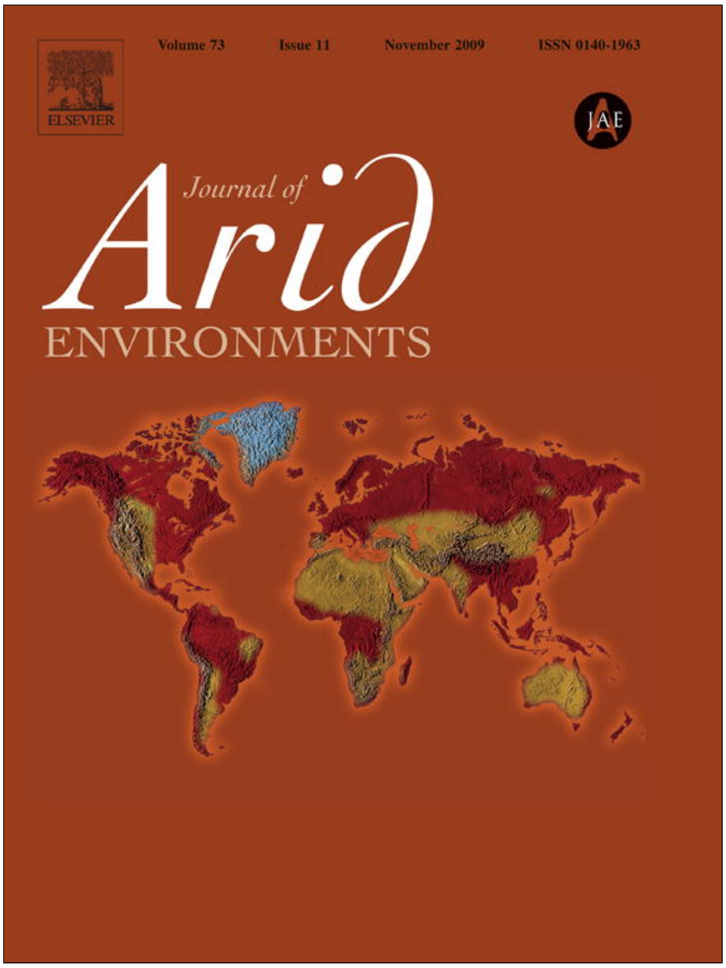
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Review

Climate and environmental change in arid Central Asia: Impacts, vulnerability, and adaptations

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ABSTRACT

Vulnerability to climate change and other hazards constitutes a critical set of interactions between society and environment. As transitional economies emerging from the collapse of the Soviet Union, the republics of Central Asia are particularly vulnerable due to (1) physical geography (which dominated by temperate deserts and semi-deserts), (2) relative underdevelopment resulting from an economic focus on monoculture agricultural exports before 1991, and (3) traumatic social, economic, institutional upheavals following independence. Aridity is expected to increase across the entire Central Asian region, but especially in the western parts of Turkmenistan, Uzbekistan, and Kazakhstan. Temperature increases are projected to be particularly high in summer and fall, accompanied by decreases in precipitation. We examine the concepts of vulnerability, adaptation, and mitigation in the context of climate change in Central Asia. We explore three major aspects of human vulnerability—food security, water stress, and human health—and propose a set of indicators suitable for their assessment. Non-climatic stresses are likely to increase regional vulnerability to climate change and reduce adaptive capacity due to resource deployment to competing needs.

1. Introduction

Great uncertainties still exist in the projections of responses of drylands to global climate change and Central Asian states of the former USSR represent a region where potential impacts of climate change are highly uncertain. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, WGI, 2007) has pointed once again to myriad gaps in our understanding of the contingent and nonlinear interactions between global climate change, regional land changes, and human vulnerabilities and adaptations to environmental change, whether in Central Asia or the planet's many other arid regions. *A Synthetic Assessment of the Global Distribution of Vulnerability to Climate Change* published by CIESIN (Center for International Earth Science Information Network) simply omits Central Asia, declaring it to be an area where "no data are available" (Yohe et al., 2006). The purpose of our study is to examine the vulnerability of arid and semi-arid zones of Central Asia to potential impacts of climate change and to discuss possible adaptations to these impacts.

