* **49** doi:10.1002/wrcr.20452

- 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** 621-638
- Woo M 2012 *Permafrost hydrology* Springer-Verlag Berlin Germany doi: 10.1007/978-3-642-23462-0
- Wright C K, de Beurs K M, Akhmediyeva 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
<https://doi.org/10.1088/1748-9326/4/4/045020>
- 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**(2) 177-187 doi: 10.1007/s11707-012-0327-x
- Yesserkepova I 1988 Estimation of air temperature changes in Northern Kazakhstan due to virgin and fallow lands development *Questions of land hydrology* Gidrometeoizdat 235-239 (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 doi: 10.1002/joc.5765
- Yusupov 2003 Interaction between livestock and the desert environment in Uzbekistan, Proceedings of NATO Advanced Research Workshop "Desertification problems in Central Asia and its regional strategic development" Samarkand Uzbekistan NATO 93-96
- Zaveri E, Grogan D S, Fisher-Vanden K, Frolking S, Lammers R B, Wrenn D H, Prusevich A and Nicholas R E 2016 Invisible water, visible impact: groundwater use and Indian agriculture under climate change *Environ Res Lett* **11**(8).
- Zavialov P O 2007 *Physical Oceanography of the Dying Aral Sea* Springer 153 p
- Zhao C Y, Wang Y, Zhou X 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** 2022-2047

Zolina O, Simmer C, Gulev S K and Kollet S 2010 Changing structure of European precipitation: longer wet periods leading to stronger extremes *Geophys Res Lett* **37** L06704 doi:10.1029/2010GL042468

Figure Captions

Figure 1. a. The NEESPI research domain map with the Dry Land 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* (2006 updated). Anomalies were calculated from the mean values for the 1951-1975 period.

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* (2013 updated) within the IMILAST project (Neu *et al* 2013) activity and applied to the ERA-Interim Reanalysis data for the post-USSR period.

Figure 3. Deviations of mean seasonal precipitation totals (mm) across the Dry Land Belt during 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 $0.5^\circ \times 0.625^\circ$ and allows relatively uniform grid spacing at all latitudes.

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

Figure 5. Evaluation of the Water Scarcity Index (WSI) for Central Asia based on combination of socio-economic data for administrative units with hydrological simulations on hydrological model taking into account a various natural and anthropogenic processes. Maps on left show water scarcity index (WSI)

based only on available local water resources. The right maps account for both local water resources and river inflow from other territories.

Figure 6. Differences of 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 the Princeton University (MFD; Sheffield *et al* 2006). MFD is available globally for the 1948-2016 period at 0.25 degree of spatial and 3-hourly temporal resolutions. It was constructed by combining a suite of global observation-based datasets with the NCEP/NCAR reanalysis.

Figure 7. a. Land cover in 2014 and **b.** land cover change from 2001 to 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 to 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.

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, cyan that is practically absent in these figures); forest (2) is green; steppe (3) is gray; and semi-desert/desert (4) is brown.

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

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 the 50°N latitude in Northern Asia from 60°E to 110° E and across the 50°E from 40°N to 50°N during the post-USSR period (1990-2017).

Period/Water	Southward	annual	flux	Eastward	annual	flux
Vapor Flux	through 50°N, kg (m×s) ⁻¹			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		

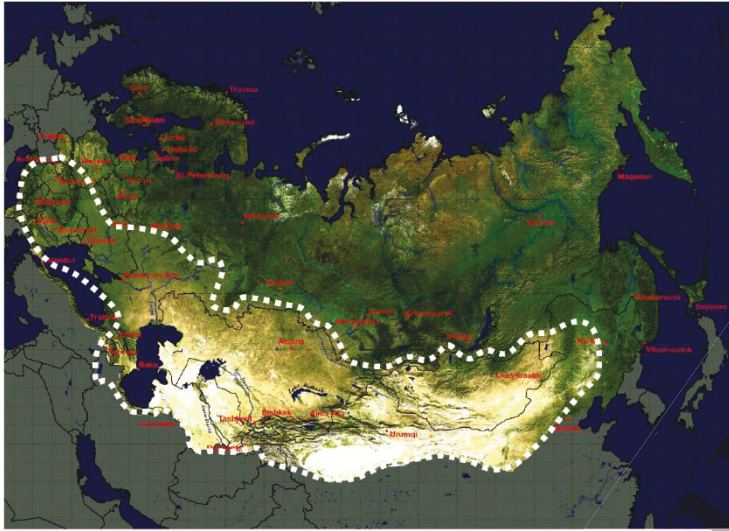
Table 3. Biome distribution (%) over the “Siberian window” (60 – 140° E and 40 – 60° N), predicted by selected CMIP5 GCMs ensemble for the 2080s.

