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Impacts of climate and land-cover changes in arid lands of Central Asia

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Abstract

Despite the growing understanding of the global climate change, great uncertainties exist in the prediction of responses of arid regions to global and regional, natural and human-induced climate change. Meteorological data series show a steady increase of annual and winter temperatures in Central Asia since the beginning of the 20th century that might have a strong potential impact on the region's natural ecosystems, agricultural crops, and human health. Analyses of the NOAA AVHRR temporal series since the 1980s showed a decrease in aridity from 1991–2000 compared to 1982–1990. While most climate models agree that the temperature in arid Central Asia will increase by 1–2 °C by 2030–2050, precipitation projections vary from one model to another and projected changes in the aridity index for different model runs show no consistent trend for this region.

Local and regional human impacts in arid zones can significantly modify surface albedo, as well as water exchange and nutrient cycles that could have impacts on the climatic system both at the regional and global scales.

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1. Introduction

Despite the growing understanding by the international scientific community of the regional impacts of global climate change, relatively little attention has been given to the impacts in arid Central Asia. The reports of the Intergovernmental Panel on Climate Change (IPCC, 2001) and the international scientific literature in general contain virtually no discussion of the potential vulnerability of this enormous arid region to global change. In addition, most existing publications on climate and environmental change in Central Asia are in Russian and generally outside the ambit of the international community.

Russian-speaking scholars have long been aware of the potential importance of climate variability in Central Asia. Based on the evidence of palaeoenvironmental changes and historical and archaeological data many Russian scientists have attributed the decline of the classical and medieval civilization of Turkistan to an increase of aridity (Shnitnikov, 1969; Doluhanov, 1985; Varuschenko et al., 1987). Other researchers rejected the hypothesis of natural climate trends in this region suggesting instead that the climate and environmental changes of the last several millennia were caused exclusively by human-induced processes (Kharin et al., 1998). Yet the question that was posed more than half a century ago, “is Central Asia getting drier?” (Markov, 1951), still remains open to discussion.

It is indeed extremely difficult to draw a clear boundary between local and regional responses to global climate change and the trends caused by local land use changes, such as massive irrigation, overgrazing and the consequent desertification processes. The Central Asian desert regions are not a pristine environment; they have been exploited by graziers for thousands of years, and in the 20th century large irrigation schemes have been added to these landscapes. Although the drama of the Aral Sea crisis has been attracting the attention of the international scientific community during the last two decades (Micklin, 1988; Glazovsky, 1995; Glantz, 1999), remarkably little thought has been given to connections between local and global changes in the Central Asian republics.

To fully understand the impact of human activities, it is also necessary to consider the extent to which anthropogenic effects have modified the background level of carbon storage, and whether change in the intensity of either process has any evident potential to take up or release carbon from the desert-zone carbon reservoir. There is significant uncertainty regarding the possible impacts of global climate change on the sequestration of carbon in the vegetation and soils of the arid zones in general, and in those of Central Asia in particular. It is possible that global climate change could result in significant changes in carbon reservoirs in these areas. Estimates of the carbon pools in the desert soils are still very uncertain.

Figures on soil organic carbon given for this region in some widely used global data sets (Zinke et al., 1984) seem to be seriously overestimated (Lioubimtseva and Adams, 2002, pp. 256–409) and, although a lot of attention has been given to estimations of vegetation biomass and production in this region (Nechaeva, 1984; Bazilevich, 1995), the question of organic carbon in the world's desert and semi-desert soils is poorly documented (Lal and Kimble, 2000, pp. 1–15). Confusion

between organic and inorganic carbon in desert and semi-desert soils, or inadequate translation from Russian into English, are often the main reasons why Western authors tend to overestimate of the levels of organic carbon in these soils. Realistic assessment of the region's carbon budget is important for governmental decisions on land use and understanding of the implications for climate change (Lioubimtseva and Adams, 2002).

2. Brief overview of the study region, climate, and physiography

The Central Asian arid region comprises the Turan Lowland and the southern margin of the Kazakh Hills (Fig. 1) and is bounded by the Middle Asian mountains (up to 7450 m) on its southern and southeastern edges. In the southwest the

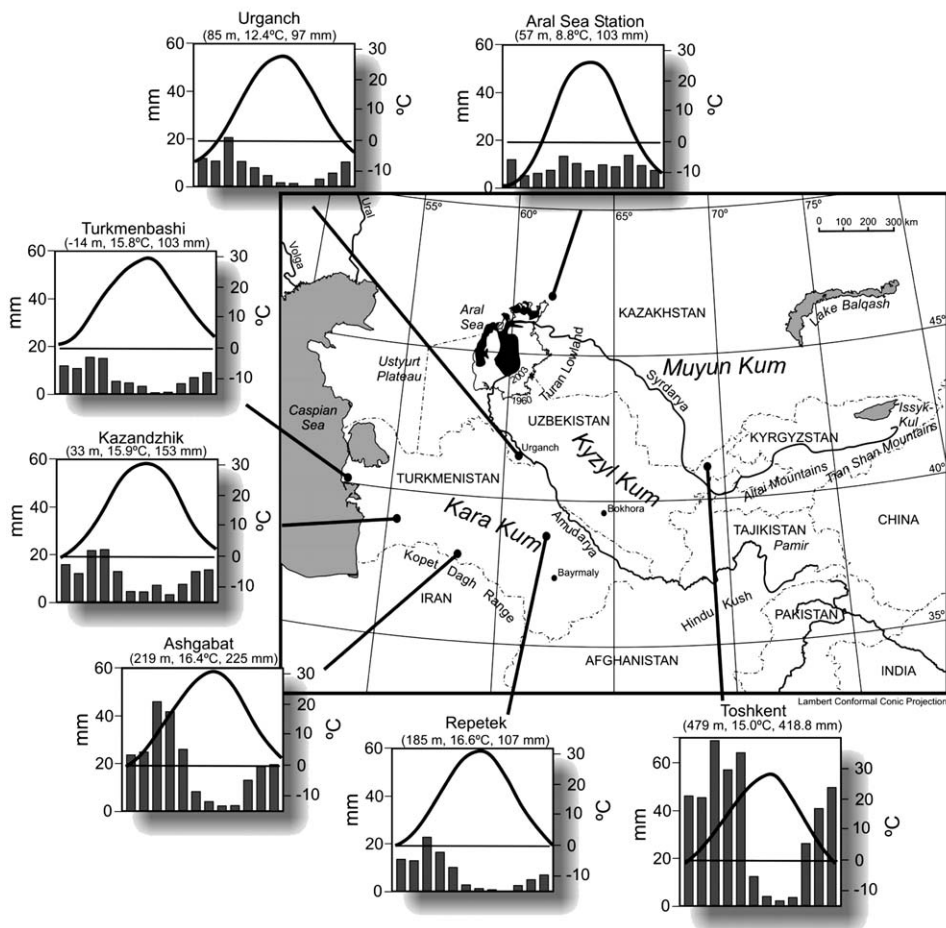


Fig. 1. The study region and its climate.

somewhat lower mountains of the Kopet Dagh (2000 m) allow monsoon precipitation to reach the western slopes of the Tian Shan and Pamir-Alaï ranges. To the north the Turanian plain descends progressively northward and westward and opens out towards the Caspian lowland. The northern boundary of this vast arid zone is rather poorly defined but it lies at approximately 48°N.

