We have successfully completed the entire Year 2 planned work to analyze regional changes in land cover/use, to understand physical and socio-economic drivers of these changes and to quantify impacts of changes on LCLU, climate, demography and economy on the regional water and food security. All results obtained during this year will be synthesized in Year-3 to provide a comprehensive metrics of changes in Central Asian drylands. The list of all publications originating from this program is given below (at the end of the report). We have been working on achieving the synthesis of LCLU changes with water and land management research.

Activities: water resources.

1. Trend analysis and understanding roles of climatic and anthropogenic drivers for land cover and land use change in the region. Primarily we have used a broad collection of data from this and our previous NASA supported projects, e.g. point and gridded datasets archived at http://neespi.sr.unh.edu including observational, census, climate re-analysis and modeled data;
2. Quantification and understanding of changes of water availability and food security through regional-scale analysis of multiple indicators characterizing water availability, land use and food production;
3. Integration of new functionality and components in the UNH hydrological model - WBM-TrANS to address needs of this project in understanding of roles of water use and re-use and to improve runoff simulation in mountain regions where most of regional water resources is generated;
4. Incorporating new model simulations and new products (i.e. NASA MERRA-2) into our Regional Integrated Mapping System (RIMS- http://neespi.sr.unh.edu/maps where they are accessible for visualization and many other manipulations for other project collaborators and scientific community.

Findings: water resources.

Analysis of potential drivers of regional land cover and use change

We have analyzed multiple climate characteristics from ground observations (station data, UDEL monthly gridded fields over 1901-2010), re-analysis products (NCEP – 1948-2015; MERRA – 1979-2015) and WBM-TrANS outputs (soil moisture, runoff, evapotranspiration, irrigation and other anthropogenic water use) in relation to remote sensing vegetation data (MODIS 2001-2014), census data for land and water use (1980-2013) to determine contribution of tested climate drivers to significant changes in regional vegetation found by remote sensing team of this project some of which is summarized in (deBeurs et al, 2015). We found that there is a general tendency to drier conditions in most regions of Central Asia due to lower precipitation and higher temperature leading to less soil moisture during vegetative period impacting not only changes in hydrological cycle, but in vegetation dynamics and land cover change trends. Figure 1 demonstrates changes in simulated with WBM-TrANS soil moisture based in
NASA MERRA reanalysis climate data over 1980 – 2014. The total change in soil moisture for the period averaged over entire Central Asia is 9.1 mm. It should be noted that there are some spatial mismatch between extreme end-members of declines in vegetation (deBeurs et al, 2015) and soil moisture. Some decrease in area of arable land found from census data could also contribute to the reduction in vegetation according to MODIS data analysis.

Figure 1 Map shows trend (annual slope) in soil moisture simulations with WBM-TrANS using MERRA climate data estimated from simple linear regression over 1980-2014.

Assessment of water availability and security indicators.

We applied the University of New Hampshire - Water Balance Model - Transport from Anthropogenic and Natural Systems (WBM-TrANS) to understand the impacts of changes in climate, water/land use, demography and economy on water availability and security through analysis of various physical parameters and indicators (indices) characterizing water resources and water use. The model accounts for sub-pixel land cover types, glacier and snow-pack accumulation/melt across sub-pixel elevation bands, anthropogenic water use (e.g., domestic and industrial consumption, and irrigation for most of existing crop types), hydro-infrastructure for large inter-basin water transfer (e.g. Karakum Canal) and reservoir/dam regulations. A suite of historical climate re-analysis (MERRA, NCEP, ERA-Interim) and temporal extrapolation of MIRCA-2000 crop structure datasets applying census based time series of land use has been used for this project. A preliminary analysis of the model simulation results covering time series of the past 30 years has shown significant spatial and temporal changes in hydrology and water availability for crops and humans across the region due to climatic and anthropogenic causes. We found that in spite of some decline in water use in 90’s after USSR breakup the regional situation with water security has significantly deteriorated by 2014, if compared with 1990, due to climatic changes, population growths and migration along with industrial development. The Figure 2 shows several indexes and variables characterizing the water availability and water use in 1990 and 2014. Evolution of changes in regional water scarcity from 1980 to 2014 is given on Figure 3. The mapped Water Scarcity Index (WSI) combines information about water abstractions and water availability. It is defined
by the intensity of use of water resources, i.e. the gross freshwater abstractions as percentage of the total renewable water resources or as percentage of internal (runoff generated within given region) water resources. The calculations of WSI (Fig.2) were made based on WBM-TrANS simulation outputs using only locally generated water resources (left plots) and total available water resources including inflow (right plots). The results were aggregated for administrative units.

These water-related regional indicators will be integrated with other variables representing regional changes in climate, land cover, demography and economy to characterize the region in terms of water and food security (Objective 3 of the overall project).

Figure 2. Variables and indices characterizing regional water availability aggregated for administrative units. Water Availability Index (WAI) compares all available water resources to the water demands (i.e. domestic, industrial and agricultural). Water availability per capita was estimated for total (b) and local water resources (c). It should be noticed that when the total water resources used, results are usually overestimated in regions with large transient rivers. Water availability per crop is based on total water resources (d). Irrigation water demand maps (e) show average annual water use for 1 grid cell (6′x6′ ~90 km²) for irrigation. Left maps show all these variables in 1990 and right maps for 2014. There is general
tendency towards decline in water availability despite significant socio-economic transformations in the region in 90s.