Vegetation Type	Baseline	20 GCMs Ensemble		5 Driest GCMs Ensemble
	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:				
(a) Steppe	23.6	25.4	29.6	36.6
(b) Semi-desert	23.5	22.1	23.2	26.0
& & desert				

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Accepted Manuscript

(a)



(b)

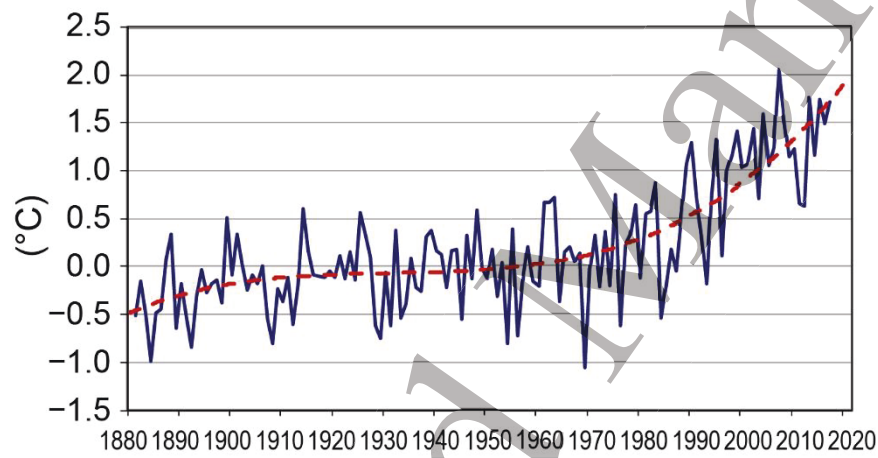


Figure 1

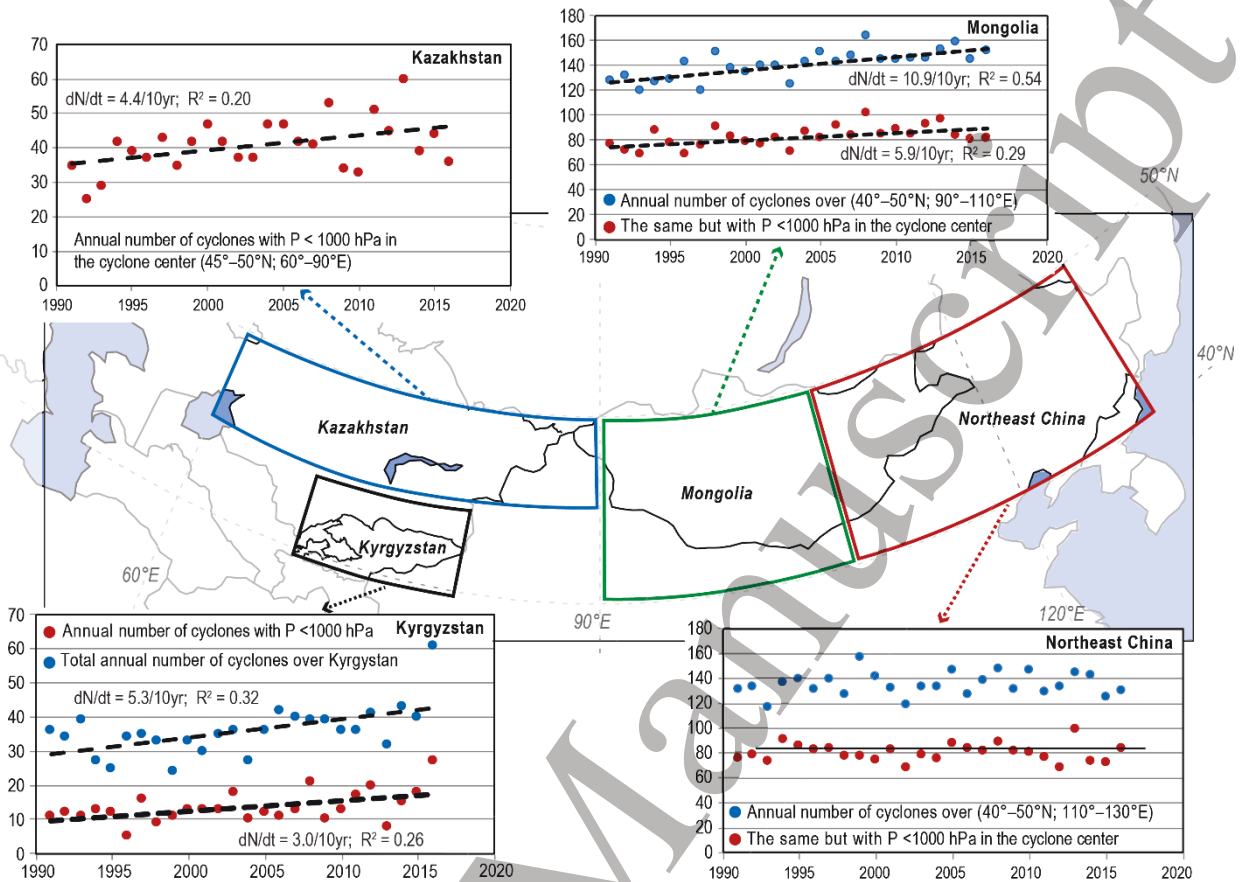


Figure 2

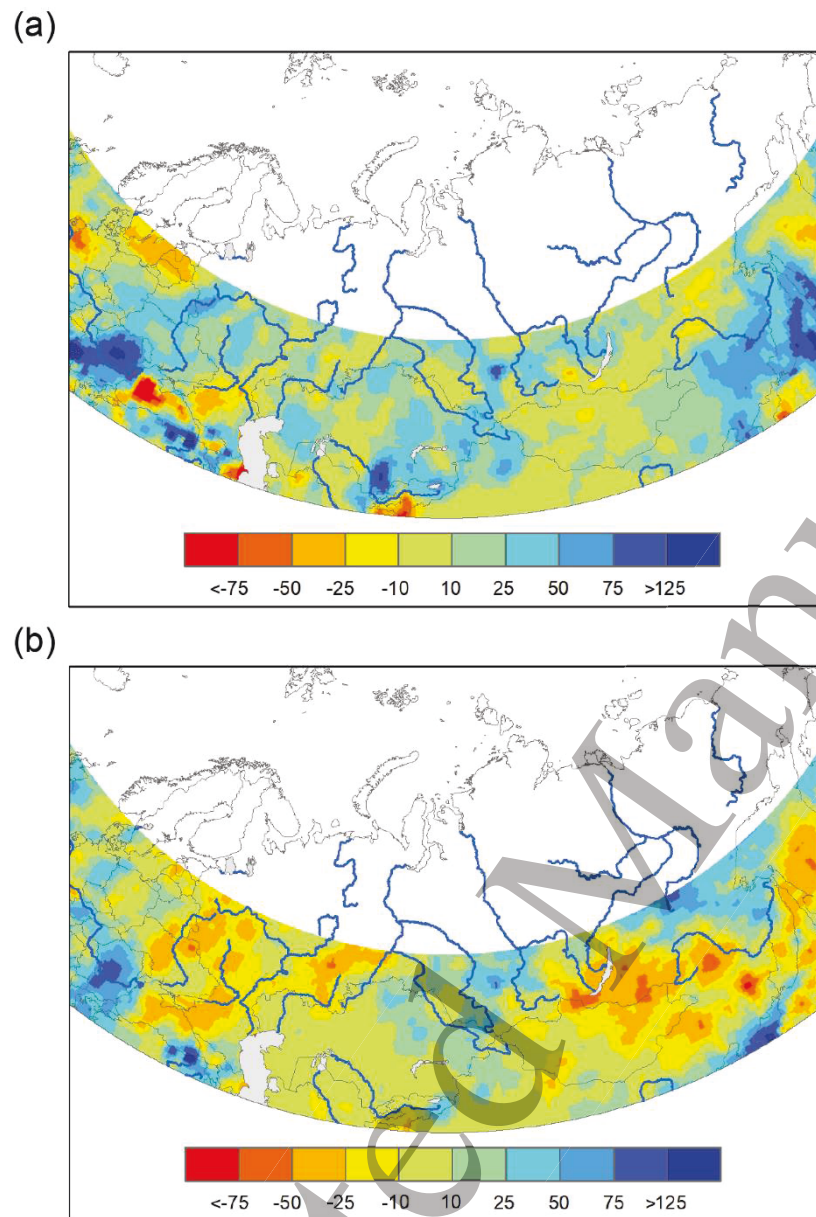


Figure 3.