The deserts and semi-deserts of Central Asia have a continental climate. Summers are hot, cloudless and dry, and winters are moist and relatively warm in the south and cold with severe frosts in the north. This arid region can be divided into two subregions: northern (mainly Kazakhstan) and southern or Iran-Turanian (Petrov, 1976; Lioubimtseva, 2002, pp. 267–283). In the north of the semi-desert zone the winters are very cold with a mean winter minimum of -26°C and absolute minimum around -40°C or colder and the annual precipitation from 155 to 270 mm. Precipitation in the northern deserts is associated mainly with the prevailing westerlies and has a distinct maximum in spring–summer as the influence of the Siberian high diminishes and convective activity becomes stronger. In the southern Iran-Turanian part of the region winters are milder with mean January temperature ranging between -10 and 0°C . The average July temperatures are about 32°C with a maximum of 52°C in the eastern Kara Kum. Precipitation in this subregion has a spring maximum, which is associated with the northward migration of the Iranian branch of the Polar front. Most frequently rain is brought by the depressions which develop over the Eastern Mediterranean, migrate north-eastwards, and regenerate over the Caspian Sea (Lioubimtseva, 2002). Westerly cyclones of the temperate zone change their trajectories in summer over the Aral Sea from a west–east to a north–south direction and approach the zone affected by the Indian monsoon over the Zagros mountains.

3. Regional climate change

3.1. Long-term climate variations

Numerous biostratigraphic, geomorphological and archaeological proxy data indicate that climate of the Central Asian deserts and semi-deserts have experienced many changes at various temporal scales. Climatic variations through the late Pleistocene resulted in multiple shifts from hyper-arid deserts to sub-humid shrublands (Varuschenko et al., 1987; Velichko et al., 1987; Kes et al., 1993; Tarasov, 1994; Tarasov et al., 1998). The landforms of the Central Asian deserts carry relict features both of relatively short humid intervals with runoff higher than nowadays, and long arid periods. The activity of ancient water flows during the periods of glacial melting in the mountains of Pamir and Tien Shan left its distinctive traces both on the piedmonts, dissected by deep dry valleys, and on the aeolian plains, where alluvial fans formed, altering their location at each stage of alluvial deposition.

Pollen and archaeological data in Kazakhstan, Uzbekistan and Turkmenistan suggest that climate change was followed by significant ecosystem shifts and

sometimes their total transformation (e.g. from desert to semi-desert and even steppe vegetation). Marine fossils, relict shore terraces, archaeological sites, and historical records point to repeated major recessions and advances of the Aral Sea during the past 10,000 years. Before the present century, century-to-millennia-scale fluctuations in its surface level were at least 20 m and possibly more than 40 m. Significant cyclical variations of regional climate and sea level during this period resulted from major changes in river discharge into it caused by climatic alteration and natural diversions of the Amudarya River away from the Aral Sea (Micklin, 1988; Vinogradov and Mamedov, 1991; Kes et al., 1993).

Environmental reconstructions based on pollen and archaeological data suggest that the Younger Dryas was featured in Central Asian deserts by colder winter temperatures, cool summers and greater aridity (Table 1). The Djanak arid phase of the Younger Dryas was followed by an increase in temperatures and precipitation during the Early and Mid-Holocene. A trend towards greater humidity during the Holocene culminated around 6000 years ago, a phase known in Uzbekistan and Turkmenistan as the Liavliakan pluvial (Vinogradov and Mamedov, 1991; Lioubimtseva et al., 1998). Vinogradov and Mamedov suggest (from a combination of pollen evidence, animal fossils, geomorphology and archaeological evidence) that annual precipitation in this region was three times higher than at present and that desert landscapes were possibly entirely replaced by mesophytic steppes, with well-developed forest vegetation along the river valleys. This humid interval has been identified in many other arid regions of the world (the Sahara; southwestern USA, Australia, Western China) and clearly corresponds to the global Holocene optimum. Note however that a number of pollen sites used by the BIOME6000 study (Yu et al., 1998) across the Chinese part of Central Asia suggest that desert was still fairly widespread 6000 years ago. The reason for this discrepancy between the ‘widespread desert’ picture put forward by Yu et al. and the ‘widespread steppe and savannah’ scenario advocated by Vinogradov and Mamedov is not clear. It suggests that careful re-examination of the range of sources of evidence is required to determine whether one or both of these scenarios are accurate. It is possible that western China remained a desert at a time when other parts of Central Asia were steppe-covered. A general trend of aridization that started approximately 5000 years ago was interrupted by multiple minor climatic fluctuations in this region at a finer temporal scale (Table 1).

Aspects of atmospheric circulation are critical for understanding the water exchange of this area with neighbouring regions. Precipitation changes in the deserts of Central Asia can be explained by the shifts of the westerly cyclonic circulation and depend on the position of the Siberian high. Two other important controls on precipitation change in the Turanian deserts are the level of the Caspian and Aral Sea and their contribution of moisture and heat to the lower atmosphere. The impact of the Caspian Sea on precipitation in this region is evidence of a very strong connection between the climate of Central Asia and the climate of European Russia because the level of water in the Caspian Sea depends entirely on climatic conditions and run-off in the basins of the Volga and Ural Rivers. On the other hand, the level of the Aral Sea, another important factor controlling the temperature and

Table 1
Climate chronology of Central Asia during the Holocene

Stages	Years ago	Regional paleoclimatic subdivisions in Uzbekistan and Turkmenistan	Mountain glaciation in the Tian-Shan	The Aral Sea chronology	Western China climate variations
		Termez xerothermic phase Sandjar pluvial			Since 2800 y.a. about the same as now
Late Holocene	1000				
	3000			Regression	3200–2800 y.a.—relatively dry phase (but still moister than present)
	4000			Uzboy phase	3200–4900 y.a. dryer than present
Mid-Holocene	5000	Liavliakan pluvial phase	Increase of glaciers	Ancient Aral (Drevnearalskij) basin	6500–4900 y.a. moist
	6000				7900–6500 y.a. dryer than present
	7000				
	8000				9400–7900 y.a.—moist
Early Holocene	9000				9900–9400—dryer than present
Younger Dryas	10,000				
	11,000				
	12,000	Djanak arid phase	Decrease of glaciation	Paskevicheskij basin	

Compiled from Varuschenko (1987), Vinogradov and Mamedov (1991), Tarasov (1994) and Guo et al. (2000).

precipitation pattern in this region, is completely dependent on the run-off of two major Central Asian rivers, the Syrdarya and Amudarya, starting in the Pamir and Tian Shan mountains, and ultimately dependent on the rhythm of mountain glaciations.

