Climate Change in Turkmenistan

Elena Lioubimtseva, Jahan Kariyeva, and Geoffrey M. Henebry

Abstract More than 80% of Turkmenistan is desert; thus, key environmental issues are associated with redistribution and supply of limited water resources. Turkmenistan is projected to become warmer and probably drier during the coming decades. Aridity is expected to increase in all republics of Central Asia, but especially in the western part of Turkmenistan. The temperature increases are predicted to be particularly high in summer and fall but lower in winter. Especially significant decrease in precipitation is predicted in summer and fall, while a modest increase or no change in precipitation is expected in winter months. These seasonal climatic shifts are likely to have profound implications for agriculture, particularly in western Turkmenistan and Uzbekistan, where frequent droughts are likely to negatively affect cotton, cereals, and forage production, increase already extremely high water demands for irrigation, exacerbate the already existing water crisis, and accelerate human-induced desertification. The Amudarya is the most water-bearing river in Central Asia; its endorheic drainage basin includes the territories of Afghanistan, Tajikistan, Uzbekistan, and Turkmenistan. Fed by seasonal snowmelt of snowpacks and glaciers, the flow of the Amudarya may increase due to intensified melting of the glaciers and snowpacks under a warming climate, which could further contribute to expansion of agricultural land use at the expense of converted natural areas. During the last few decades, Turkmenistan has experienced widespread changes in land cover and land use following the socioeconomic

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and institutional changes in the wake of the disintegration of the USSR in 1991, and subsequently followed by a decade of drought and steadily increasing temperatures. These changes in the vegetated landscape are sufficiently broad to be detectable from orbital sensors at multiple scales.

Keywords Arid environments, Central Asia, Climate change, Deserts, Drylands, Hydrology, Land cover, Land use change

Contents

1 Introduction

Located in Central Asia Turkmenistan is a largely desert country that lies between 35°08′ and 42°48′N and between 52°27′ and 66°41′E, north of the Kopetdag mountains, between the Caspian Sea in the west and Amudarya River in the east. Turkmenistan territory expands 650 km from north to south and 1,100 km from west to east. To its north Turkmenistan borders Kazakhstan, to east and northeast, Uzbekistan, to south, the Islamic Republic of Iran, and to southeast, Afghanistan. On the west, Turkmenistan abuts on the Caspian Sea. The economy of Turkmenistan is linked with the use of land and water resources and continues to rely on agriculture that is dependent on irrigation. Major freshwater sources for Turkmenistan are the Amudarya that flows into the Aral Sea and is the main irrigation source for Turkmenistan [1], Murghab and Tedjen Rivers that disappear in the Karakum Desert, and the Karakum Canal – an unlined canal, which diverts water from the Amudarya [2]. More than 80% of Turkmenistan is desert. Turkmenistan occupies an area of 491,210 km^2 and had a population of 5,041,995 in 2010 [3]. The Karakum Desert comprises 80% of the area of the country, while 17% either mountainous or various types of clay, loess, and stony deserts. Only about 3% of the area is suitable for agriculture [4]. Turkmenistan has some fertile land and modest water resources located primarily in the eastern part of the country.

Because farming is the main industry in the Central Asian region [5], key environmental issues are associated with redistribution and supply of water resources and the limited water availability throughout the territory. Redistribution of surface water resources of the region is as follows: Tajikistan uses 44% of the total regional river flow, Kyrgyzstan – 26%, Uzbekistan – 10%, Kazakhstan – 3%, and Turkmenistan – 2% [6]. About 15% of the flow belongs to Afghanistan.

Despite its extensive oil and gas resources, Turkmenistan remains a poor, predominantly rural country with the majority of population relying on intensive agriculture in irrigated oases and is extremely vulnerable to climate change. During the last few decades, Turkmenistan has experienced widespread changes in land cover and land use following the socioeconomic and institutional transformations of the region catalyzed by the USSR collapse in 1991. The decade-long drought events and steadily increasing temperature regimes in the region came on top of these institutional transformations, affecting vegetation–climate feedbacks at multiple spatial and temporal scales.

According to the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4), developing nations and arid regions of the world are particularly vulnerable to climate change and climate variability [7, 8]. Climate change and variability affect arid ecosystems and their productivity through the changing patterns in temperature and precipitation, droughts, floods, heavy winds, and other extreme events. Water availability and food security of arid and semiarid zones has been always unstable due to their low natural productivity and high variability in both rainfall amounts and intensities. The increasing pressures caused by the global climate change on livelihoods deteriorate the human vulnerability to the on-going desertification processes and natural climatic variability. The impacts of climate change in desert countries, such as Turkmenistan, are likely to lead to still larger populations being affected by water scarcity and the risk of declining crop yields and increase the risk of environmental migrations and political conflicts caused by the decline of resources that are important to sustain livelihoods [9].

The goal of this chapter is to explore the interconnections between the climatic changes and variability that might be linked to the dynamics of the global atmospheric system and the regional-scale climatic and land cover changes. Particular attention will be given to the discussion of changing trends and future scenarios of climatic and environmental changes in Central Asia and Turkmenistan in particular. This chapter consists of the introduction, three major sections, and conclusions. The first section discusses past and present climate change and variability in Turkmenistan and a broader region of Central Asia. The second section provides analyses of climate change scenarios until the end of the next of the century and their potential implication for water resources and food security. The third section examines land use and land cover changes based on vegetation indices derived from remote sensing data. The final concluding section draws preliminary recommendations for adaptation measures to impacts of climate change.