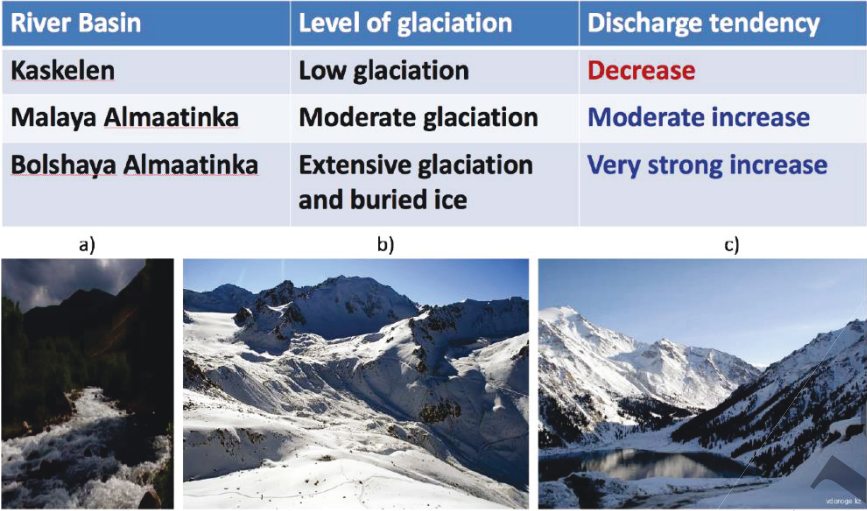


Figure 4.