Although palaeodata indeed provide valuable insights on possible geomorphological, hydrological and biological responses to climate change one should be very cautious using palaeoenvironmental reconstructions as possible analogous scenarios for future climate and environmental changes. There is strong agreement among climatologists that the climate transition from the LGM conditions to the Holocene was triggered by changes in seasonal sunlight distribution caused by oscillations in the Earth's orbit and the tilt of the Earth's axis (Berger, 1978). The physical differences of climate change forcings imply that one might expect quite different regional responses to future human-induced climate change compared to the Holocene climate in terms of their rapidity and amplitude.

Based on palaeoanalogue scenarios, using the past to predict the future, Central Asian deserts are often predicted to become moister as a result of global warming because they are located north of 30° latitude and are expected to benefit from the southward shift and probable intensification of the westerly cyclones similar to the early Holocene conditions. On the other hand, the palaeodata—although they improve our understanding of the global and regional mechanisms of climate change during relatively long time intervals (centuries and millennia)—usually do not capture the pattern of finer fluctuations of temperature and precipitation and should be used with caution.

3.2. Current trends

The IPCC report *Regional Impacts of Climate Change, 2001* addresses Central Asian republics in Chapter 7 “Middle East and Arid Asia” but provides very limited information about climate change in arid Central Asia (IPCC, 2001). “There were no discernible trends in annual precipitation during 1900–95 for the region as a whole, nor in most parts of this region” (IPCC, 2001, Chapter 7). The aridity index shows no consistent trends for Central Asia as a whole (IPCC, 2001). The report does point out a likely 1–2 °C/century temperature increase for Central Asia.

Meteorological data series show a steady increase of annual and winter temperatures in this region since the beginning of the past century (Fig. 2). Unfortunately only a few stations in Central Asia have a period of observations spanning more than a century. Most stations have records for a relatively short time, roughly 50–60 years. In addition, many meteorological stations in the region practically stopped functioning after the collapse of the USSR as a result of severe funding cuts (Chub, 2000).

Great spatial variability in temperature and precipitation trends can be observed at the landscape scale and seems to be controlled by land use and landcover characteristics. For example, a study by Neronov (1997) in Eastern Turkmenistan revealed significant differences between the trends of annual precipitation and aridity index in the sandy desert of the eastern Kara Kum and the neighbouring irrigated

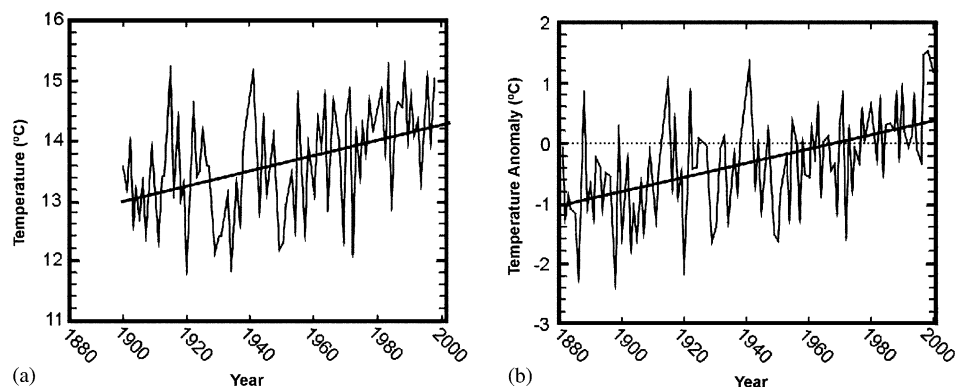


Fig. 2. Temperature increase from 1900 to 2000: (a) Toshkent station (adapted from Chub, 2000); (b) temperature anomaly for 1880–2000 for arid zones of Central Asia (based on GHCN data set, Peterson and Vose, 1997).

lands. He analysed annual and monthly temperature and precipitation data series from the Repetek meteorological station (located in the quasi-pristine landscape of sandy desert within the Repetek biosphere reserve) and Bayramaly stations (located in the Murghab oasis with extensive irrigated lands, 110 km southeast from Repetek), covering the periods of 1919–1997 and 1890–1997, respectively. Both sites have experienced very similar temperature increases during the period of instrumental observations and especially since the middle of the past century (Fig. 3). Steady temperature increases in these two stations and in the Turanian deserts in general might be an indication of some general factor affecting atmospheric circulation in Central Asia. The steady increase in both mean annual temperature and mean winter and summer temperature trends can be the result of the decreasing effect of the southwestern periphery of the Siberian high in winter and the intensification of summer thermal depressions over Central Asia. On the other hand, precipitation trends show a dramatic difference between the two sites and are apparently responsible for the difference between the trends of the mean annual aridity index. Although the index of aridity increased almost two-fold (from 0.42 in 1891 to 0.71 in 1994) in Bayramaly, there was only a slight change from 1910 to 1954 (0.41–0.46). A steady increase of precipitation, especially since the middle of the 20th century was also reported for several oases in Central Asia and can be attributed to the micro-regional human-induced climate change caused by the expansion of irrigated lands. Such trends usually show remarkable spatial variability and are much more intensive in the big oases where the area of irrigated lands has dramatically grown during the past century (such as Urganch, Bokhora and Toshkent oases) in western Uzbekistan or Murgab, Tedjen and Ashgabat oases in Turkmenistan). Significant changes in precipitation due to expansion of irrigation has been reported in many other arid regions, for example, in the US southwest (Diem and Brown, 2003).