![Figure 3](image)

Figure 3 The mapped Water Scarcity Index (WSI) is defined by the ratio $\text{WSI} = \frac{W}{Q}$, where $W$ are the annual freshwater abstractions and $Q$ is the annual available water. The severity of water stress is classified in several categories (see legend). This indicator neglects temporal and spatial variations as well as water quality data. The calculations of WSI were made based on WBM-TrANS simulations using only locally generated water resources (left plots) and total available water resources (including inflow).

**Model development: water resources.**

In order to address sub-national scale analysis of water indicators with land use/change and socio-economic data, during the second project year we have developed a new functionality for the UNH hydrological model WBM-TrNS to combine land and water use census data for administrative units produced by this project local collaborators. This data includes a suite of high resolution spatial datasets on irrigated and rainfed crops for all 64 crop types that can be modeled by WBM-TrANS based on MIRCA-2000 crop management algorithms ([https://www.uni-frankfurt.de/45218023/MIRCA](https://www.uni-frankfurt.de/45218023/MIRCA)). We combined this data with the annual regional census reports (sub-national scale) for land and water use to adjust major crops and irrigated areas available in MIRCA for each individual year during 1980-2013 assuming that in
2000 the census and MIRCA data are consistent. Thus, the gridded time series of major crops for the Central Asia were established and used in the hydrological model to better estimate changes in water balance components and agricultural water use. As an example, Figure 4 shows Central Asian countries and sub-country administrative units with inserted plots which demonstrate several trajectories of changes in area of irrigated lands over 1980-2013 years. The changes in irrigation are highly variable across the region due to different socio-economic, demographic and political transformations.

Additional modules of WBM-TrANS have been developed to simulate water withdrawal for domestic, industrial and livestock demands using country-based statistical socio-economic information along with spatio-temporal data on population density, industrial structure, and livestock distribution. Thus, the present version of the hydrological model takes into account all major anthropogenic impacts, including effects of reservoirs and large inter-basin water transfers, and can be used for more reliable assessment of regional water security on sub-national (administrative units) scales.

Data acquisition, integration, collaboration and community outreach progress

In this reporting year we have continued to acquire and update/maintain existing time series data sets needed for this project. This project data management framework is based on NEESPI RIMS tools and software components developed for out prior NASA
funded projects (http://neespi.sr.unh.edu). All model output data (runoff, discharge, evapotranspiration, soil moisture, reservoir storage, gross irrigation demand, domestic water demand, industrial water demand, livestock water demand, reservoir storage, fraction of snowmelt, rainwater and glacial melt) have been uploaded to NEESPI RIMS system to be analyzed along with climate, LCLUC and socio-economic data collected for this project spatial domain. All new regional data for Central Asia including 270 data layers were tagged by NASA-CA project keyword to facilitate their search in NEESPI RIMS. Figure 5 shows screen shot from our project website with map of long-term annual river runoff for the Central Asia (entire Ob river basin was included in hydrological domain) and data search insertion (to the right) with list of project data. The map clearly demonstrates areas of runoff generation in Central Asia, which are mainly located in Tajikistan and Kyrgyzstan.

Figure 5. Screen shot of the project website (http://neespi.sr.unh.edu/maps/) shows map of long-term mean annual runoff simulated with WBM-TrANS based on MERRA climate data over 1979-2015. Insertion to the right shows the data search engine for project specific (NASA-CA) data.

Land use and land cover characterization and its impacts conducted by the Sokolik’s group.

We have reconstructed the historical dynamics of LCLUC over the Central Asia study domain. The reconstruction involves the development of maps of land use/land cover classification using the USGS-based recommendation. These reconstructions have been incorporated into two different models WRF-Dust and WRF-Smoke and have been used to study the climatology of the dust and smoke emission, respectively (Longlei and Sokolik, 2016) and (Park and Sokolik, 2016). These are the first assessments of the
climatology of dust and smoke emissions that explicitly take into account the LCLU dynamics. The impact of dust and smoke on the vegetation growth are being assessed. The vegetation growth are being affected via the reduction of PAR and due do direct deposition of dust particle on vegetation.

Prof. Sokolik and Collaborator Dr. Abdulaev have developed a new approach to reconstruct the climatology of dust storms in Tajikistan by integrating various types of ground-based observations. This work will result in a fist climatology of dust storms. Dr. Abdulaev is currently working on the assessment of the impact of dust storm on the cotton production in the region.

Profs. Henebry and DeBeurs have been working on the analysis of the impact of LULC dynamics on the surface reflectivity. Their results are in the preparation for the publication and will be published during Year3 of the project. Some results of the analysis of significant trends 2001-2014 across Central Asia & vicinity for MODIS NBAR Tasseled Cap brightness and MODIS White Sky Albedo in the visible, near infrared, and shortwave bands are presented below. In de Beurs et al. (2015) the MODIS NBAR Tasseled Cap brightness component was analyzed for significant trends from 2001-2013 using the nonparametric Seasonal Kendall test. We have extended that analysis here in two ways. First, we recalculated the trends through 2014. Second, we analyzed the MODIS White Sky Albedo products from MCD43C3 for visible, near infrared, and shortwave bands, separately.