2 Past and Present Climate and Water Resources

2.1 Climate and Physical Environments

Turkmenistan has a distinctive continental climate with average annual air temperature ranging from 12–17°C in the north to 15–18°C in the southeast and the absolute maximum temperature of 48–50°C in the Central and South-East Karakum Desert [10]. Geographic landscape of Turkmenistan is separated in two unequally divided ecoregions: the larger (80% of the area) ecoregion is represented by desert plains, primarily the Karakum (Black Sands) Desert, with limited precipitation [11], and the smaller (20%) one by mountains and their foothills. Water is of critical importance to Turkmenistan that is characterized by dry and continental climate and limited river network and fresh water resources [11]. Turkmenistan's climate is classified by the Köppen climate classification as *Bwk*, which is used to designate mid-latitude arid areas. Summers are long (from May to September), hot, and dry, with the average July temperature reaching more than 30°C with an absolute maximum of 52°C in the eastern Karakum [12]. Winters are relatively cold and moist in the north with a mean annual temperature of the coldest month, January, ranging from −10°C to 0°C. In the south, along the Kopetdag Mountains winters are warm and moist (with a January temperature typically 0°C or above). Very high daily temperature variability occurs with frequent sand storms and intense sunshine [13]. As in many other arid and semiarid regions, climate of Turkmenistan is highly variable. Throughout Turkmenistan, annual wind speeds are weak to moderate (0–5 m/s). Higher wind speeds (6–9 m/s) can be found along the northern slopes of the Kopetdag and the Caspian shore [13, 14].

The highest amount of precipitation is observed in the mountains – up to 398 mm in Koyne Kesir, the smallest – less than 80 mm above the Kara-Bogaz-Gol Bay. Temporal variability of precipitation is very high and precipitation has a distinctive spring maximum throughout most of the region. Precipitation during the cold season of the year is two to three times higher than during the warm months [14].

The major controls on precipitation change include latitudinal shifts of the westerly cyclonic circulation and position of the Siberian high [12]. The North Atlantic Oscillation (NAO) exerts an important control over the pattern of wintertime atmospheric circulation variability over arid and semiarid zones of Central Asia. Over the past four decades, the pattern captured in the NAO index has altered gradually from the most extreme and persistent negative phase in the 1960s to the most extreme positive phase during the late 1980s and early 1990s. Additionally, the patterns of precipitation as well as drought conditions in Central Asia have been linked to El Niño – Southern Oscillation (ENSO) phases [15]. Cold ENSO phases generally result in drought conditions in the region, while warm ENSO phases result in an increased precipitation [15, 16] and intensified vegetation response in nonagricultural area [17].

The processes in the Caspian Sea area and its level have a major impact on the balance of moisture and heat in the boundary layer atmosphere of western Turkmenistan. The Caspian Sea level correlates with climatic variability over

European Russia, because it depends entirely on climatic conditions and runoff in the basins of the Volga and Ural Rivers. After several decades of a steady raise, the level of the Caspian Sea has been going down since during the past 7 years [18]. On the other hand, the hydrology of Turkmenistan is determined by the runoff of the Amudarya, Tedjen, and Murghab Rivers and the major man-made “river” – the Karakum Canal.

2.2 Hydrological Network

Due to its arid climate more than 80% of Turkmenistan’s territory lacks a constant source of surface water flow. The Amudarya is the most water-bearing river in Central Asia. Its endorheic drainage basin includes the territories of Afghanistan, Tajikistan, Uzbekistan, and Turkmenistan and occupies the area of about 465,000 km^2. Its upper part – known as the Pianj River – flows from the Lake Zorkul in Pamir Mountains and is called the Pamir River before it is joined by Vakhandaria in Afghanistan. From east to west, the following big tributaries flow into the Pianj: Gunt, Bartang, Yazgulem, Vanch, Kyzylsu, and Vakhsh. After joining Vakhsh, the Pianj changes its name to Amudarya. It received more tributaries in Tajikistan: Kafirnigan, Khanaka, Karatag, and Surkhandarya. All these rivers start in the Pamir and their runoff is entirely determined by the regime of the mountain glaciers. The source of the Amudarya or Pianj and its several tributaries starts in the Vrevskiy glacier on the north slope of the Hindukush at a height of about 4,900 m above sea level. Already between the confluence of the Pianj and the Vahsh to the town Kerki about 40% of the river runoff is used for irrigation, with considerable amounts being lost for evaporation and infiltration. The riverbed here is divided into multiple channels and forms the numerous islands. Most irrigated lands along the Amudarya valley stretch from Kerki in Eastern Turkmenistan to Nukus in Uzbekistan.

In the past and as recently as in the Middle Ages, the flow of Amudarya changed several times diverting water to the Sarykamysh hollow and further down to the Caspian Sea along the ancient Uzboy River [19]. The flow of water along the Uzboy continued almost to the end of the sixteenth century. The Amudarya changes its riverbed many times, eroding the right bank most of all and constantly displacing to the east. The Amudarya has two flow peaks: one in April–May, caused by the maximum of precipitation in the mountains and snow melting on the low mountain slopes. The second peak flow takes place in summer, in June and July, due to melting of the glaciers in the Pamir and Hindukush Mountains.