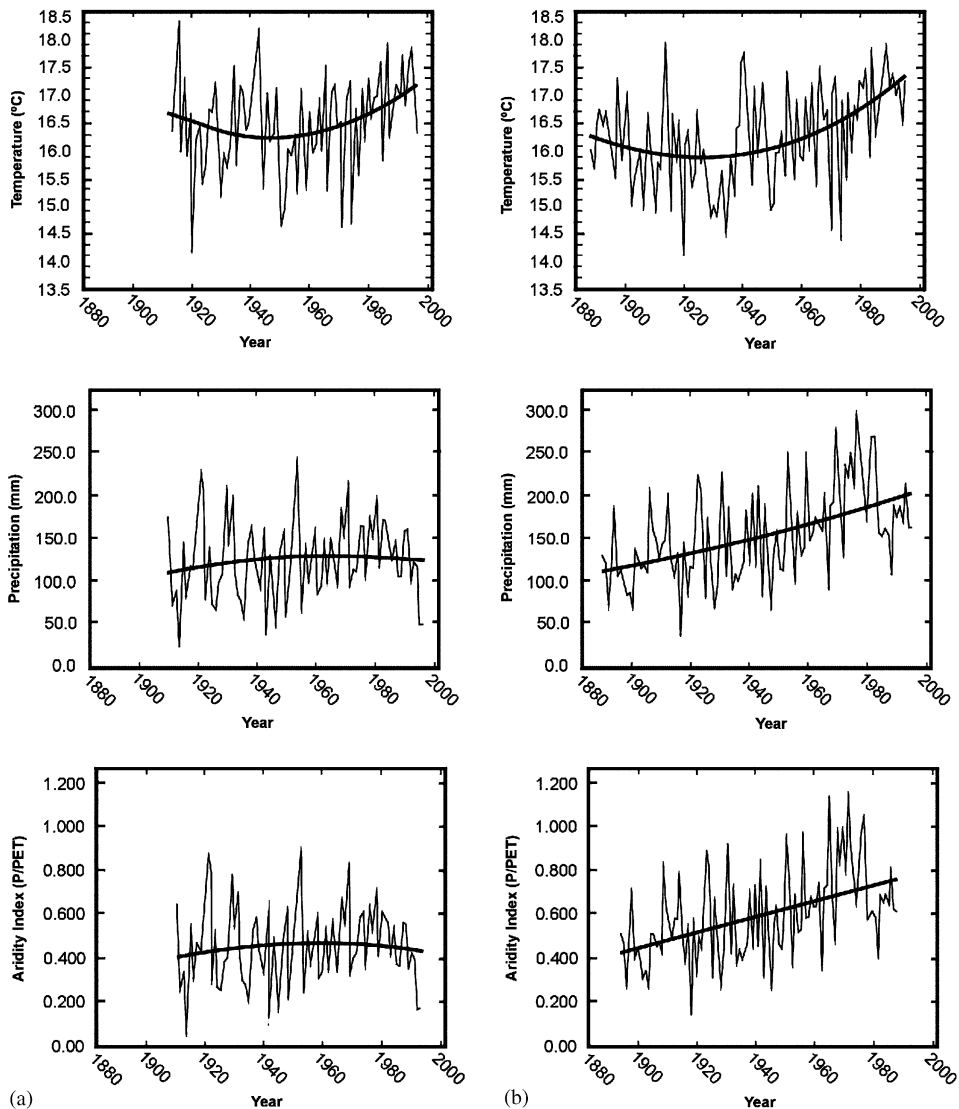


Fig. 3. Precipitation, temperature, and aridity index (P/PET): (a) Repetek Station, Turkmenistan, 1910–1995; (b) Bayramaly Station, Turkmenistan, 1910–1995. Adapted from [Neronov \(1997\)](#).

It is important to note, however, that there is still significant uncertainty in the estimations of the extent of arid lands in the temperate zone of Eurasia as a result of ambiguity in the indices of aridity used in different studies. The boundary between arid and semi-arid climates as shown on the commonly used ([UNEP, 1992](#)) map, which was based on the Thornthwaite index, is located 150–200 km south of the arid/semi-arid boundary in the USSR climate classification. Long temporal series of

remote sensing data offer another useful approach to climate change monitoring based on the estimation of the statistical relationship between climate aridity and vegetation phytomass estimations from satellite imagery (Kogan, 1995; Lambin, 1997; Nicholson et al., 1998). Most of this research was focused on climate change in the Sudan–Sahelian zone of Africa and the Western USA. Zolotokrylin (2002) developed a new empirical aridity index for Central Asian deserts and semi-deserts, which can be defined as duration of the period with a normalized difference vegetation index (NDVI) less than 0.07. This indicator reflects the zonality of heat exchange between arid land and atmosphere as the relation of radiation and evapo-transpiration mechanisms in the regulation of thermal conditions of soil surface and the lower layer of atmosphere (Zolotokrylin, 2002) (NDVI is defined as the normalized difference of reflectance in red and infrared bands of the electromagnetic spectrum). Analyses of the NOAA AVHRR temporal series since the 1980s showed a decrease in aridity from 1991–2000 compared to 1982–1990 in the northern part of the region (mainly Kazakhstan) and a southward shift of the northern boundary of the desert zone in Central Asia (Zolotokrylin, 2002).

3.3. Model scenarios

Climate models predict that the temperature in arid Central Asia will increase by 1–2 °C by 2030–2050, with the greatest increase in winter. Precipitation projections vary from one model to another and projected changes in the aridity index for different model runs show no consistent trend for this region (Fig. 4). Some models project greater aridity in the future and some predict less; it is becoming increasingly apparent that climate change modelling in arid zones is extremely uncertain, partly because of the extreme natural variability (both temporal and spatial) of the desert climate and partly because of inherent uncertainties in global and regional climate modelling (Lioubimtseva and Adams, 2004). Atmospheric dynamics are known to be very sensitive to natural climate variability at relatively short time-scales and the effect of short-time variability on longer (decadal-to-millennial) time-scales are not fully understood.

Both theoretical considerations and numerical models have shown a significant sensitivity of the climate of arid regions to vegetation distribution. Ground-cover parameters can significantly alter the modelled climate (Wang and Eltahir, 2000; Claussen et al., 2003).

Climate change scenarios, unfortunately, do not incorporate regional controls on climate. The impacts of the extensive redirection of montane and lacustrine water resources to irrigated agriculture in Central Asia and the degradation of the Aral Sea remain unmeasured in current climate models yet may be of significant importance in regional climate change. Although it is clear that both observed and predicted climate changes might be partly caused by global climate change and partly by local anthropogenic processes it is extremely difficult, if not impossible to delineate the boundary between these two factors.