![Figure: 6 significant trends in the MODIS White Sky Albedo for (top) visible bands, (1st middle) near infrared, and (2nd middle) shortwave bands. The trends for the MODIS NBAR Tasseled Cap brightness component (bottom) for comparison. Significant (p≤0.01) trends are displayed in purple for increases and orange for decreases. Spatial resolution of the data is 0.05°.](image)

In Figure 6, note that the TC brightness component shows an abundance of significant positive trends across Central Asia and very limited decreasing trend in Central Asia, though there are plenty of decreasing trends in TC brightness outside of Central Asia. In contrast, the visible WSA shows far fewer significant positive trends and
some expansion of decreasing trends, e.g., around Lake Balakhash in Kazakhstan. NIR WSA has a spatial pattern of increasing trends that is distinctly different, though related, to the trends in visible WSA. There is a large area of decreasing albedo in western Turkmenistan that is captured more by NIR WSA and TC brightness than visible WSA. The significant trends in shortwave WSA are less extensive than TC brightness and possibly less noisy. Given the regional droughts & heatwaves over the past decade (e.g., Wright et al. 2014), the extensive increase in albedo is not surprising. More interesting are the areas of decreasing albedo that are scattered across Central Asia. Many of these areas are likely due to agricultural expansion or intensification; however, we are waiting on the results from the land surface phenology (LSP) modeling to confirm these changes.

Dr. Shkolnik has been working on assessments of the climate change on the agriculture productivity in the region. The results of his work were presented at the international conference and published in the peer reviewed literature. His report is provided below as an Appendix 1.

**Economics component.**

Prof. Shemyakina has conducted the research on a comparative analysis of the ongoing land privatization processes among the countries in the Central Asia study domain. She has presented her work at our group meeting that has been conducted via telecom. This work will be completed and results will be submitted for publication in Year 3 of the project. Prof. Laruille has been working on a comparative analysis of the water privatization processes across the Central Asia domain.

The major findings of these work are summarized below.

Central Asia undergone a significant change in the structure of land ownership and the land reform since 1991. Land reform in Tajikistan has been hampered by the civil war (1991-1997). Kyrgyzstan has been the most aggressive in pursuing land privatization and promoting market reforms. Land reforms in Kazakhstan and Turkmenistan appear to have followed a similar path, with Turkmenistan more focused on smallholder farms and Kazakhstan giving a preference to development of large commercial farms. Uzbekistan has followed a step-by-step reform with few realized changes, with most of the control over land and production retained by the government.

In the region, substantial improvements in labor productivity in agriculture and an increase in agricultural output came from distributing land to small landholder farmers’ households, for individual farm leases and private household plots. However, these productivity improvements were hampered by a host of things. These include but are not limited to government mandates and production quotas (Tajikistan, Turkmenistan and Uzbekistan), allocation of land of differential quality – according to the type of ownership – private or lease, with poorer quality land given for private ownership; "requests" to "voluntarily" lease allocated farm land back to large commercial farms; poor availability of credit for small farms; indebtedness of dehkan and collective farms in Tajikistan; poor access to machinery for cultivation and high cost of renting it that drains profits from smaller farms; poor information on updates in the land laws and other legislation in all of the countries and poor institutional support.

Furthermore, in all countries but Kyrgyzstan, land cannot be bought, sold or exchanged, it can be inherited. In Kyrgyzstan, one can purchase a parcel of land, with certain restrictions on an individual’s place of residence, where urban dwellers and legal
entities are not allowed to purchase land; and where an individual can only purchase a pre-set by an official parcel of land without being able to choose a specific type of land, e.g. irrigated. This policy has been known in Soviet times, as “purchase with a weight” (“pokupka s nagruzkoi”), where a product in demand is being bundled for sale with a poorly moving product.

In all of these countries, land rights are incomplete. There are multiple and ever changing restrictions on the rights of use, sale and ownership of land. Most of the states, except Kyrgyzstan, retained control over rights on sale of agricultural land, when land is allocated for leases, the state may start with giving only short-term leases of land that are contingent on the proper use of land, e.g. cultivation, improving the land, investing in irrigation systems, etc. Short term leases and inability to sell land restrict access to loans (as the land cannot be mortgaged), and therefore, limit investment in land improvement, as the majority of population have a low disposable income and limited savings. These limitations hamper potential for further increase in agricultural production, and may impact food security.

In all of the countries, improvements in Gross Agricultural Output (GAO) were driven by the production by private household plots and private farms. Private household plots appear to be a most productive (per unit of land) type of agricultural enterprise. They are not typically subject to government mandates on production of certain crops, and thus, can use market prices and relevant agricultural technology to improve their productivity.