The Amudarya is fed by seasonal snowmelt of snowpacks and glaciers and intensified melting of the glaciers and snowpacks occurs under conditions of warming climate [20], causing temporary increase in river runoff, which further contributes to expansion of agricultural land use at the expense of converted natural areas. Unpredictability in runoff dynamics results from a simultaneous interplay of two dynamic processes: climate change impact coupled with transformations in socioeconomic priorities in newly independent countries. This unpredictability introduces a new concern related to changes in land use and land cover.

The nonagricultural ecosystems of the Amudarya composed of *tugai* woodlands, shrubs, and reeds were once continuous and typical ecosystems used to cover the floodplains of the Amudarya. These riparian woodland communities are comprised of the poplars, willows, tamarix, and honeysuckle woods, which alternate with meadows that occupied by reeds, cattails, and licorice [21, 22]. As a result of extensive land reclamation and clearance projects in the Soviet Union, most of the Amudarya *tugai* ecosystems were destroyed to promote irrigated agriculture and only 10% of the native vegetation remains [21]. *Tugai* forests represent a habitat for numerous endangered and valuable flora and fauna species, which are severely threatened through habitat destruction with virtually no virgin forest remaining today [21]. The total area of the Amudarya riparian woodlands now been reduced from about 500 km^2 to around 50 km^2, of which less than 10–15 km^2 is considered to be in relatively healthy condition [21]. Located in regularly flooded river valleys, the *tugai* forest areas represent the most favorable agricultural lands of the region owing to soil quality and more favorable moisture regime [23].

The Amudarya is a transboundary river crossing Turkmenistan, Uzbekistan, Tajikistan, and Afghanistan, but it is chiefly Turkmenistan and Uzbekistan, who share its waters for their agricultural needs. In January of 1996, Turkmenistan and Uzbekistan signed the "Agreement between Turkmenistan and the Republic of Uzbekistan on Cooperation in Water Use" that regulates the amount of water withdrawn from the river to 22 billion cubic meters (BCM) of the annual water flow of 54–68 BCM, for each country [1].

Two other major rivers in Turkmenistan are Murghab and Tedjen. Murghab starts in the Paropamisus Mountains in Afghanistan. After receiving its tributary Abykaisara it enters Turkmenistan. The river valley up to the delta is divided into two sections: ancient part, formed mainly by sand, which was exposed to considerable weathering, and the younger section with clayey deposits. It ends in a dry delta in the Karakum Desert about 100 km below the town Mary.

The Tedjen River starts at a junction of the Paropamisus and the Hindukush mountains on the border of Iran and Afghanistan. After passing the Herat valley, the river turns north and flows about 300 km in Turkmenistan. In summer, Tedjen dries up below the Pulihatum village because of the water withdrawal for irrigation. The Tedjen delta is a sandy–clayey plain occupied by irrigated croplands and reed marshes.

The Karakum Canal is the largest man-made river in Turkmenistan and also one of the largest irrigation and water supply canals in the world. Started in 1954 and completed in 1988, it is navigable over much of its 1,375 km length; it carries 13 cubic km of water annually from the Amudarya River across the Karakum Desert. The canal opened up huge new tracts of land to agriculture, especially to cotton monoculture heavily promoted by the Soviet Union, and supplying Ashgabat, the capital of Turkmenistan, with a major source of water. Prior to construction of the Karakum Canal, the total irrigated area in Turkmenistan was about 166,000 ha. In western Turkmenistan and the Pre-Kopetdag regions, water was insufficient not only for irrigation but also for domestic use [4]. Unfortunately, the canal allows almost 50% of the water to escape en route, creating lakes and ponds along the canal, and a rise in groundwater leading to widespread soil salinization problems [5].

2.3 Climate Change in the Past

Palaeoclimatic and archaeological data indicate that climate of Turkmenistan has experienced many natural fluctuations in the past. Its landforms carry relict features both of relatively short humid intervals with runoff higher than nowadays, and long arid periods [24–26]. Pollen and archaeological data from Central Asia suggest that climate change was followed by significant ecosystem changes [27]. Significant cyclical variations of regional climate and sea level during this period resulted from major changes in river discharge into it caused by climatic variability and several natural diversions of the Amudarya River away from the Aral Sea [19, 24, 28, 29]. Environmental reconstructions based on pollen and archaeological data from several locations in Central Asia suggest that climate of this region was featured by colder winter temperatures, cooler summers, and greater aridity during the Late Glacial Maximum (around 20–18,000 years before present) and again in the Younger Dryas (12,800 and 11,500 years before present) [24, 30, 31]. The so-called Djanak arid phase of the Younger Dryas was followed by an increase in temperatures and precipitation during the Early and Mid-Holocene. A trend toward greater humidity during the Holocene culminated around 6,000 years ago, a phase known in Uzbekistan and Turkmenistan as the Liavliakan pluvial [29, 32]. According to pollen reconstructions, mean annual precipitation in the deserts of Central Asia could be three times higher than at present in the middle of Holocene, when desert landscapes were probably entirely replaced by mesophytic steppes, with well-developed forest vegetation along the river valleys [33]. A general trend of aridization that started approximately 5,000 years ago was interrupted by multiple minor climatic fluctuations in this region at a much finer temporal scale [26].