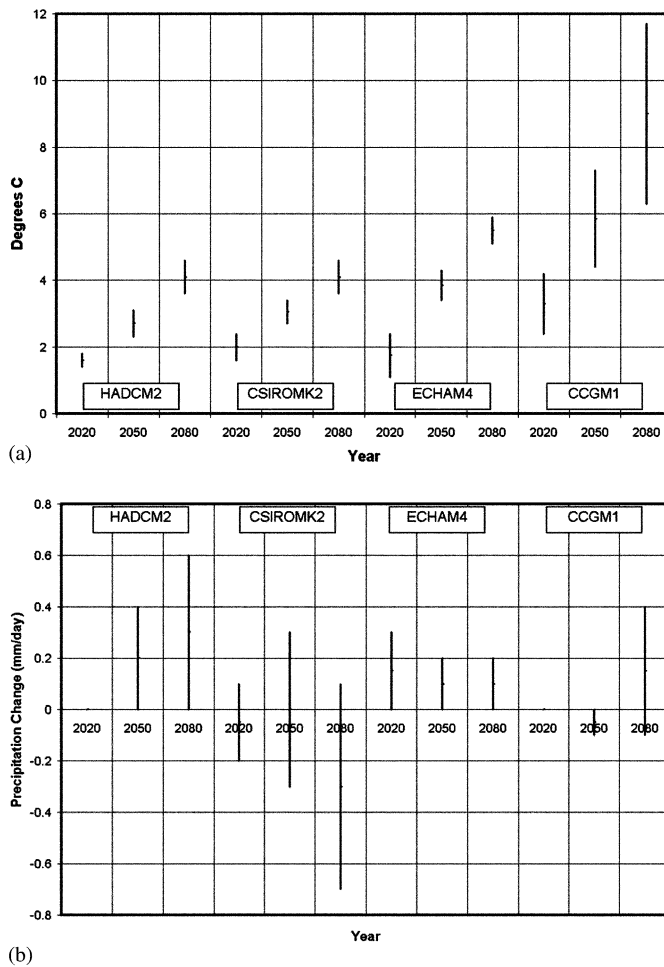


Fig. 4. GCM scenarios for arid zones of Central Asia, 2020–2080 (derived from [IPCC Data Distribution Centre, 2004](#)): (a) temperature range (°C); (b) precipitation range (mm per day).

4. Possible implications of CO₂ increase for desert ecosystems

While the predictions based on the palaeoanalogues, recent climate trends, and GCM scenarios still rather strongly disagree about the direction, frequency, rapidity, and amplitude of the possible regional climate changes that might be caused by the global greenhouse warming, it is likely that any changes in the regional circulation and climate regime will affect various landscape components, such as vegetation, soils, hydrological regimes, biogeochemical cycles, and landforms.

4.1. Vegetation responses to CO₂ concentrations

One of the most intriguing questions about possible implications of global climate change for desert ecosystems is how arid vegetation and other photosynthesizing organisms would adapt to the increasing concentrations of CO₂ and how this would affect other processes in arid ecosystems (e.g. hydrological cycle, biogeochemical cycles, etc.). In addition to its effect on climate, an increased atmospheric CO₂ concentration has direct and relatively immediate effects on two important physiological processes in plants: it increases the photosynthetic rate, but decreases stomatal opening and therefore the rate at which plants lose water. The combination of these two factors, increased photosynthesis and decreased water loss, implies a significant increase of water efficiency (the ratio of carbon gain per unit water loss) and productivity and a reduction in the sensitivity to drought stress in desert vegetation as a result of elevated atmospheric CO₂ (Smith et al., 2000).

No regional modelling studies have been conducted in this region but global biogeography models (Melillo et al., 1993; Woodward et al., 1998) predict relatively strong responses of arid ecosystems to global climatic change.

The Kara Kum and Kyzyl Kum deserts of Central Asia are strongly dominated by vegetation with the C3 photosynthetic pathway with only few C4 and CAM species (mainly succulents). It is often expected that plants using the C3 photosynthetic pathway will respond more strongly to raised CO₂ than species with the more water-efficient and CO₂-efficient C4 photosynthetic system (Table 2). The significance of

Table 2
Comparison of the general characteristics of C3, C4, and CAM

Photosynthetic pathway	Species	Light saturation	Optimum temperature (°C)	Water loss rate (g H ₂ O g ⁻¹ C fixed)	Photosynthetic rate (mg CO ₂ dm ⁻² leaf h)
C3	<i>Smirnowia turkestanica</i>	1/4 full sunlight	~25	~600	20–30
	<i>Senecio subdentatus</i>				
	<i>Rheum turkestanicum</i>				
	<i>Tamarix ramosissima</i>				
	<i>Populus pruinosa</i>				
	<i>Ephedra strobilacea</i>				
C4	<i>Atriplex dimorphostegia</i>	Higher than sunlight	~45	~250	55–65
	<i>Stipagrostis karelinii</i>				
CAM	<i>Haloxylon persicum</i>	Fixes C at night	~35	~50	3–4
	<i>Salsola richteri</i>				
	<i>Calligonum caput-medusae</i>				

different photosynthetic pathways in the adaptation of perennial plants to life in extreme desert environments is still hotly debated (Idso et al., 1993; Whitford, 2002). Most publications on this subject are based on chamber experiments and the recent Free-Air CO₂ Enrichment experiments studying responses of desert vegetation to increased CO₂ levels conducted in the south-western USA where desert vegetation cover is dominated by C4 species.

Much research on vegetation responses to elevated CO₂ concentrations was conducted in the former Soviet Union in the 1970s and 1980s followed by the decline in experimental research caused by financial difficulties in the 1990s. CO₂-enrichment experiments (both chamber and free-air) conducted in the Kara Kum (Voznesensky, 1977) and Kyzyl Kum (Voznesensky, 1977; Zelensky, 1977) deserts showed a 2–4 times increase in the photosynthetic rate under the saturating CO₂ concentrations. Three Kara Kum species (*Eminium lehmanii*, *Rhemum turkestanuikum* and *Ephedra stobilacea*) responded with a six-fold increase in photosynthetic rate (Nechaeva, 1984).

The CO₂ fertilization effects included not only higher vegetation but also microphytic communities including mosses, lichens, fungi, algae, and cyanobacteria (blue-green algae). These microphytic communities form biogenic crusts on the soil surface varying from a few millimetres to several centimetres in thickness and play a significant role in the desert ecosystems controlling such processes as water retention and carbon and nitrogen fixation in soils. In the Kara Kum desert of Turkmenistan the accelerated growth of such biogenic crusts, known among the local herders as “*karaharsang*” (*turk*—black moss), has been observed during the past 40–50 years and usually has been attributed to the undergrazing caused by the decrease of the wild fauna and insufficient pressure on the desert rangelands. It is possible, however, that the main reason for the accelerated growth of “black mosses” in the Kara Kum is a response of microphytes to increasing concentrations of CO₂ in the atmosphere.

If the increased CO₂ concentrations result in the significant increase of vegetation productivity one might expect also significant changes in runoff, precipitation regime, and circulation. It was demonstrated in several modelling studies in other arid regions (Wang and Eltahir, 2000; Claussen et al., 2003) that vegetation plays a prominent role in the energy, moisture and carbon exchange between the land surface in arid and semi-arid zones and the atmosphere. However, vegetation-climate feedbacks and their role in global and regional climate change are still relatively poorly understood and it is difficult to predict feedbacks caused by these possible changes in the desert vegetation cover. If indeed, the desert vegetation can respond to CO₂ fertilization it is still unclear how it would affect the surface runoff. So far these aspects are not taken into account by climate models.