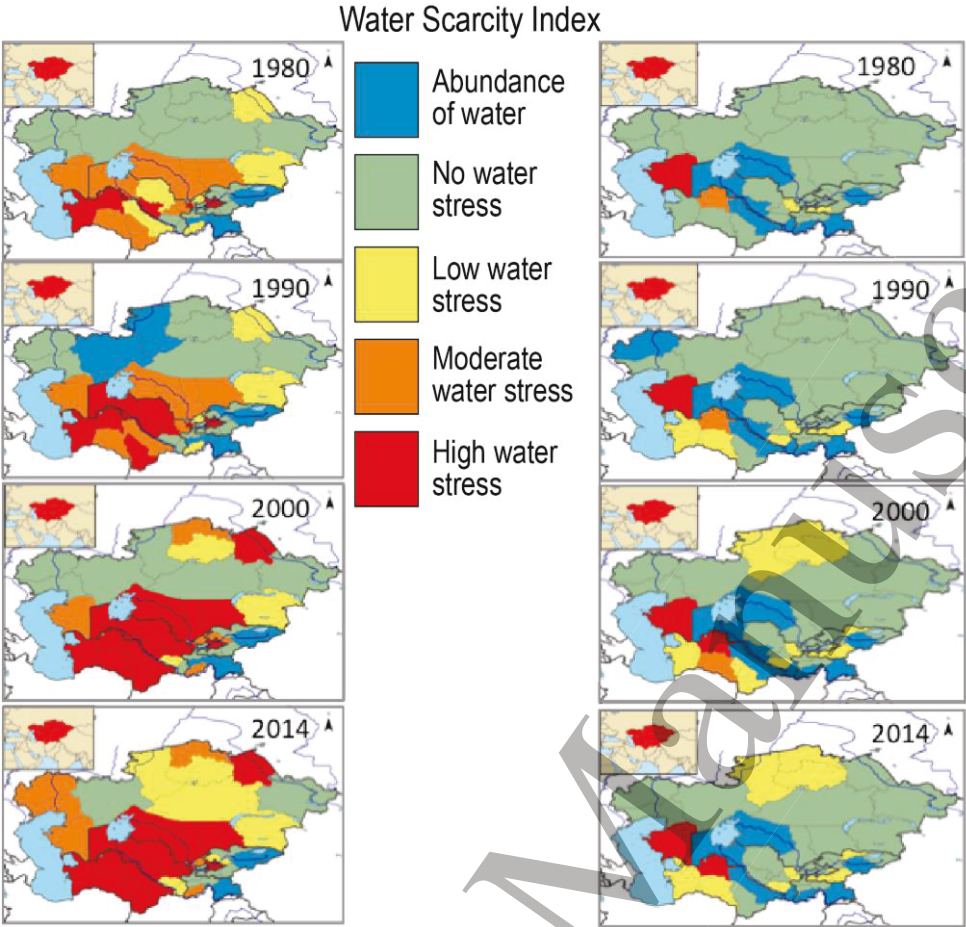


Figure 5.

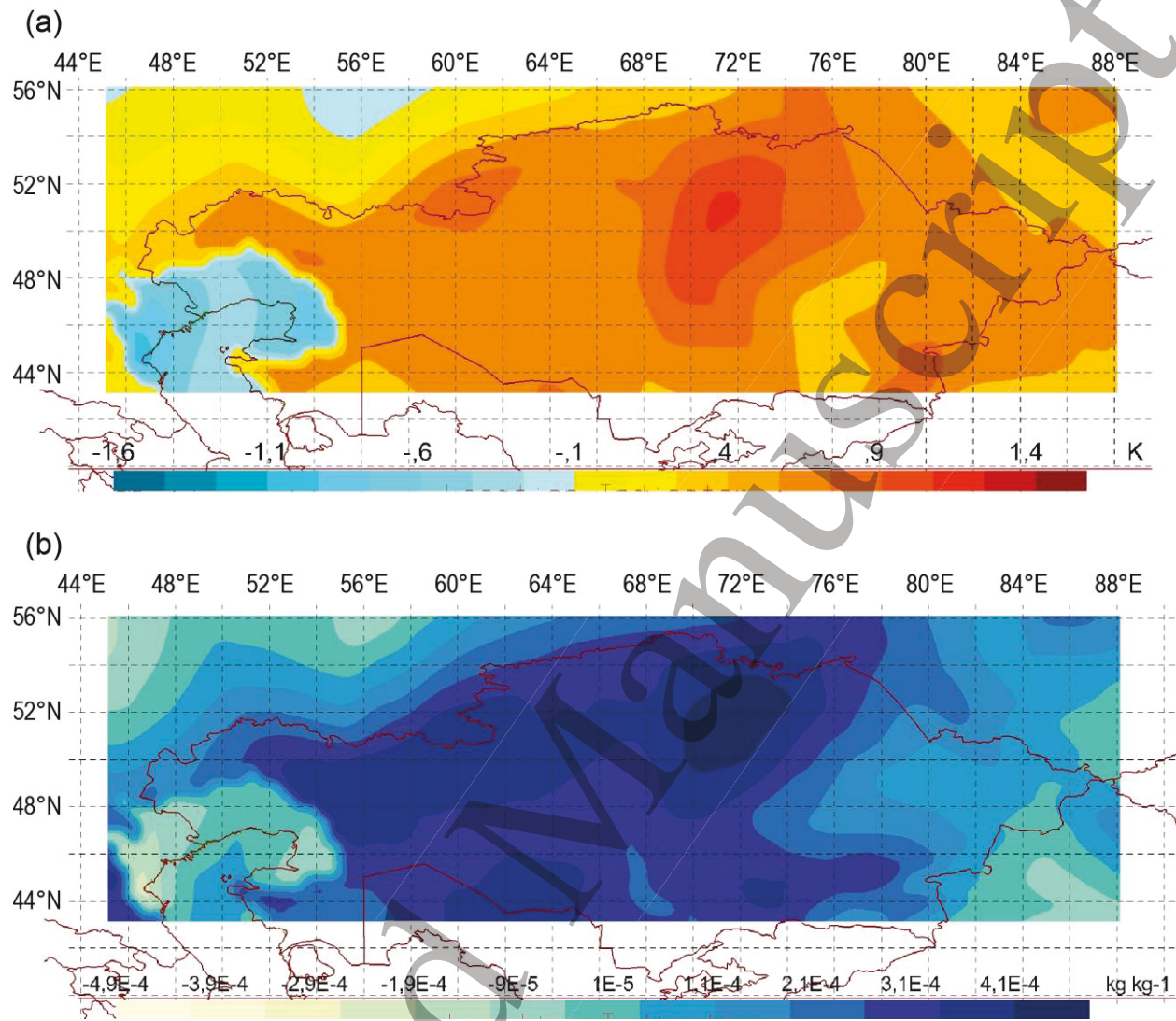


Figure 6.