In all of the countries, large commercial farms are the least productive. In some of the countries, and more specifically, Kazakhstan, re-organization or de-statization of large commercial farms was not favored by government officials who perceived “large” as being productive due to the economies of scale. Despite of limited land reform and lack of substantial gains in productivity, welfare of rural residents in Kazakhstan improved, potentially driven by favorable market prices on oil and wheat.

In Tajikistan, Turkmenistan and Uzbekistan, agricultural production is not driven by market prices for inputs and output and land productivity. All of these countries issue production quotas for cotton and wheat for private and dekhan farmers. The resulting output is then acquired by the government (Turkmenistan and Uzbekistan) and by lending and marketing entities, so called “futurists” (Tajikistan), typically at prices well below the market prices for the products. In Turkmenistan and Uzbekistan though, farmers get substantial subsidies from the government in purchase of seeds and other inputs. Farmers pay multiple taxes, which is some cases, as in Turkmenistan, could be waived for the new leaseholders (5 year).

Prof. Laruelle has been working on the comparative analysis of the water privatization processes across the Central Asia. The major findings of this work are summarized below.

In theory, the Central Asian region—Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan—should not endure large water shortages: Central Asia is sufficiently endowed with water (20,525 m³/year) as compared to the Near East (7,922) or Northern Africa (2,441). But this water is unevenly distributed: the two water towers of Kyrgyzstan and Tajikistan control a vast share of the flows of two of the great rivers, the Amu Darya and the Syr Darya, while the three downstream countries—Kazakhstan,
Uzbekistan and Turkmenistan—require large amounts of water to irrigate their arable land.

Moreover, technical and economic causes for water mismanagement should not be neglected. Central Asian countries have to manage both their Soviet legacy—with an economic development centered on large energy-consuming industries—and the paradoxical effects of the transition to a market economy. Ageing installations and obsolete distribution networks have required costly investments that the states could not finance without international aid. Their markets, however, have proved relatively unattractive for potential foreign investors: administrative apparatuses are riddled by corruption, governments keep electricity prices low to avoid social discontent, and bankrupt companies or others considered strategic are reluctant to pay their electricity bills. In addition, the established elites pay little attention to long-term questions of profitability or sustainable development; they privilege quick revenues in foreign currency and therefore favor centralized, large-scale hydroelectric projects in which they are more likely to gain from bribery. Lastly, the energy choices made by the Central Asian governments are highly politicized: they often rely on rationales that valorize national sovereignty without much connection to economic rationality. The complexity and diversity of these problems, compounded by the further deterioration of interstate relations, as well as the escalation in official discourse, which systematically associates energy negotiations with state security, makes finding nuanced decisions particularly difficult.

Water use in Central Asia is largely an issue of misuse, and therefore of governance. Household and industrial water usage is largely inefficient, but waste appears to be most rampant in the agricultural sector. The Soviet Union was known for its water-intensive agriculture and using chemical pollutants that depleted the soil, leading to the infamous Aral Sea catastrophe. But the newly independent Central Asian states are pursuing policies similar in many points to Soviet policy, involving the increase of agricultural production (cotton, rice, wheat) and arable lands in the name of food security. However, the deterioration of irrigation facilities due to lack of resources invested by the independent states and permanent postponement of maintenance have aggravated the situation: today, between 30 and 60 percent of the water flows into poorly maintained irrigation channels and is lost through evaporation or leakage. Individual farmers, often on the brink of food insecurity, tend to clandestinely divert water in order to irrigate sections of private land, and collective farms illegally irrigate new plots that often go unreported to authorities. As a result of decades of mismanagement, an increasing amount of land is contaminated with salt, and hundreds of stagnant pools of water, polluted groundwater, or artificial lakes have been created, contributing to a decline in crop quality, with a massive impact on health.

Such levels of water mismanagement are unique in terms of scale: Central Asian states consume more water per capita and per dollar of GDP than residents of any other region on the planet. Turkmenistan and Uzbekistan consume more than twice as much water as the United States, which itself cannot be considered a model. With just 700,000 inhabitants, water consumption in Ashgabat, the capital of Turkmenistan, is equivalent to that of the city of Chicago, which has a population of 2.7 million. With a similar climatic environment and equally developed agriculture, Israel consumes only about 5 percent of the water that Turkmenistan does.
The use of water for agricultural purposes largely depends on the reforms of land rights and privatization processes. All of the five countries created Water Users Association (WUA), a non-profit organization that is initiated, and managed by the group of water users along one or more hydrological sub-systems regardless of the type of farms involved. On the paper, WUA should promote democratic practices of decentralization, user participation and empowerment in a market-oriented context where users pay a fee to access water and should in theory use it efficiently. However, very few of these countries make figures of water use available, and for sure those accessible are not considered as reliable, which limits our ability to analyze the current transformations of water uses.