4.2. Uncertainties regarding the soil carbon budget

The seasonal dynamics of CO₂ fluxes on desert and semi-desert vegetation of Central Asia have not been measured and no data exist on their possible and long-term changes. Even more uncertain is the soil carbon budget of the region. It seems that currently existing global databases (e.g. Zinke et al., 1984; Batjes and

Sombroeck, 1997) tend to overestimate the carbon content in arid ecosystems of the former USSR and Mongolia (i.e. 10.0 t C ha^{-1} in Zinke et al., 1984) or lack such data. Most of the desert soils data discussed and used in the biogeochemical literature comes from the English-speaking world, primarily North American deserts and semi-deserts. Russian sources indicate much lower values for the same areas (between 1 and 3.5 t C ha^{-1} in dark sierozems and sandy soils and relatively high only in the light sierozems—up to 4.5 t C ha^{-1}). This contradiction between global and regional data is discussed by Lioubimtseva and Adams (2002).

Our assessment of the databases suggests that the soil profiles where soil carbon values were obtained for the Central Asian republics of the former USSR and used by Zinke et al. (1984) as a reference, fall outside of the desert zone (Fig. 5 and Table 3). The larger of the two sampling areas used in this global dataset is comprised of seven sampling sites. It is situated on the mountain slopes and the Ili river valley eastward from Alma-Ata, Kazakhstan. All of them are taken within mountain steppe or meadow ecosystems where soil groups vary from light chestnut soils on the piedmonts to meadow chernozems in the alpine meadows. This sampling area continues in North-Western China, also on the slopes of the Tiang-Shan Mountains, and at even higher altitudes.

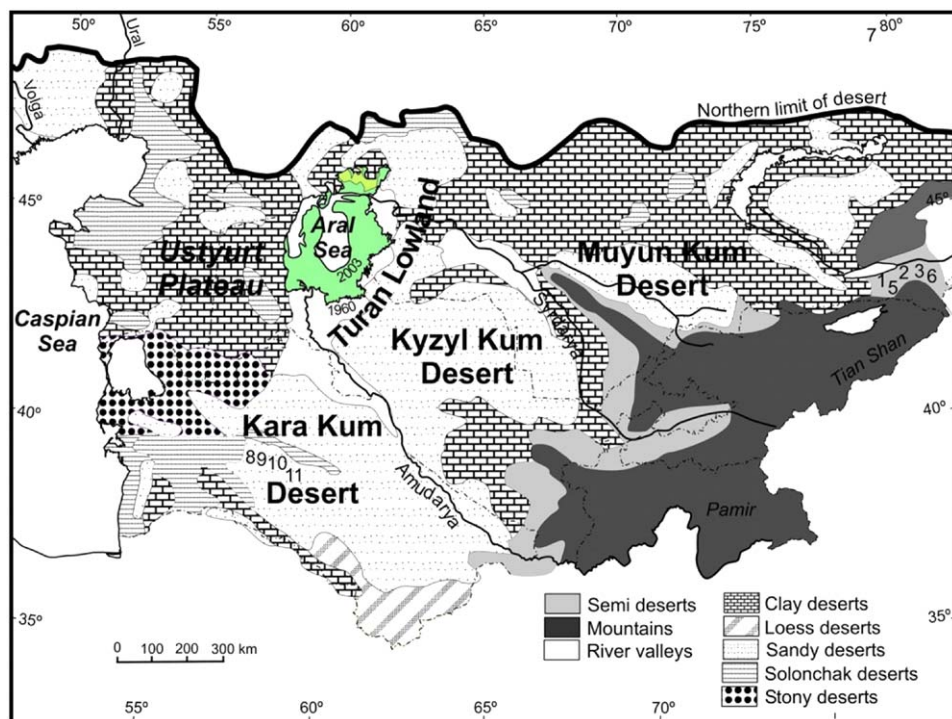


Fig. 5. Soil sample sites in Central Asia in the Worldwide Organic Soil and Nitrogen Database.

Table 3
Soil sampling sites in Central Asia available in the Worldwide Organic Soil Carbon and Nitrogen dataset (Zinke et al., 1984)

No. on the map	Soil profile (Zinke et al., 1984)	SOC (Zinke et al., 1984)	Latitude	Longitude	Ecosystem type (Russian Academy of Science, 1994)	Soil group (Glazovskaja, 1996)
1.	2050001	15.3	53.0N	78.6E	Alpine meadow	Mountain meadow dark soils
2.	2050002	6.3	54.0N	78.7E	Halophyte semi-desert	Siero-burozem
3.	2050003	8.0	53.3N	78.3E	Piedmont semi-desert	Siero-burozem
4.	2050004	5.5	52.3N	79.1E	Alpine steppe	Mountain burozem on light clayey carbonate deposits
5.	2051001	8.3	53.5N	80.2E	Alpine meadow	Mountain underdeveloped chernozems
6.	2051002	6.6	53.5N	80.2E	Alpine meadow with halophytes	Mountain saline underdeveloped meadow chernozems
7.	2052001	4.3	53.4N	79.0E	Semi-shrub dry mountain steppe	Light chestnut soils
8.	2069001	8.7	49.6N	57.2E	Halophytic vegetation	Solonchak
9.	2069002	6.0	49.6N	57.2E	Halophytic vegetation	Solonchak
10.	2069003	7.8	49.6N	57.2E	Halophytic vegetation	Solonchak
11.	2069004	12.4	49.6N	57.2E	Halophytic vegetation	Solonchak

Table 4

A summary of the range of types of soils found in the Central Asian desert region, together with typical organic carbon storage and the range of land uses. Based on the literature review by Lioubimtseva and Adams (2002)

Soil group	Ecosystem/ landscape type	Soil organic C (t C ha ⁻¹)	Depth of humus horizon (cm)	Dominant land-use
Chernozem like meadow soils	Meadow steppe	5–6	30–35	Pastoral, arable
Alkanized chestnut earth	Semi-desert	2–3	35–40	Pastoral, arable irrigated
Burozem	Rock desert (hammada)	0.8–1.6	1–2	Pastoral
Siero-burozem	Rock desert (hammada)	0.8	0.5–1.5	Negligible (extensive pastoral)
Light sierozem	Loess desert	1–1.5	3–5	Pastoral Arable irrigated
Solonchak	Saline desert	0.5–2	1–3	Pastoral
Solonetz	Semi-desert	1.7–2.8	5–10	Seasonal pastoral
Sandy desert soils	Sandy desert	0.5–1.5	1–2	Seasonal pastoral
Takyr	Clayey desert	Negligible	Negligible	—
Alluvial meadow and swampy soils	Floodplains and delta	3–4	10–20	Arable or pastoral

The second smaller sampling area included into the dates falls within the Uzboy dry valley. The Uzboy is an ancient *wadi*, which used to support a river until Medieval times and than has progressively dried out after an earthquake changed the flow (Varuschenko et al., 1987). Several times over the past 10,000 years, the Amu Dar'ya naturally diverted westward from the Aral Sea into the Sarykamysch hollow, filled it and overflowed into the Uzboy (Micklin, 1988; Kes et al., 1993). The valley is now full of alluvial sediments of various ages, which are not typical of the entire zone; intrazonal ecosystems are found here with much higher values of vegetation biomass (succulent halophytes) and higher values of soil carbon than the surrounding desert.