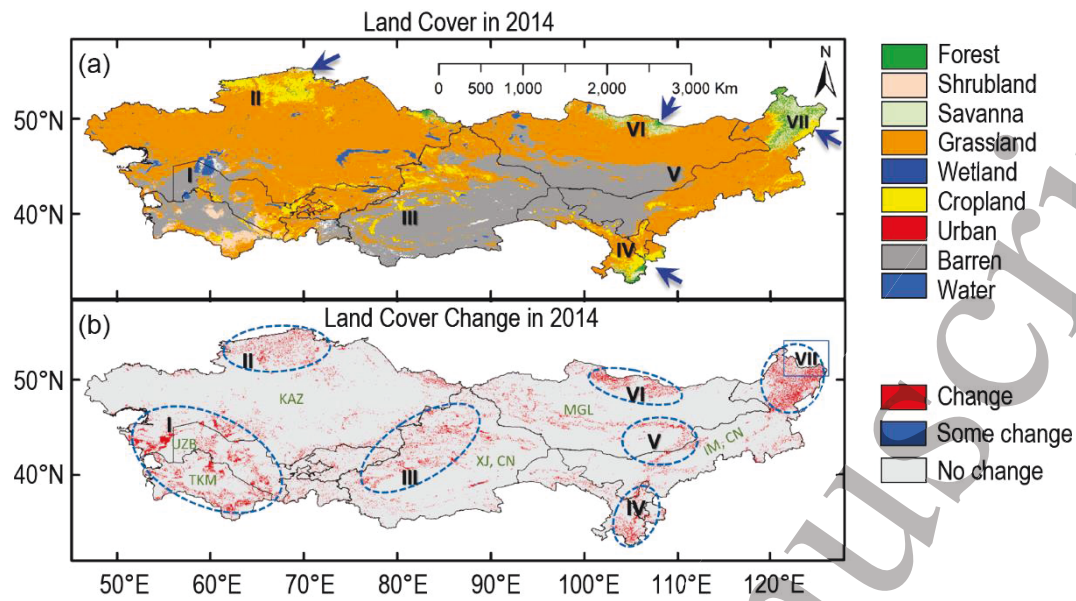


Figure 7.

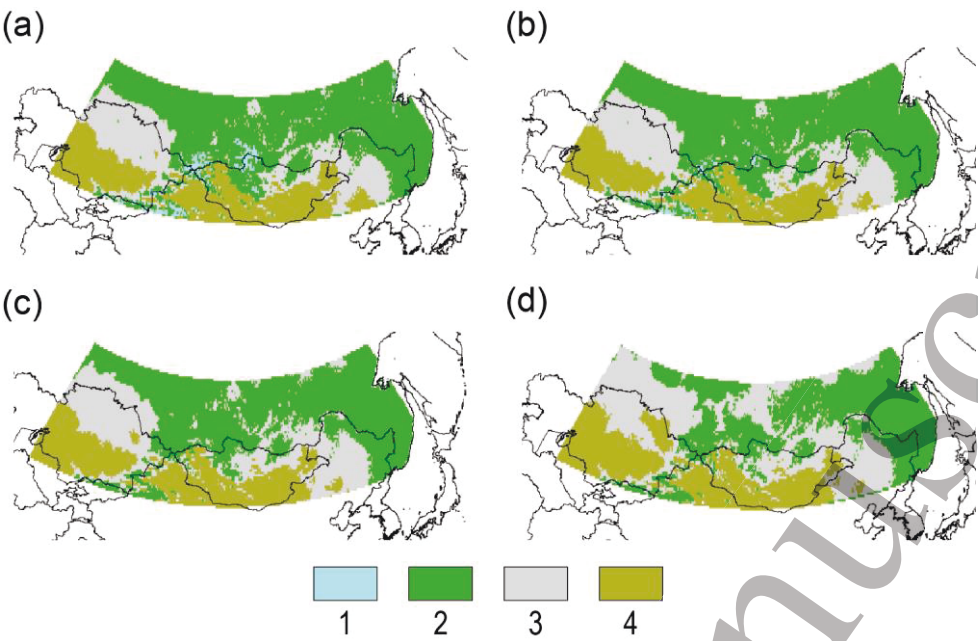


Figure 8.

