Supplement Materials to "Dry Land Belt of Northern Eurasia: Contemporary Environmental Changes and Their Consequences"

by Groisman, Bulygina, Henebry *et al*.

Supplement 1. Human dimension changes in DLB.

After dramatic institutional shifts of the 1990s, the DLB region experienced major changes in the "human dimension" including changes in population, migration, urbanization, and economic development (Figure S1). While the population of the region increased by 6% from 1990 to 2016, seven out of the sixteen countries experienced a population decline. Moreover, in contrast to the overall increased global urbanization, more than half of the DLB countries experienced a declined urbanization measured by urbanization ratio (*i.e.,* the percentage of total population living in urban areas). Nevertheless, expansion of urban built-up area is ubiquitous, as all countries experienced increased urban built-up area from 1990 to 2014. Dramatic institutional shifts exerted an additional serious impact on the economy of the DLB region. Except China, Hungary, and Slovakia, all other DLB countries experienced declines of their economic development measured by GDP per capita (GDPpc) from 1990 to 2000 with the following increase from 2000 to 2016. This reflects the "lost decade" of the 1990s after the collapse of the USSR.

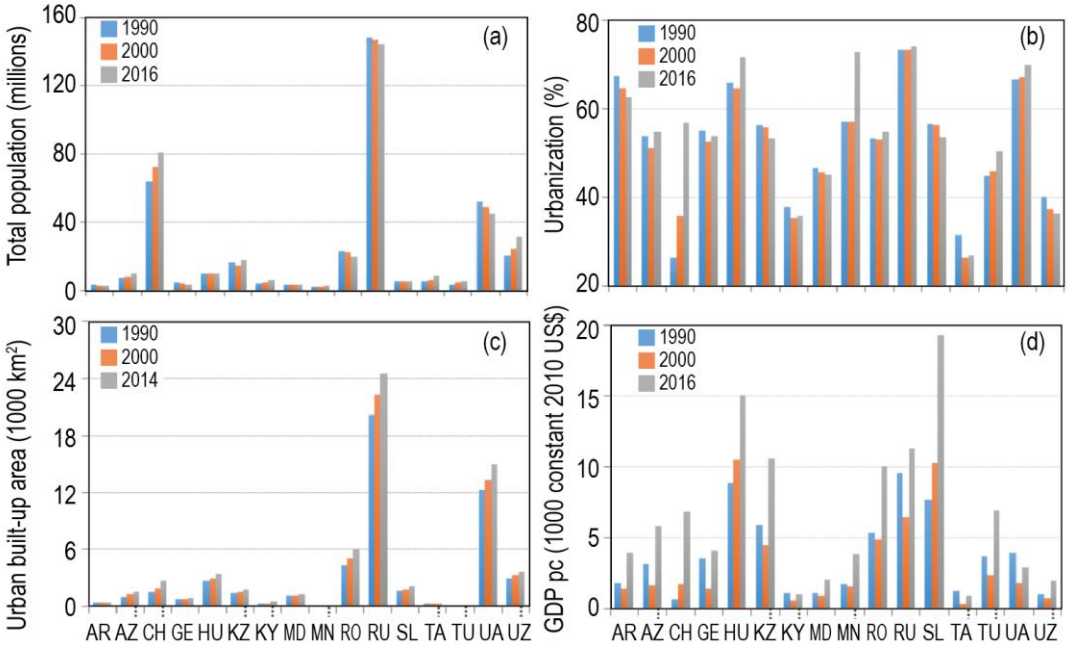

Figure S1. The human dimension data for the DLB countries: (**a**) total population, (**b**) urbanization, (**c**) urban built-up area, and (**d**) Gross Domestic Product per capita (GDPpc). Note: Total population and urban built-up area in China refer only to the Dryland Region of China, noted as China (DL), which includes four provinces: Gansu, Inner Mongolia, Ningxia, and Xinjiang. Country abbreviations are: AR – Armenia, AZ – Azerbaijan, CH –China Dry Land Region, GE –Georgia, HU – Hungary, KZ –Kazakhstan, KY –Kyrgyzstan, MD – Moldova, MN –Mongolia, RO –Romania, RU –Russia, SL –Slovakia, TA –Tajikistan, TU –Turkmenistan, UA – Ukraine, UZ –Uzbekistan. Source for (a, b, and d) is http://databank.worldbank.org/, while the urban built up areas were computed using the 250-m resolution Global Human Settlement Layer product (http://ghsl.jrc.ec.europa.eu/datasets.php).

Supplement 2. Changes in river discharge over Northern Eurasia.

These changes are presented for two large regions of the subcontinent: The Russian Federation and Central Asia. Total runoff and river streamflow (*i.e.*, discharge) are main hydrological measures for regional water budget. Annual river discharge from the Russian territory was 5% higher in 1981-2012 than that in 1936-1980 according to the Roshydromet National Assessment (Georgievsky *et al* 2014). However, this tendency is not uniform across the Russian Federation (Figure S2). Southern Siberia and steppe regions of Western Siberia show some decreases in annual river discharge during 1978-2010, compared with 1946-1977 (Figure S2a).