A very detailed literature review and discussion on the magnitude of vegetation and soil organic carbon pool for different ecosystems in Central Asia can be found in Lioubimtseva and Adams (2002). Table 4 provides a summary of the range of types of soils found in the Central Asian desert region, together with typical organic carbon storage and the range of land uses.

5. Regional human impact on climate

Although artificial irrigation in oases of Central Asia has been known for almost three millennia, the most important environmental changes in this region have occurred during the past 30–40 years as a result of massive irrigation schemes started in the 1960s (Glazovsky, 1995; Glantz, 1999). Cotton monoculture is the main

reason for the degradation of water and soil resources of the Central Asian republics. Irrigated arable land has increased by 60% from 1962 to 2002 (FAO, 2004). The total irrigated area in the countries that make up the study area increased by over half a million hectares (5.2%) just from 1992 to 2002 (FAO, 2004). Turkmenistan alone accounted for 59% of the change, increasing its irrigated area by 300,000 hectares (20%).

Since 1960, cotton production in this region has doubled and now accounts for almost half of the irrigated area. While there have a slight decline in the cotton production in the region after 1988 and some countries (in particularly the leading cotton producer in this region—Uzbekistan) have been making significant efforts to diversify their agriculture, other central Asian republics (Turkmenistan, Kazakhstan, Tadjikistan) have increased cotton production during the past 3–4 years (FAO, 2004) (Fig. 6).

In 1988, the water withdrawal in the Aral Sea basin for all purposes was 125% of the average annual water resources of this area (Glazovsky, 1995). Dramatic human-induced changes in the hydrological cycle led not only to a significant decrease of river runoff, changes in the number and area of lakes and rise of ground-water levels but also to significant changes in evapo-transpiration and precipitation patterns modifying micro and meso-climatic characteristics. Changes in albedo and other biophysical parameters of vegetation cover caused by massive irrigation could establish totally new equilibria in the climate-vegetation relations and reverse previously existing feedback mechanisms. While a desert environment is featured by strong negative biosphere-atmosphere feedbacks, perturbation of a large area by

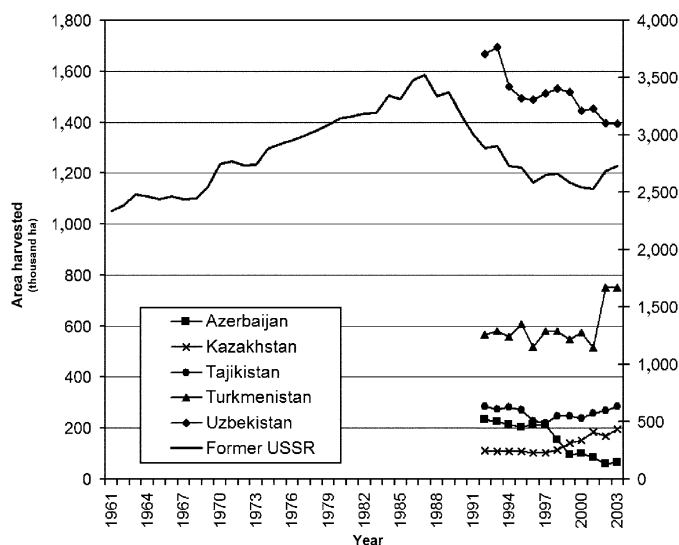


Fig. 6. Seed cotton area harvested, 1961–2003: former USSR and Central Asian Republics. Based on FAO Agricultural Data, <http://apps.fao.org/> (accessed September 2004).

irrigation induces a positive feedback that might bring the system to more humid climatic conditions with new climate-vegetation equilibrium.

Most research on climate change in the Central Asian republics during the past two decades has been focused on the Aral Sea areas and a large number of publications exist on this subject, mostly in Russian (e.g. [Molosnova et al., 1987](#); [Semenov, 1990](#); [Glazovsky, 1995](#); [Zolotokrylin and Hmelevskaya, 1999](#); [Chub, 2000](#)).

A general trend towards a more continental climate has been suggested by an increase in summer and decrease in winter air temperatures at stations near the shore by 1.5–2.5 °C and a decline in mean annual relative humidity of 2–3%, while the occurrence of drought days has increased by 300% ([Middleton, 2002, pp. 497–510](#)). Precipitation records also show a shift in seasonality. While in the 1950s maximum precipitation in the Aral Sea area occurred during February–March and minimum in September, in the 1970s the maximum was observed in April and the minimum in July. Spring frosts have been recorded later and autumn ones earlier ([Glazovsky, 1995](#); [Middleton, 2002](#)). The reduction of the sea surface area also caused a significant decrease of precipitation since the 1960s and saline dust from the exposed lake bed has been implicated in rapid climate and vegetation change.

The Aral Sea desiccation caused significant climate change not only in the coastal area but affected the entire system of atmospheric circulation in its basin. Summer and winter air temperatures at the stations near the sea shore increased by 1.5–2.5 °C and diurnal temperatures increased by 0.5–3.3 °C ([Glazovsky, 1995](#); [Chub, 2000](#)). Near the coast the mean annual relative humidity decreased by 23% and recurrence of drought days increased by 300% ([Glazovsky, 1995](#)). The annual cycle of temperature and precipitation has also changed. A seven-fold rise in the albedo of the area previously occupied by the Aral Sea caused a three-fold increase in reflected solar radiation and increased overall continentality of the climate ([Chichasov, 1990](#); [Glazovsky, 1995](#)). Regional modelling scenarios suggest that rise of the air temperature in Central Asia should cause further 8–15% increase in evaporation, while further aridization of the climate in the Aral Sea area may result in another 20% of evaporation increase in this region ([Chub, 2000](#)).

In addition, the exposure of the former lakebed areas, especially on the eastern side of the Aral Sea, represents an enormous source of highly saline wind-blown material (up to 1.5% salt in the total mass of hard particles transported by the wind). Deposition of the Aral Sea dust has been reported at a distance of several thousand miles from the source and many data suggest that the aeolian deposition of salts has adversely affected the vegetation of vast adjacent areas. According to [Semenov \(1990\)](#) the amount of aeolian redeposition from the former Aral seabed is exceeding 7.3×10^6 ton per year, comprised of between 5 and 7×10^4 tons of salt per year. Today the drying bed of the Aral Sea has become one of the biggest sources of dust aerosols in the world. Salty dust blown into the atmosphere is another important factor that needs to be considered in model simulations of both global and regional climates. Dust tends to cool the earth by reflecting sunlight back into space, and it decreases rainfall by suppressing atmospheric convection. GCM simulations of future climate which include changes in dust loading tend to yield different results

from those that do not, and the incorporation of iterative feedbacks between simulated future climate, vegetation cover and dust flux from changes in vegetation cover, tends to further amplify the changes in arid-land climates (Zeng et al., 1999). Following an initial increase in rainfall over arid areas, dust flux decreases due to increased stabilizing vegetation cover and moister soils. This decrease in dust flux tends to cause rainfall to increase further. Although the world is generally forecast to become moister as greenhouse gas levels increase, this effect is patchy and according to certain models some desert areas may become drier. In this case increased dust flux may increase aridity and also suppress rainfall outside the desert areas themselves.