Historical records available from the weather stations show a steady increase of annual and winter temperatures in this region since the middle of the twentieth century. The precipitation trends, however, are highly variable across the region, both spatially and temporally, reflecting the great natural rainfall variability and landform diversity. Precipitation records available in this region since the end of the nineteenth century show a slight decrease in the western part of the region, little or no changes throughout most of the region, and relatively significant increase in precipitation recorded by the stations surrounded by irrigated lands during the past 50–60 years [34]. This precipitation decrease in the area between the Caspian and Aral Sea mainly occurred since 1960 and coincides with the Aral Sea desiccation. Both the degradation of the Aral Sea and the dramatic fluctuations of the Kara-Bogaz-Gol Bay caused by the construction in 1980 of the Caspian-Kara-Bogaz-Gol Dam (followed by its demolition in 1992) have caused significant changes in albedo, hydrological cycle, and mesoclimatic changes throughout western parts of Kazakhstan, Uzbekistan, and Turkmenistan [27].

Meteorological data reveal an increase of annual and winter temperatures in Turkmenistan since the beginning of the past century. The mean annual temperature has increased by 0.6°C in the northern part of the country and by 0.4°C in the south since 1931. At the same time, the number of days with temperature higher than 40°C has increased since 1983 [35].

Durdyev [35] used records from 24 meteorological stations as a reference base to examine natural climate variability and demonstrate the temperature fluctuations from 1950 to 2004 in Turkmenistan. The study revealed that period from 1950 to 1970 was relatively stable period in temperature fluctuations, with obvious peak in temperature regimes 1971 [35]. These findings were supported by similar results that were found for Uzbekistan where temperature reference data from 40 meteorological stations were used to assess climate variability from 1930 to 1995 [23]. The results of Uzbekistan study had longer period of observation and were able to reveal two eras of variation/circulation patterns: 1931–1960 and 1961–1990 [23].

3 Future Climate Change Projections

Warming of the global climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level. Changes in atmospheric concentrations of greenhouse gases (GHGs) and aerosols and land cover alter the energy balance of the climate system. Global GHG emissions due to human activities have grown since preindustrial times, with an increase of 70% between 1970 and 2004 [20].

Atmosphere Ocean Global Climate Models (AOGCMs) representing physical processes in the atmosphere, ocean, cryosphere, and land surface are the most advanced tools currently available for simulating the responses of the global climate system to increasing GHS concentrations. Climate models predict temperature increase in Turkmenistan of 3–4°C by the middle and by more than 5°C by the end of this century. Precipitation projections are highly uncertain but given the exiting aridity and high interannual and interseasonal variability of climate of Turkmenistan, even a slight temperature increase is likely to deepen the existing water stress in the region [10].

The rates of the projected changes significantly differ across seasons, with much higher temperature changes generally expected during the winter months. Despite significant differences in the ranges of change among the scenarios, the majority of the recent AOGCM experiments tend to agree that precipitation is likely to increase both northward (European Russia and Central Siberia) and southward (Northern India, Iran, and Pakistan) from Central Asia [26]. For the Central Asian plains, however, the expectation is for increasingly dry conditions with a slight increase in winter rainfall but decreases particularly in spring and summer. This trend toward higher aridity is projected to be more significant west from 70°E to 72°E. The AR4 supports these findings, pointing out that Central Asia, particularly its western parts, is very likely to become drier during the coming decades [20]. The AOGCM scenarios appear to be consistent with the observed temperature and precipitation trend over the past decades in most of the region. However, it is uncertain the extent to which the observed and projected trends result primarily from the global restructuring of atmospheric circulation and changes in the teleconnections controlling macroclimatic conditions over Central Asia versus mesoclimatic changes induced by regional land use change [34].

We have conducted several assessments of the annual, seasonal, and monthly climate change scenarios for Central Asia produced by the AOGCMs used in the IPCC Third [36] and Fourth Assessment Reports [20]. Detailed discussion of the climate change scenarios for Central Asia can be found in Lioubimtseva [30], Lioubimtseva et al. [26], Lioubimtseva [37], and Lioubimtseva and Henebry [34]. AOGCM scenarios indicate a generally good agreement that the current trend of temperature increase in arid Central Asia is likely to continue. The ranges of precipitation projections are still uncertain. The majority of climate models project a slight decrease in precipitation rate over most of the region with a stronger decrease in the west and southwest and a very slight increase in the north and east of this region [37]. However, given the low absolute amounts of precipitation and high interannual, seasonal, and spatial patterns of precipitation across the region, the changes in precipitation rate projected by climate models should be treated with caution. It is the change in the temporal and spatial variability of precipitation and its seasonal distribution – rather than absolute precipitation values – that are more important for the assessment of human vulnerability of this arid region, but they are also more difficult to assess and project.

We have used the Model for the Assessment of Greenhouse-induced Climate Change (MAGICC) and Global and Regional Climate Change Scenario Generator (SCENGEN), version 5.3.2 [38] to generate regional climate change scenarios for Turkmenistan for the time intervals, centered around 2025 and 2050. MAGICC/SCENGEN software has been developed by the National Center for Atmospheric Research (NCAR). MAGICC model consists of a suite of coupled gas-cycle, climate, and ice-melt models integrated into a single software package. The software allows the user to determine changes in GHG concentrations, global-mean surface air temperature, and sea level resulting from anthropogenic emissions. SCENGEN constructs a range of geographically explicit climate change projections for the globe using the results from MAGICC together with AOGCM climate change information from the CMIP3/AR4 archive. We have constructed climate change scenarios for Turkmenistan centered on 2025 and 2050, assuming policy changes based on the A1B–AIM SRES marker scenario [36, 39]. MMD assessment involved scenarios from the AOGCMs developed by the following organizations: Canadian Centre for Climate Modelling and Analysis (CCCma), Centre National de Recherches Météorologiques, Météo France, National Center for Atmospheric Research, CCSR/NIES/FRCGC, Japan, CSIRO, Australia, and Hadley Centre for Climate Prediction and Research, Met Office United Kingdom (Tables 1 and 2).