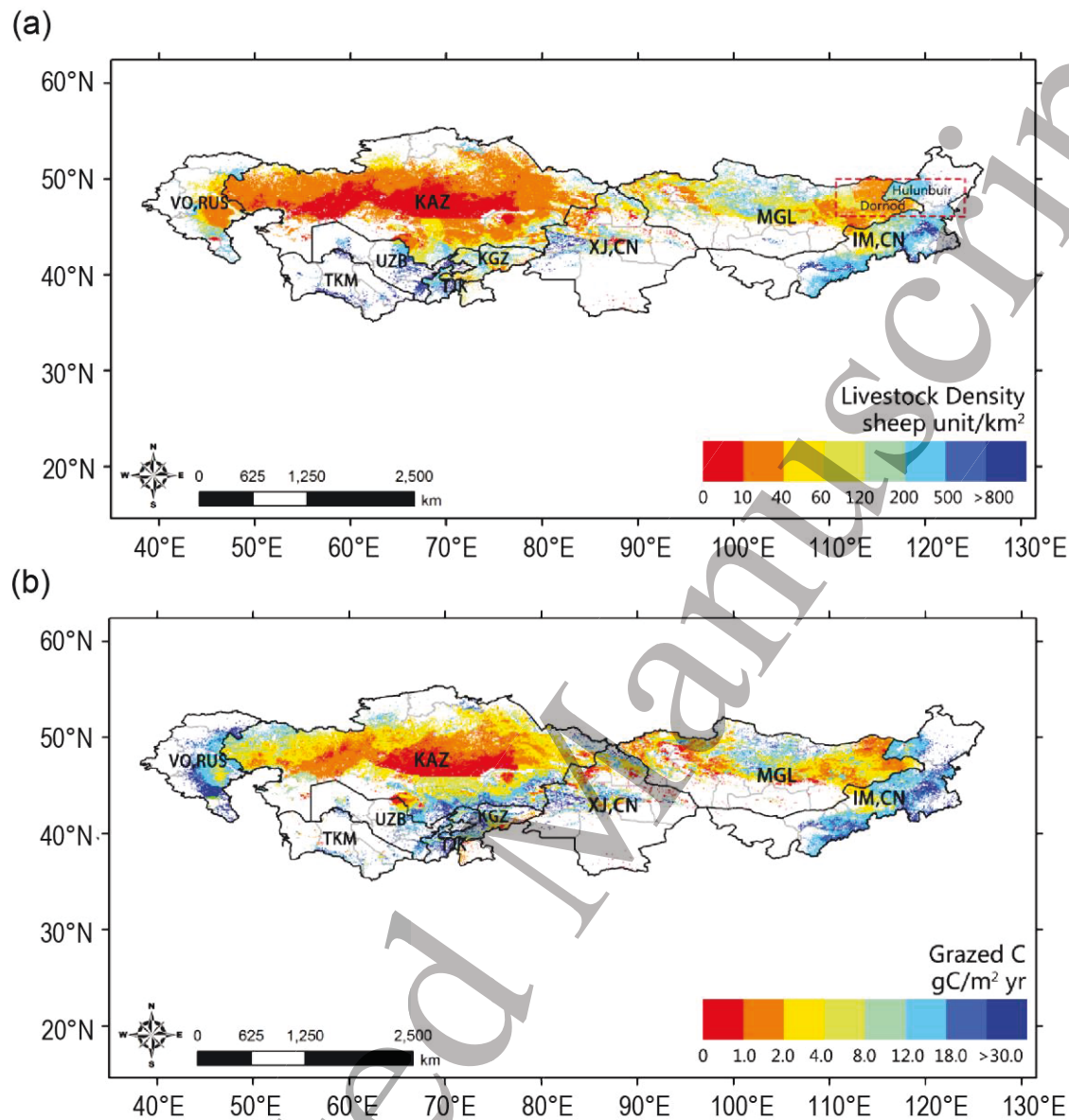


Figure 9.