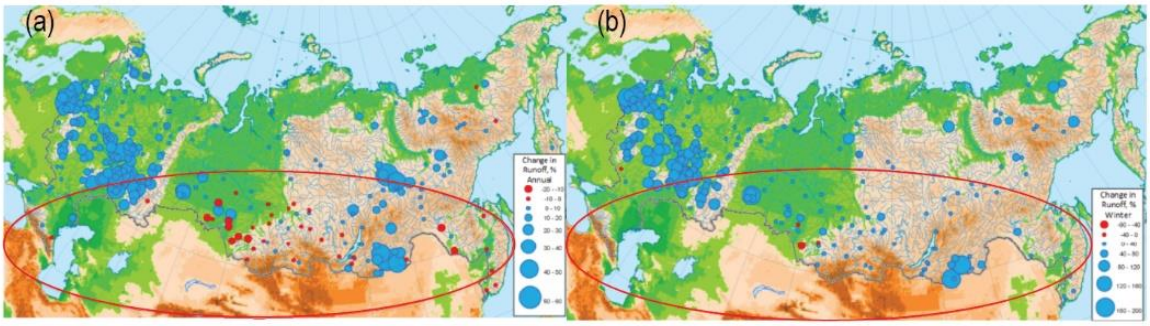

Figure S2. Anomalies of annual (**a**) and winter (**b**) runoff across the Russian Federation based on observational records from rivers minimally impacted by human activities during 1978-2010. The deviations of mean annual (a) and winter runoff (b) over 1978-2010 were calculated from mean runoff over previous observational period 1946-1977 and are shown in percent. Background colors show elevation above mean sea level with greens indicating lower elevations and oranges higher elevations.

This decline is mainly due to less runoff during spring and early summer as a result of less snow storage before spring snowmelt (Georgievsky *et al* 2014, Shiklomanov and Lammers 2013). River flow during winter demonstrates a very consistent and significant increase throughout the Eurasian DLB. Significant increases in winter runoff up to 100% have been observed in Southern Volga Basin and in the south of the Eastern Siberia. The changes in annual and seasonal discharge across Eurasia are well documented (Peterson *et al* 2002, Shiklomanov *et al* 2007, Smith *et al* 2007, Shiklomanov and Lammers 2009, Shiklomanov and Lammers 2013, Troy *et al* 2012, Holmes *et al* 2016); however, the causes of these changes remain unquantified (Bring *et al* 2016).

Precipitation, the most important water source for runoff, does not show a significant change across the DLB (see Section 2.3) to support the observed increasing river discharge. However, spatial and seasonal changes in precipitation are highly variable. In contrast, the increase in air temperature across the DLB is very consistent and is expected to continue with higher rates in the future (IPCC AR5 WG1 2013). The air temperature rise would lead to significant changes in the regional cryosphere including less

snow, thinner thickness of frozen soil in winter, deeper annual thaw propagation in the permafrost zone (deeper active layer), and melting of glaciers. Several local and regional studies have shown the important influence of changes in different cryosphere components on river discharge, including permafrost thaw (Streletsky *et al* 2015, Woo 2012), glacier melt (Bennett *et al* 2015, Bliss *et al* 2014, Section 2.4), frozen ground (Markov 2003, Kalyuzhny and Lavrov 2012, Frauenfeld and Zhang 2011), and river ice (Shiklomanov and Lammers 2014, Gurevich 2009). However, few comprehensive, larger scale studies of the region had explored the causes for the changes in discharge (Bring *et al* 2016).

The annual and seasonal river discharge for the Central Asia was examined using observational river gauge data (http://neespi.sr.unh.edu; Shiklomanov *et al* 2016). To quantify the relationship between annual river flow and climatic change, discharge data from montane rivers with minimal human impact located in the Syr Darya River Basin were analyzed. Small rivers in the Tien Shan Mountains, including the Syr Darya Upstream Basin, show significant upward trends in annual discharge since the end of 1970s (Figure S3). The seasonal runoff variation for rivers in Tien Shan Mountains have shown that the observed increasing tendencies in annual discharge are mainly due to the higher discharge rates during the spring and summer (data not shown), suggesting that snow and glacier melt due to increasing regional air temperature are the driving forces. A similar increasing tendency in river discharge starting in mid-1970s is evident for entire Syr Darya. This pattern probably results both from decreases in water withdrawals after breakup of the Soviet Union and from increases in runoff from highland basins due to regional temperature increases. In contrast, there are no obvious trends in river discharge for the Pamir Mountains and the Amu Darya River Basin (Chevallier *et al* 2014).