WUA in Central Asia have limited rights: they cannot control water utilization, distribute water, nor approve quotas of water for users. These decisions fell under the umbrella of the local administration or hokimiyat, who give priority to well-connected farmers and do not distribute water quotas in an equitable and accountable way. While central and local state institutions continue to take the main decisions, they transfer cost of irrigation and maintenance of irrigation structures (main canals as well as secondary and tertiary canal systems) to the farmers via the WUA. Associations are cleaning canals, making repairs, and are responsible for collecting Irrigation Service Fees (ISF). This fee is charged to all members of the association, as well as to farmers who are not member but use water within the hydrological boundary of the WUA—membership is done on a voluntary basis. Members pay on average 20 to 50 percent less ISF for water delivery than non-members. However, WUA cannot really assess the water needs to many of its non-members who owns small private plots (0.10-0.50 ha each) or dehkan farms: as the water intakes are not measured, these farmers can misuse water without being penalized. Last but not least, WUA cannot act against those who refuse to pay, and therefore it seems a growing number of farmers refuse now to become member or to pay the fee, especially those located at the closest to the main canals.

The lack of secure private property of farmlands impacts water reasonable use. Farmers are not willing to pay for the costs associated with water delivery infrastructure and do not want to invest time and labor into canal maintenance. In many aspects, water decentralization in Central Asia is an illusion: in fact it is a process of the state stopping taking responsibilities for water management and passing the costs on to the farmers. But the cost of maintenance is higher than the income from irrigated agriculture, which is bough by the state at an artificially low price. The lack of affordable agro-inputs would help farmers accepting the notion to pay for water delivery. Indeed, individual private plots continue to be the most productive sector of the national agriculture, while it is the one making intensive use of water and inputs, largely diverted from the other sectors. As the result, the overtly centralized mechanisms of water management in Central Asia is counterproductive.

3. Publications that have resulted from Year2:

Abdualev, S., and I.N. Sokolik, Towards developing a climatology of dust storms in Tajikistan. GT Report, 2016, (also the paper has been submitted for the publication into the J. of Arid Environment)
McClelland J. W., S.E. Tank, R.G.M. Spencer, and A.I. Shiklomanov, 2015. Coordination and sustainability of river observing activities in the Arctic. *Arctic* VOL. 68 (SUPPL. 1) 2015 http://dx.doi.org/10.14430/arctic4448


5. Presentations in Year 2.

Shiklomanov A., A. Prusevich, I. Sokolik, R. Lammers. Contemporary changes of water resources, water and land use in Central Asia based on observations and modeling. AGU Fall Meeting, 12-16 December 2016 San Francisco, USA.


Appendix 1.

Progress report
Voeikov Main Geophysical Observatory (MGO)
Collaborator: Dr. Shkolnik

Task: Perform an analysis of exploring how projected climate change will affect the production of cotton and wheat, e.g., via changes in temperature and precipitation during growing seasons.

1. Brief of climate characteristics of Central Asia

The natural geographical area of Central Asia is located in the center of vast territory of Eurasia and includes the southern part of the Republic of Kazakhstan, as well as the territories of other republics, such as Kyrgyzstan, Uzbekistan, Turkmenia and Tajikistan. The territories appear to be endorheic extremely dry area of the cut-off Aral-Caspian basin. A wide variety of landscapes and weather conditions in that area is associated with large territory of Central Asia (about 1,500 km from north to south and 2,500 km from west to east). There are massive world’s highest mountain ridges. Large internal water bodies, particularly, Caspian Sea have significant influence on the regional climate.

The geographical location of Central Asia in the center of Eurasian continent, its remoteness from the oceans, provides the regional climate with some features which
allow referring to the major part of the territory as an area of continental subtropical climate.

The common features of all climatic and landscaping zones of Central Asia are high temperatures in summer as well as frequent and long-lasting droughts. These are major reasons for the existence of vast deserts in the region area. In the plain lands of Central Asia the annual precipitation amounts range from 70-75 to 300-400 mm. Average annual amplitude of temperature is found within the range 38-40°C in the north and 28-30°C in the south. Sharp fall in the annual amplitude of temperature southwards from 45°N is caused there by more intensive insolation and less severe thermal regime during winter as compared with northern regions. The largest variation in the amplitude of daily temperature cycle occurs in the end of summer (August/September) when it is 12 to 13°C in the north and 18 to 20°C in the southern areas. In the individual year or day amplitudes of temperature could be much larger due to high- frequency climate variability. During all seasons high wind velocities can occur due to outbreaks of cold air masses. These outbreaks are often accompanied by frosts.

Climatic regimes of the northern and southern parts of the territory of Central Asia differ significantly. For the north part which is influenced by the winter Siberian anticyclone, severe and long winters with continuous frost periods and sustainable snow cover are typical. Mean monthly temperature of January varies from -16°C in the north up to -7°C in the south. The southern part is characterized by mild winters with unstable snow cover and frequent air temperatures crossing freezing point. The mean January temperature there varies from -7°C in the north to +4°C in the south. The winter temperature regime is significantly affected by the Caspian Sea, on the tideland of which temperatures are 5-7°C higher than that in the adjacent desert areas. Impact of Aral Sea reveals itself only in the narrow shoreline near the northern Aral where temperature usually 4-5°C higher as compared to temperatures in other regions.

Climatic conditions of warm period also exhibit large interregional differences. In the northern part of Central Asia, summer is significantly shorter than that in the south with lower temperatures and moderate amounts of precipitation. However, despite the fact that maximum of precipitations happens in summer time, those regions sometimes suffer from long and intensive droughts. According to observations, there is at least one drought per 60 days. Moreover, a number of days with drought in particular years ranges from 20 to 120. Average temperature of July varies from 20-21°C in the North to 26-27°C in the South.