A1 family scenarios assume rapid global economic growth that leads to high energy demand and hence to a steep increase in CO_2 emissions in the first decades of the twenty-first century [39]. Structural changes in the energy supply become effective only in the longer term because of the inertia caused by long periods of capital turnover. With respect to alternative energy supply technologies, the A1B scenario group assumes a "balanced" approach, in which none of these technologies

Table 1 Temperature change scenarios for 2025 and 2050

Model	Institution	Temperature change by 2025 (°C)	Temperature change by 2050 (°C)
CCCMA-31	Canadian Centre for Climate Modelling and Analysis (CCCma)	+0.95–1.01	+2.03–2.23
CNRM-CM3	Centre National de Recherches Meteorologiques, Meteo France, France	+0.96–1.02	+2.12–2.22
NCAR-PCM1	National Center for Atmospheric Research (NCAR), NSF, DOE, NASA, and NOAA	+1.02–1.05	+2.20–2.36
MIROCMED	CCSR/NIES/FRCGC, Japan	+0.65–0.74	+1.47–1.57
CSIRO-30	CSIRO, Australia	+0.52–0.64	+1.35–1.65
UKHADGEM	Hadley Centre for Climate Prediction and Research, Met Office United Kingdom	+0.99–1.15	+2.1–2.85
MMD average		+0.74–0.95	+1.83–2.12

Table 2 Precipitation change scenarios for 2025 and 2050

Model	Institution	Precipitation change by 2025 (%)	Precipitation change by 2050 (%)
CCCMA-31	Canadian Centre for Climate Modelling and Analysis (CCCma)	−5.6 to −2.1	−8.6 to −4.8
CNRM-CM3	Centre National de Recherches Meteorologiques, Meteo France, France	−6.8 to −5.5	−4.2 to −2.8
NCAR-PCM1	National Center for Atmospheric Research (NCAR), NSF, DOE, NASA, and NOAA	−1.5 to +0.8	−3.1 to +1.9
MIROCMED	CCSR/NIES/FRCGC, Japan	−1.3 to +1.7	−2.9 to +3.8
CSIRO-30	CSIRO, Australia	+1.5 to +7.5	−1.8 to +3.3
UKHADGEM	Hadley Centre for Climate Prediction and Research, Met Office United Kingdom	−4.8 to −1.9	−9.4 to −4.8
MMD average		−1.4 to +0.4	−0.3 to +1.7

gain an overwhelming advantage. This scenario group includes the A1B marker scenario developed using the AIM model [36].

In the A1B–AIM marker scenario, the global average per capita final energy demand grows from 54 GJ in 1990 to 115 GJ in 2050 and to 247 GJ in 2100 [36]. At the same time, the final energy carbon intensity declines relatively slowly until 2050 (from the current 21 tC per TJ of final energy to 16 tC per TJ), which results in a steep increase in CO_2 emissions in the first decades of the twenty-first century. After 2050, when structural changes in the energy sector take effect, carbon intensity declines rapidly to reach 7.5 tC per TJ. Emissions peak around 2050 at a level 2.7 times (16 GtC) that of 1990 and fall to around 13 GtC by 2100, which is about twice the current level. The total, cumulative 1990–2100 carbon emissions in the A1B–AIM scenario equal 1,499 GtC [39].

All the five models used in our studies predict temperature increase close to 1°C or slightly less (MMD average varies geographically from 0.74°C to 0.95°C) by 2025 and about 2°C by 2050 (MMD average varies from 1.83°C to 2.12°C). Canadian, French, NCAR, and UK model have very similar temperature change projections temperature over +2°C by 2050, whereas Japanese and Australian models predict a temperature increase about 1.5°C.

Like in many other parts of the world, precipitation change projections for Turkmenistan are less certain and scenarios by different models differ significantly, with MMD averages ranging geographically between −1.4% and 0.4% for 2025 and between −0.3 and 1.7% by 2050. There are significant differences between the models, as well as different parts of Turkmenistan. Both Canadian and UK models predict precipitation decline order of 8–9% by 2050, while Japanese and Australian models predict increase of 3.3–3.8% in some parts of the country.

There are several sources of uncertainties associated with climate change scenarios predicted by the computer models. The spatial resolution of AOGCMs is quite coarse (a horizontal resolution of between 250 and 600 km, 10–20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans). Many physical processes, such as those related to clouds, occur at more detailed scales and cannot be adequately modeled; instead, their known properties are averaged over the larger scale in a technique known as parameterization [36]. Other uncertainties relate to the simulation of various feedback mechanisms in models concerning, for example, water vapor and warming, clouds and radiation, ocean circulation and ice and snow albedo, and land cover dynamics [20, 40, 41].