Many studies in the Central Asia republics (Neronov, 1997; Kharin et al., 1998) indicate that the grazing impact on vegetation has been constantly decreasing during the past decade and is currently insignificant with the exception of Priaralye (the Aral Sea area). Cattle, camel, horse, and sheep populations have decreased dramatically in the Central Asian countries by 27%, 18%, 28%, 53%, respectively over the last 10 years (FAO, 2004). Goats, which accounted for only 5% of the small stock (sheep and goats) in 1992, increased by 31% to account for 14% of the total small stock population in 2002. But overall, the numbers of small stock have decreased over the past 10 years by over 30 million head. In many parts of the Kara Kum and Kyzyl Kum deserts, undergrazing rather than overgrazing has been the main reason for environmental changes.

With the almost total extinction of the natural ungulate fauna in this area and the significant decrease in grazing impact on vegetation cover, annual grasses or moss gradually replace the sparser natural perennial vegetation, and the surface becomes more compacted. As was mentioned earlier, unprecedented growth of *karaharsangs* (microphytic communities) during the last decades, perhaps in response to increasing CO₂ fertilization, occurs only in the undergrazed areas.

6. Conclusions

The complexities of precipitation changes, vegetation-climate feedbacks, and direct physiological effects of CO₂ on vegetation present particular challenges for understanding and modelling climate change in temperate arid regions. Great uncertainties exist in the prediction of responses of arid landscapes of Central Asia to elevated CO₂, as well as to global and regional, natural and human-induced climate change.

There has been a general warming trend in Central Asian republics on the order of 1–2 °C since the beginning of the 20th century that might have a strong potential impact on the regional temperature and precipitation regimes and also on natural ecosystems, agricultural crops and human health. The amplitude of this trend seems to be comparable with Holocene climate variability. However, because the mechanisms of palaeoclimatic variability were different from those caused by the current greenhouse warming, any palaeoanalogies should be treated with a great caution.

Climate change projections in this region vary from one global model to another. Despite the great progress in global climate modelling, the GCMs give very variable results, with large spatial differences in the areas forecast to receive higher or lower precipitation. The lack of integration of such factors as dust aerosols, biophysical and biochemical feedbacks caused by land-cover changes, as well as the regional factors of human-induced climate change, such as irrigation, are the major sources of uncertainties. For example, the dust aerosols from the drying Aral Sea bottom might have a very significant impact on regional climate but they are not taken into account by the models.

Projections based on biogeographic models suggest considerable changes in desert and semi-desert vegetation due to a combination of greenhouse-related climate change and direct physiological CO₂ effects on vegetation, such as changes in photosynthesis and water-use-efficiency over the coming century. This could likewise have implications for crop growth in desert-marginal areas, favouring greater productivity, and perhaps increase productivity and biomass of natural desert vegetation and soil organic matter. However, the very limited number of CO₂ enrichment experiments in the Kara Kum and Kyzyl Kum do not always confirm this thesis. Moreover, the results of CO₂ fertilization experiments in other arid regions of the world, such as the Negev desert in Israel ([Grünzweig and Körner, 2000](#)) and Mojave desert in the US ([Smith et al., 2000](#)) are rather mixed—which only contributes to the uncertainty about the implications of the doubled CO₂ concentrations for desert ecosystems. The accelerated growth of biogenic crusts (observed during the past 40–50 years) in this arid region might be a response of microphytes to increasing concentrations of CO₂ in the atmosphere. However, because such responses occur only on the undergrazed desert rangelands it is still unclear if the CO₂ increase really is the major cause or such growth, rather than land-use change.

One of the major sources of uncertainty about vulnerability and impacts of climate and land-cover changes in arid lands of Central Asia is the lack of reliable and accurate data on climate and ecosystems necessary for regional climatic and biogeographic modelling. Although a considerable amount of research was conducted here in the 1970s and 1980s, the pervasive lack of funding for environmental monitoring and research, corruption of the local authorities, political and language barriers, and often political instability has resulted in a significant lack of up-to-date information about the climate and landscapes of this vast arid area. While some uncertainties about climate data and soil carbon budget have been discussed above, many other variables related to climate and environmental change need further discussion but are beyond the scope of this paper. For example, the accuracy of the agricultural statistics or the absence of monitoring of the net primary production and biomass in this region during the past decades. Uncertainty and sometimes the total lack of quantitative data represent the major challenges for regional climate and environment modelling and contribute into great uncertainty about the possible implications of global climate change for the Central Asian republics during the next decades.

While the local responses to global climate change have been a source of major uncertainties, it is clear that there have been very intensive human-induced regional climate and environmental changes in Central Asia, primarily associated with massive irrigation schemes, the desertification crisis in the Aral Sea area, and changes in the grazing pressure on desert rangelands. Local and regional human impacts in arid zones can significantly modify surface albedo, as well as water exchange and nutrient cycles that could potentially have impacts on the climatic system both at the regional and global scales. On the other hand, improved management techniques can increase the carbon sequestration capacity of semi-desert rangelands and arable lands.

There are many urgent research needs that should be addressed to help resolve uncertainties about climate and ecosystem change in Central Asia. A number of research priorities can be identified as they cut across all sectors sensitive to climate change:

1. Improve climate data monitoring by the local weather stations, improve the quality of monitoring and data processing, as well as increase the density of the weather station network. Unfortunately, this issue cannot be addressed until the overall economic situation in Central Asia improves. Significant improvement is highly unlikely without the help of external donors.
2. Assess the vegetation and the soil carbon budget of Central Asia and improve understanding of the spatial distribution of carbon sources and sinks and the local and regional scales.
3. Improve understanding of the long- and short-term climate variability in Central Asia. Palaeoenvironmental research and reconstructions of the Late Pleistocene and Holocene environments could significantly improve understanding of the atmosphere–biosphere interactions and amplitude and variability of climate and landscapes in this vast arid region and possibly identify important thresholds in climate change for landscape responses.
4. Seek a better understanding of the inter-relationships between climate, ecosystem, and land-use changes using remote sensing, field observations and modelling experiments.
5. Conduct more research on the human dimensions of regional vulnerability and adaptation to climate and environmental change.

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