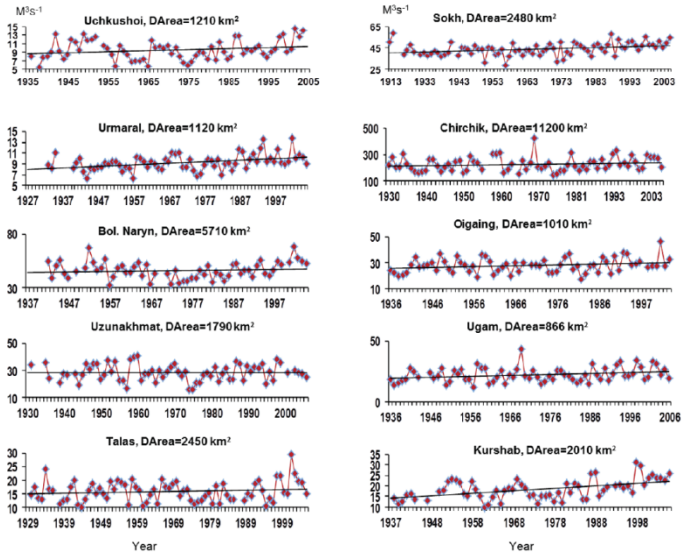

Figure S3. Variation in annual discharge ($m^3 \times s^{-1}$) for rivers with minimal human impact in the Tien Shan Mountains (http://neespi.sr.unh.edu). Note that both the inter-annual variation and the magnitude of discharge increased since the mid-1970s. "DArea" indicates the river basin area upstream of the gauge.

Supplement 3. Water balance and biosphere modeling employed for projections to the nearest decades of environmental changes in Northern Asia.

The University of New Hampshire Water Balance Model (WBM with 6' spatial resolution) was used to understand the consequences of changes in climate, water use, demography, and economy on key variables and indices characterizing regional water security. The WBM accounts for sub-pixel land cover types (with up to 0.5 km linear size), glacier and snowpack accumulation/melt across sub-pixel elevation bands, anthropogenic water use (*e.g.*, domestic and industrial water consumption, irrigation for most of existing crop types), and hydro-infrastructure for large inter-basin water transfer (e.g., Kara-Kum Channel in the Central Asia) and reservoir dam regulations (Zaveri *et al* 2016, Wisser *et al* 2013). Census data about land use, crops and irrigated area from 1980 to 2012 for the administrative units have been combined with gridded MIRCA2000 rainfed and irrigated crop data (Portmann *et al* 2010) to provide land use inputs for WBM simulations.

The biospheric model simulations of dryland distributions over Siberia were run by coupling the bioclimatic vegetation model SiBCliM (Tchebakova *et al* 2009) with bioclimatic indices and permafrost layers for the baseline period 1960-1990 and for the 2080s. In this analysis, the study area was the DLB "Siberian" window (60 – 140° E and 40 – 60° N) including bordering countries at the southern latitudes (Kazakhstan, China, Mongolia) that are expected to be significantly impacted by desertification.

Climate data of January and July temperature and annual precipitation, were collected for the baseline period 1960-1990 in the Siberian window from Reference Books on Climate (1961-2010).

Miao *et al* (2014) focused on the models of the Coupled Model Intercomparison Project phase 5 (CMIP5, www.ipcc-data.org) to evaluate different multi-model ensemble techniques to project the future temperature changes under different emission scenarios. They based on numerous findings that multi-model ensembles were superior to single models because contained information from all participating models. We calculated climate change data for the 2080s from the ensemble of 20 general circulation models CMIP5 GCMs out of 24 that Miao *et al* (2014) used in their analyses, *i.e.*, we used only those GCMS that had both RCP 2.6 and 8.5 scenarios outcomes (*cf*, Parfenova *et al* 2018).

Two climate change scenarios were used to characterize the range of climate change: mild climate change (Representative concentration pathway, RCP 2.6 scenario) and sharp climate change (RCP 8.5 scenario) (IPCC AR5 WG1 2013). A simple model averaging method was used to calculate ensemble means of 20 GCMs outputs of January and July temperatures and annual precipitation, which were used as an input to SibCliM. To characterize the possible driest conditions at the 2080s, the five driest GCMs (CanESM2, CESM1(CAM5), CSIRO-Mk3.6.0, HadGEM2-AO, NorESM1-M) were selected by evaluating

largest drylands extent under running all 20 GCMs. Here we concentrated on the dry lands, including steppe and semi-desert/desert biomes. Therefore, SiBCliM was simplified to four biomes: tundra, forest, grasslands, and semi-desert/desert. The model was based on bioclimatic indices: (1) growing degree-days, base 5°C, GDD_5; (2) negative degree-days below 0°C, NDD; (3) Annual Moisture Index, AMI, in the form of the ratio of GDD_5 to annual precipitation; and (4) the presence/absence of permafrost.

Twenty GCM-based ensemble means of January and July temperatures and precipitation indicate both temperature and rainfall increase over the DLB Siberian window by 2.6°C (RCP 2.6) and 6.8°C (RCP 8.5) in mid-winter; 1.9°C (RCP 2.6) and by 5.7°C (RCP 8.5) in mid-summer; and by 40 mm and 90 mm (in RCP 2.6 and RCP 8.5 respectively). As projected by the CMIP5 models, Siberia would have milder and more moderate climates with less permafrost coverage by the 2080s.

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