4 Land Use and Land Cover Changes

During the last few decades, Turkmenistan has experienced widespread changes in land cover and land use following the socioeconomic and institutional transformations of the region catalyzed by the USSR collapse in 1991. The decade-long drought events and steadily increasing temperature regimes in the region came on top of these institutional transformations, affecting the long-term and landscape scale vegetation responses. A few studies have been conducted to examine land cover changes in Turkmenistan and other parts of the Central Asian region using coarse-resolution (8 km at 10–15 days) NDVI (Normalized Difference Vegetation Index) data. By analyzing the Pathfinder AVHRR Land (PAL) data from 1981 to 1999, de Beurs and Henebry [42, 43] found three distinct patterns of significant difference in land surface phenology (LSP) models that linked the NDVI with accumulated growing degree days to describe the seasonal course of vegetation activity. Using similar modeling techniques, Henebry et al. [44] focused on irrigated areas in Turkmenistan and Uzbekistan in two time periods spanning the disintegration of the Soviet Union: 1985–1988 and 1995–1999. They found no significant change in land surface phenology in the irrigated areas of Karakalpakstan between periods. However, there were significant changes in the LSP patterns in the

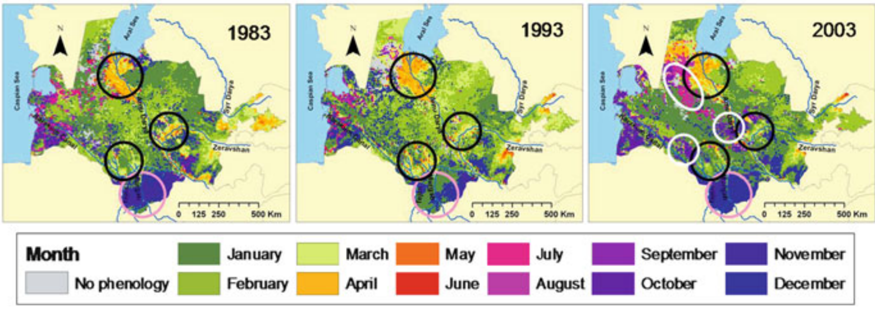

Fig. 1 Examples of imagery representing the dates for the start of the growing season derived from the NDVI time series data for 1983, 1993, and 2003 for Turkmenistan and Uzbekistan. *White circles* highlight the newly irrigated and expanded areas in Turkmenistan, *black circles* identify traditionally cotton crop areas, and *pink circles* – climate-driven fluctuation in the start of season in nonagricultural Badghyz–Karabil semidesert zone in Turkmenistan [17]

irrigated areas along the Zarafshan River in southern Uzbekistan and along the Karakum Canal in Turkmenistan.

Kariyeva [17] also found significant LSP changes following institutional changes using a different modeling approach, namely, phenological metrics extracted from the GIMMS NDVI data set [45] using the Timesat algorithm [46]. She found differences in land cover trends in Turkmenistan before and after the USSR collapse with shifts in crop preferences and expansion of agricultural areas (Fig. 1).

In the years since independence, the agricultural sector of Turkmenistan has seen significant shifts in the overall agricultural production as well as the composition of that production (Fig. 2). Estimated agriculture production rose by 189% between 1992 and 2010 [47]. The Turkmenistan economy shifted away from reliance on cotton exports and food imports toward more balanced food security portfolio. Cotton production decreased by 17% and its importance in the agricultural sector fell from 43% of production in 1992 to just 12% in 2010 (Fig. 2). Cereals production rose by almost 800%, moving from 12% of the agricultural production in 1992 to roughly 40% during the first decade of the twenty-first century; animal production rose by over 300%, rising from 21% in 1992 to 31% by 2010; and production of fruits and vegetables rose by a comparatively modest 109% but dropped its share from 24% in 1992 to 18% by 2010 (Fig. 2).

The drought of the last decade resulted in relatively low NDVI values compared to the 1990–1995 years. Increased precipitation in Central Asia during this interval is linked to warm ENSO (El Niño/La Niña-Southern Oscillation) phases [16] and the 1990–1995 ENSO event was the longest warm ENSO phase since 1882 [48]. The Southern Oscillation refers to variations in the temperature of the surface of the tropical eastern Pacific Ocean (warming and cooling known as El Niño and La Niña, respectively) and in air surface pressure in the tropical western Pacific. The two variations are coupled: the warm oceanic phase, El Niño, accompanies high air surface pressure in the western Pacific, while the cold phase, La Niña, accompanies

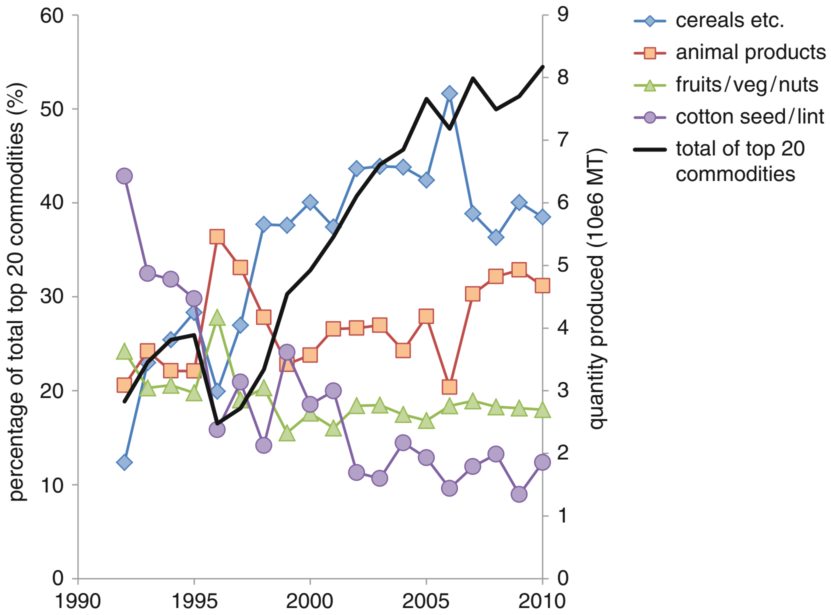

Fig. 2 FAO agricultural production data for Turkmenistan 1992–2010 [47]

low air surface pressure in the western Pacific. There is correspondence between ENSO phases and annual averaged NDVI in Central Asia [17], which tends to increase and decrease with warm and cold ENSO phases, respectively, in nonagricultural areas of Turkmenistan (Fig. 3).