In the southern part of Central Asia temperature of July rises from the north to the south from 27-28°C to 31-32°C. The highest air humidity is observed in winter and spring when precipitation amounts from 70 to 90% of its annual amount. The maximum precipitation falls on March and April. Extreme shortage of precipitation occurs during the crop season from June to October, when there is almost no rain. Rare showers have scarce practical importance. While the whole territory typically undergoes extreme droughts, mountainous areas are characterized by satisfactory humidification. On the windy slopes, there falls a large quantity of precipitations with its annual amount in some locations exceeding 1500-2000 mm.

2. Impact of climate change on agroclimatic conditions for cotton growth in Central Asia
2.1. Current agroclimatic conditions for cotton growth

Highlands among the deserts of Central Asia are “accumulators” of water and supply water to thousands of mountain streams which provide favorable conditions for highly productive irrigated cropping. Abundance of warmth and light, along with long-lasting crop season, allows one to grow such a thermophilic plant as cotton.

Agroclimatic resources of the territory are usually estimated using agroclimatic indicators which define conditions of heat and water availability during the crop season. Cotton is an irrigable crop. Provided that sufficient irrigation is available, the main indicator for its growth appears to be the thermal regime. Let us estimate agroclimatic resources for cotton growth based on thermal regime since evaluation of the water supply for this plant is beyond the scope of this study.

Lower temperature limit for cotton growth (base growth temperature) is 10°C. Because of this, thermal resources during the cotton crop season are estimated using the number of active and effective air temperatures for the time between the days with temperatures above (below) the above threshold in spring (autumn). Such period is called an active vegetation period of crops. The number of active temperatures is a sum of average daily temperatures for that period. Effective temperature is a difference between daily mean temperature and base growth temperature of the crop.

The important thermal characteristic while measuring agroclimatic conditions of cotton cultivation is frost-free period. Late spring frosts (when temperature falls in the range -0.5 to -2.0°C) cause loss of cotton sprouts, and therefore, lead to blindness in seedlings and to overplanting over large areas. In autumn harmful frosts are those accompanied by temperatures 3-4°C below zero when cotton balls cease to unfold.

For evaluation of current thermal conditions during cotton crop season in the Central Asia the ERA-Interim reanalysis for surface air temperature blended with observational data spanning 30 years from 1979 to 2009 (the baseline period in relation to future climate change projection period from 2050 to 2059, see chapters 2.2 and 3.2 below) has been used. Using this data the agroclimatic indicators such as (1) the number of active and effective temperatures for the period with temperature above 10°C, (2) the dates when temperature goes above or below 10°C, (3) the duration of that period, and (4) the period without frosts have been calculated. Calculations are not conducted for mountainous areas where extrapolation procedures have been used.

During the baseline period the number of active temperatures in Central Asia (Fig.1a) varies from 3000°C on the latitude of 50N to 5600°C in the extreme South (36N). The number of effective temperatures has similar spatial distribution ranging from 1500°C to 3000°C (Fig. 2a).

The duration of period when surface air temperature is above 10°C can be found in the range of 160 days in the north to 250 in the southern regions. An exception is the region in the north from Lake Balkhash (the south part of Kazakh Upland) where the duration of that period decreases to 120 days. It should be noted that this area is outside of territory of cotton cultivation which is described below along with different cotton breeds’ cultivation locations.

Spatial distribution of period lengths without frost is more complicated since it strongly depends on conditions of underlying surface. Generally, in the considered area frost-free period increases from 130-135 days in the north to 225-230 in the south. The duration of the frost-free period as well as that with air temperatures above 10°C tend to
decrease in the region of Kazakh Upland and constitutes there 105 days. The frost-free period tends to be longer in the coastal regions (in the regions adjacent to Caspian sea the length of such periods amounts to 270 days). On the coast of Aral Sea the frost-free period is about 180 days, however, such durations can be found only in the narrow coastal line.

Comparison of the frost-free period with the period when surface air temperature is above 10°C (crop season) shows that on the major part of territory the frost-free period is shorter than the crop season and thus there is a danger for cotton to be harmed by frost.

2.2. Future changes of agroclimatic conditions for cotton growth in the mid 21st century.

To evaluate impact of global warming on conditions for cotton growth, agroclimatic indicators have been calculated for the period of 2050-2059 using MGO Regional Climate Model. Three member ensemble of model simulations at 25 km resolution have been carried out for the territory of Central Asia using ‘aggressive’ IPCC RCP8.5 scenario. Each of the decadal long simulations started with different initial conditions in the atmosphere to generate full range of interannual climate variability (3×10=30 years in total). The ensemble averaged output is used as an input for evaluation of future changes in agroclimatic conditions.

It has been shown that the active temperature sums are expected to increase by the mid-21st century by approximately 1000°C across Central Asia resulting in sums ranging from 4000°C at 50°N to 6600-6800°C in the southern regions (Fig. 1b). Thus, the sums of active temperatures will shift by 5° northwards as compared to baseline period. The spatial distribution of effective temperatures will change similarly and increase accordingly by 500°C or more so that the latitudinal shift will be around 5°C, as well (Fig. 2b).