Two-decade long institutional transformations have resulted in substantial changes in now independent and market-based economic priorities of the Central Asian countries: shifts in crop preferences, favoring food crop (wheat) over cash crop (cotton) production [17], increases in the agricultural labor force, particularly in Turkmenistan and Uzbekistan [49], expansion of agricultural areas, and withdrawal of more water for agriculture from the Amudarya and Syrdarya rivers, tributaries of the drying Aral Sea. The rivers are fed by seasonal snowmelt of snowpacks and glaciers of the Pamir and Tien Shan Mountains of Tajikistan and Kyrgyzstan. Intensified melting of the glaciers and snowpacks occurs under conditions of warming climate [20], causing temporary increase in river runoff, which further contributes to expansion of agricultural land use at the expense of converted natural areas. Unpredictability in runoff dynamics results from a simultaneous interplay of two dynamic processes: climate change impact coupled with transformations in socioeconomic priorities in newly independent countries. This unpredictability introduces a new concern related to changes in land use and land cover. Given a growing water demand by an increasing population in five Central Asian countries that are no longer a single institutional and administrative entity, the aforesaid concern relates directly to sustainable development of the region: the long term projected exhaustion of the water source is expected to impact the

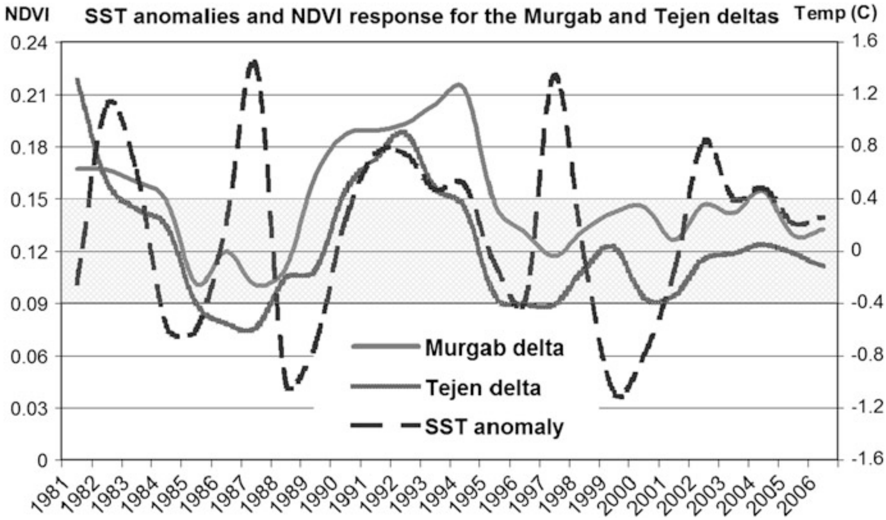

Fig. 3 NDVI time-series based phenological trajectories for the Murghab River delta zone and the Tedjen River delta zone and time series of the Sea Surface Temperatures (SST) anomalies (1981–2006) from *Niño 3.4 Region* dataset spanning 5°N to 5°S and 170° to 120°W used to define ENSO phases [17]. *Note*: ENSO phase thresholds at ±0.4°C [55]

agricultural potential of newly developed agricultural sites and coping capacities of regional ecosystems to natural and human-driven perturbations.

Kariyeva [17] explored the relationship between change patterns in land surface phenology and long-term climate variation in Central Asia. Statistical analysis included assessment of the standardized measures of linear associations between climatic and phenological variables. The phenological metrics of irrigated agricultural zones showed the lowest variability in response to precipitation regimes over time. Temperature regimes were the most noticeable climate drivers for the growing season dates in irrigated areas and explained the greatest amount of spatial variation in vegetation dynamics in. Start and peak of growing seasons were shown to have earlier timing onsets with warmer spring and summer temperatures. The duration of the growing season was shown to be longer with the increasing temperatures during spring, summer, and fall seasons. The productivity (greenness) metric was shown to have increased values with increasing rainfall and summer temperature regimes. Earlier season start and longer season length with increasing spring temperatures are occurring in almost all riparian and irrigated cropland areas of the Amudarya delta. However, the end dates of growing season are not changing for irrigated croplands of the Amudarya, which means that the end of growing season is not shifting accordingly to season start date. These observations can either be attributed to changed crop preferences that have longer growing season periods during the last three decades of agricultural production and/or decreased amount of meltwater reaching the delta. Nonagricultural areas in Turkmenistan had later season start dates with increasing temperatures with no changes in season length dates. This pattern can be explained by the fact that these dry and precipitation-driven desert ecosystems are affected by decreased trends in winter and spring precipitation. Combination of increasing temperatures and decreasing precipitation in the drylands of Turkmenistan can increase rates of potential evapotranspiration, leading to further water stress conditions for vegetation productivity. Shifting climate regimes might have direct implications for agricultural and natural land cover types in the region. Natural land cover types might experience reduction of overall vegetation productivity and irregularity in the growing season, which altogether could lead to phenological asynchrony across trophic levels caused by temporal mismatches between supply, availability, and demand.