For quantitative assessment of spatiotemporal variability of accumulated temperatures, the relative difference between projected period and baseline simulation has been used. The largest changes in the amounts of active temperatures will occur in the area of the Aral Sea, Kazakh Upland and foothill areas of the southeast. In these areas, the sum of active temperatures will increase by 30% or more (Fig. 3). Spatial distribution of changes in the amount of effective temperatures generally resembles the distribution of changes in the amount of active temperatures but the magnitude of changes in effective temperatures is 5-10% larger than that of active temperatures (Fig. 4).

The estimation of changes in the length of period with surface air temperatures above 10°C and frost-free period plays very important role for assessment of the prospects in the development of cotton production. Both of the periods on the entire territory of Central Asia by the middle of the 21st are projected to increase by approx. 10-15 days in northern areas to 30-35 days in the southern regions (Fig. 5, 6). However, the areas with relatively small changes in the periods (below 15 days) occur primarily due to changes in the frost-free periods rather than changes in the base growth temperature periods. Increase in the periods with temperatures above 10°C and, therefore, an increase in the sums of temperatures for this period makes it possible to shift the northern boundary of area of cotton cultivation in the future further northwards. At the same time,
an increase in the length of the frost-free period reduces the risk of damaging the cotton by devastating frosts.

Different ripening varieties of cotton require different thermal conditions. According to the length of growing season (from germination to maturation of bolls), the breeds of cotton can be divided into four kinds, namely, early-ripening (100 - 110 days), middle-ripening (115-120 days), middle-late (130-135 days) and late (150-170 days) groups of cotton breeds. The late breeds consist of fine-filamented cotton.

For the growth of different breeds certain values of effective temperature sums are required (Table 1).

<table>
<thead>
<tr>
<th>Breeds of cotton</th>
<th>The sum of effective temperatures (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early-ripening</td>
<td>1720 – 1730</td>
</tr>
<tr>
<td>Middle-ripening</td>
<td>1795 – 1805</td>
</tr>
<tr>
<td>Middle-late</td>
<td>1875 – 1885</td>
</tr>
<tr>
<td>Late</td>
<td>1970 – 2100</td>
</tr>
</tbody>
</table>

According to the Table 1 and maps of the distribution of effective temperature sums for the baseline and future periods (Fig. 2), one can easily define the boundaries of cultivation of specific breeds of cotton for both periods.

Provided at 99% exceedance probability level, for early-ripening and late cotton the average amount of effective temperatures will be 2070ºC and 2450ºC, respectively. That evaluation of exceedance probability 99% is given for the extreme values of average amounts of effective temperatures (1720 and 2100ºC). Fig. 7 displays four contour lines: the first and the third ones are for 99% exceedance probability of thermal resources for early-ripening cotton (2070ºC) in the baseline (1979-2009) and future (2050-2059) periods, respectively; the second and the fourth lines are the same probabilities for very late (fine-filamented) cotton. The first and the third contours are also related to relative provisions of thermal resources for the middle-ripening and late cotton at 90% and 75% levels. The figure clearly indicates that the projected change in the thermal regime by the mid-21st century results in the considerable shift of cultivation boundaries of both early and late breeds of cotton northwards and generally implies significant increase in the cotton-growing area in future.

3. The impact of climate change on agroclimatic growing conditions of spring wheat in Central Asia.

3.1. Current agroclimatic growing conditions of spring wheat.

Interchange of dry and relatively wet periods in the background of insufficient water resources in the Central Asia stipulates specifics of agriculture in the region. Using hydrothermal resources of winter and transition seasons during which the most of annual
precipitation is provided, it is possible in some areas to develop non-irrigated (rainfed) farming and grow spring grain crops including spring wheat.

Spring wheat is not much demanding for heat. The seeds begin to germinate at temperature of 3-5°C; seedlings appear viable at 5-7°C. The optimum temperature for growth and development is 15-20°C; the temperature of above 30-35°C causes depressing effect on the plants. Spring wheat is quite frost resistant, its seedlings can withstand freezing down to 9-10°C below zero.

Spring wheat of both the early and late ripening breeds in the plains and foothill areas is provided annually with heat. The amount of active temperatures required for the maturation of wheat during the growing season 85-120 days is 1200-1700°C. Thus, with a sufficient amount of heat under extremely arid conditions, a limiting factor for rainfed agriculture is the amount of precipitation. Therefore, to describe agro-climatic resources of cultivation of spring wheat in this study a quantitative assessment of conditions of heat and moisture availability during wheat growing season is performed. Heat availability is determined here by the sum of active temperatures during the growing season of 85 and 120 days. As the first date there was accepted the date of sustainable transition of temperature above 7°C. Adding to that date 85 and 120 days, the last dates of the periods have been calculated.

Humidification of the region depends not only on precipitation but also on the thermal regime. The higher the temperature is, the greater quantity of precipitation evaporates. Evaluation of water availability can be accomplished through a variety of indicators of humidification. A major indicator can be described by a relationship between rainfall totals and evaporation potential. The latter is estimated using the temperature, dew-point deficit or other parameters. To estimate the degree of humidification and its changes in the future one can find convenient to use Selyaninov hydrothermal coefficient (HTC) calculated as follows:

\[ \text{HTC} = \frac{\Sigma P}{0.1 \Sigma T}, \]

where \( \Sigma P \) is the sum of precipitation during the crop season simulated by regional climate model, \( \Sigma T \) – the sum of simulated temperatures for the same period. The HTC calculated for growing season of spring crops takes into account the amount of heat and moisture during this particular period so that it is critical for harvest of spring crops.

During the growing season of early breeds of spring wheat (85 days), on the most part of the territory of Central Asia the HTC is very low (<0.3 or less, Fig. 8a). Small values of HTC (0.2 or less) cover an area southwards of the Aral Sea. Towards the north (in the southern part of Kazakhstan at latitude 50N), the HTC increases up to 0.4-0.5. An increase of HTC also takes place towards the mountain ridges. In the foothills in the south of the Central Asia the HTC increases up to 0.8. The sharp increase in the value of HTC occurs in the foothills and mountain valleys in the southeast, where it exceeds values of 1.0.

During the crop season of late breeds of spring wheat (120 days), HTC throughout the territory of Central Asia reduces in comparison with the period of 85 days, and the area with HTC value of less than 0.2 already comprises a significant part of the territory (Fig. 8b). This is due to the growing season of 120 days includes summer months (June-July) when precipitation decreases sharply and droughts occur. Thus, the climate
conditions in Central Asia are more favorable for early breeds of spring wheat rather than for the late breeds.

3.2. Future changes in agro-climatic growing conditions of spring wheat in the middle of the 21st century.

Vast areas of Central Asia will experience significant warming due to global temperature rise by the mid-21st century. The monthly mean temperatures in some regions will be well above 7°C throughout the year. However, despite of presence of favorable conditions including sufficient humidification and heat supply for spring wheat, the sum of active temperatures over crop period might be still insufficiently low for ripening. Therefore, to determine the beginning of the crop season the condition of accumulated heat amount has been taken into account. In the areas where the projected monthly mean surface air temperature in spring is below 7°C, for the first date of the crop season of wheat the date of first sustainable rise of the temperature above this threshold is used.

The values of HTC have been calculated for the crop seasons of 85 and 120 days over future period (2050-2059) and compared to that for baseline simulation. It has been shown that during the crop season of early breeds of spring wheat (85 days), HTC will increase over the most territory of Central Asia (Fig. 9). The magnitude of HTC increase is larger in the southern regions. In the northern part of Central Asia the HTC will increase by 10-20% while in the southern regions it will increase by a factor of 1.5. During the crop season of late spring wheat (120 days) the HTC is expected to generally increase, as well (Fig. 10). Spatial distribution of changes in the values of HTC for this period to a large degree portrays changes in the period of early breeds of spring wheat.

An increase in values of hydrothermal coefficient shows that by the middle of the 21st century on the territory of Central Asia the agroclimatic conditions of spring wheat growth on the rainfed soil will be more favorable than in the past. Under climate warming the sums of temperatures will increase sharply in the region while precipitation totals are not expected to change much. This will cause drier climate and some decrease of HTC during warm seasons. However, due to temperature increase the length of crop season of spring wheat (and consequently the entire crop season) will start earlier so that there will be more water available for growth because annual maximum of precipitation falls in the Central Asia on winter and spring.
Fig. 1. Sums of active air temperatures (1000×°C) calculated over the period with temperatures above 10°C for 1979-2009 (a) and 2050-2059 (b).
Fig. 2. Sums of effective air temperatures (1000×°C) calculated over the period with temperatures above 10°C for 1979-2009 (a) and 2050-2059 (b).
Fig. 3. Changes (%) of active temperature sums above 10°C by 2050-2059 relative to baseline period. Scenario RCP8.5.

Fig. 4. Changes (%) of active temperature sums above 10°C by 2050-2059 relative to baseline period. Scenario RCP8.5.
Fig. 5. Changes (day) in duration of period with surface air temperatures above 10°C by 2050-2059 relative to baseline period. Scenario RCP8.5.

Fig. 6. Changes (day) in frost-free period by 2050-2059 relative to baseline period. Scenario RCP8.5.
Fig. 7. Sufficiency of thermal resources for cotton.

*Legend:* contour marks borders of the republics of Central Asia; shading shows the mountains.

1 and 3 – 99% exceedance probability of thermal resources for early-ripening cotton in 1979-2009 and 2050-2059, respectively;
2 and 4 – 99% exceedance probability of thermal resources for very late (fine-filamented) cotton in 1979-2009 and 2050-2059, respectively.
Fig. 8. The hydrothermal coefficient during the crop season of spring wheat of 85 days (a) and 120 days (b) for baseline period.
Fig. 9. Changes (%) in hydrothermal coefficient during 85 days of spring wheat crop season by 2050-2059 relative to baseline period. Scenario RCP8.5.

Fig. 10. Changes (%) in hydrothermal coefficient during 120 days of spring wheat crop season by 2050-2059 relative to baseline period. Scenario RCP8.5.