5 Future Outlook

Arid zone of Central Asia represent an area with diverse and overlapping environmental, social, and economic stresses. The well-being and security of Turkmenistan depends on interplay of several groups of internal and external factors, such as climate variability and change, institutional changes and the subsequent regional land use changes, and internationalization of economy or globalization.

Turkmenistan is projected to become warmer and probably drier during the coming decades. Aridity is expected to increase in all republics of Central Asia, but especially in the western part of Turkmenistan. The temperature increases are predicted to be particularly high in summer and fall, but lower in winter. Especially significant decrease in precipitation is predicted in summer and fall, while a modest increase or no change in precipitation is expected in winter months. These seasonal climatic shifts are likely to have profound implications for agriculture, particularly in western Turkmenistan and Uzbekistan, where frequent droughts are likely to negatively affect cotton, cereals, and forage production, increase already extremely high water demands for irrigation, exacerbate the already existing water crisis, and accelerate human-induced desertification. The ongoing series of severe droughts of the past decade and continuous degradation of the Aral Sea and its tributaries, the Amudarya and Syrdarya, has already resulted in multiple water disputes and increased tensions among the states of the Aral Sea basin. The arid interfluve lowlands of both, the Amudarya and Syrdarya are already experiencing the effects of climate change with increased drought frequency and glacier recession [20]. Increased melting of the glaciers and snowpacks that is occurring under conditions of warming climate [20, 23, 50] will most likely cause temporary increases in water runoff over the next couple of decades and promote further expansion of unsustainable in the long-term run agricultural land use. Knowing that the aridity and water stress are likely to increase, new political and economic mechanisms are necessary to ease such tensions in future.

The ability of this western subregion of Central Asia to adapt to hotter and drier climate is limited by the already existing water stress and the regional land degradation and poor irrigation practices. Central Asia inherited many environmental problems from the Soviet times but many years after independence, the key land and water use-related problems remain the same. Deintensification of agriculture immediately after independence, documented by agricultural statistics, was significant enough to produce a signal in the temporal series of remote sensing data. Agricultural transformation had extremely high social cost, but agricultural reforms and transition to market have remained problematic across most of the region. Increasing rural poverty and unemployment, particularly among females, growing economic inequality, and shortage of adequate living conditions, medical care, and water management infrastructure have significantly increased human vulnerability of the majority of population in the region.

To cope with the multiple regional stresses in the context of multiple increasing stresses, both related and nonrelated to climate change, it is important to consider adaptation strategies that could place equal importance on environmental, social, and economic considerations. Development of such adaptation strategy involves inevitable trade-offs between environmental, economic, and sociocultural and political considerations and priorities. There is compelling evidence from around the world that development and implementation of adaptation strategies and policies are successful only when they are driven by the interests of stakeholders, groups of individuals, and communities vulnerable to the risks of climate change [51–53]. At the national and regional scale, adaptations are usually undertaken by the governments on behalf of the entire society or particular groups but, regardless the geographic scale, these decisions, policies, and projects must be driven by "place-based" initiatives and integrate the needs of various communities at multiple scales. Communities rarely face only one effect or risk of climate change at a time and the interaction of multiple vulnerabilities often can lead to amplification of risks [53, 54]. Climate change impacts are interconnected with land use changes, socioeconomic changes, and many other processes that interact in the human–environmental system. Therefore, adaptations can be sustainable only if they target multiple processes and risks in the integrated manner, reaching across various aspects of human life (food security, water resources, health, quality of life, etc.) at multiple geographic and temporal scales. For example, further reduction of cotton monoculture, diversification of crops including drought-resistant varieties, and application of no-tillage techniques in agriculture could not only help to increase food security but also would decrease the use of water, improve soils through the nitrogen fixation in soil. Moreover, these practices could be useful as climate change mitigation measures to increase carbon sequestration. The renovation of the existing irrigation network and introduction of more advanced irrigation techniques, such as drip irrigation not only could significantly reduce the loss of water resources but also would improve crop productivity, reduce the soil losses due to salinization, and help to reduce the risks of water contamination and transmission of many vector-borne and water-borne diseases.

Turkmenistan signed and ratified the UN Framework Convention on Climate Change in 1995. In January 1999, Turkmenistan ratified Kyoto Protocol and published the document titled "Turkmenistan: Initial National Communication on Climate Change." Being covered under the Kyoto Protocol's Clean Development

Mechanism, Turkmenistan can trade carbon credits with the countries that fall under the Joint Implementation Mechanism [10]. The major sources of carbon emissions in Turkmenistan include the oil and gas extraction, petroleum refining, chemical industry, as well as motor transport concentrated mainly in Ashgabat, Turkmenbashi, Balkanabat, Mary, Turkmenabat, and Dashoguz. Turkmenistan has taken some steps to reduce carbon emissions, such as massive tree plantation drive throughout the country (Green Belt Project), modernization of Turkmenbashi and Seyidi refineries to conform to modern ecological standards, and removal of the cement factories away from inhabited areas. However, the widespread poverty, recent decline in the educational system, and economic dependence on cotton and hydrocarbon exports still leave Turkmenistan very vulnerable to high climatic variability, desertification, and droughts.

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