Vulnerabilities to climate change and other natural hazards constitute a critical set of interactions between society and environment. Research on vulnerability and adaptations to future climate change is a major component of the assessments conducted by the Intergovernmental Panel on Climate Change (IPCC), the United Nations Framework Convention on Climate Change (UNFCCC), the United Nations Environmental Program (UNEP), the International Geosphere–Biosphere Program (IGBP) and the associated International Human Dimensions Program (IHDP), and many national and regional climate change programs. Factors defining regional vulnerability and adaptations to climate change include both biophysical and socio-economic variables (Fischer et al., 2005; Parry et al., 2004; Smit and Skinner, 2002). Climate change may have substantial impacts on ecosystems, agricultural crops, water resources, as well as human health and livelihood across Eurasia. Transitional economies of the former USSR, such as the republics of Central Asia might be particularly vulnerable to current and projected environmental changes, both due to their physical geography and the manifold political, economic, and institutional changes since 1991.

This review is focused of the five Central Asian states of the former Soviet Union. In the Russian-speaking literature Turkmenistan, Uzbekistan, Tajikistan, and Kyrgyzstan are usually defined as "Middle Asia", while the term "Central Asia" includes Kazakhstan, as well as parts of China and Mongolia (Cowan, 2007). In western publications (and increasingly in Russian literature of

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the past decade), the term "Central Asia" is used to define the five Asian republics of the former Soviet Union (Glantz, 2005; Lioubimtseva et al., 2005; Micklin, 2007). A detailed discussion of geographic usage of these terms can be found in Cowan (2007). In this paper we use the term "Central Asia" as referring to the five republics of the former Soviet Union located in Central Asia.

The next section (Section 2) of this paper provides a review of the ample scientific literature on vulnerability, adaptations, and impact assessments based on climate change scenarios. It is crucial to consider adaptations to climate change. Even if GHG emissions were abruptly reduced now, the inertia in the climate system would mean a long period until stablization (IPCC and WGI, 2007).

Section 3 provides analyses of climatic and land cover trends in the arid and semi-arid zones of Central Asia as well as AOGCM (Atmosphere Ocean General Circulation Model) scenarios and discusses the key uncertainties about these scenarios.

Section 4 examines the major aspects of human vulnerability in the Central Asian republics, such as food security, water stress and human health, and proposes a set of indicators suitable for their assessment. Particular attention is given to the interplay between the projected climate change and non-climatic factors, such as political, socio-economic and institutional changes after the collapse of the former USSR.

Section 5 examines potential options for adaptation to the regional climate change in Central Asia and discusses how multidisciplinary multi-scale integrated adaptation strategies can help to reduce human vulnerability in a long-term sustainable way. The concluding section discusses some challenges and limitations of vulnerability and adaptation research driven by climate change scenarios.

2. Human vulnerability and adaptations to climate change

2.1. Dimensions of vulnerability and resilience

While change is a concept distinct from variability, change can be masked by variability and variability itself can change. Many geographic regions and socio-economic groups that are already vulnerable to contemporary climate variability and extreme weather events are very likely to become more vulnerable in future, due to the changing frequency of extreme events exacerbated by the increasingly unequal distribution of material resources, marginalization, and continued underdevelopment (Adger et al., 2005; Handmer et al., 1999). Central Asia constitutes a particularly vulnerable region because of its physical geography (dominated by temperate deserts and semi-deserts), its relative underdevelopment resulting from an economic focus on agricultural exports from monocultures (wheat and meat in Kazakhstan, cotton in Uzbekistan, Tajikistan, and Turkmenistan, wool in Kyrgyzstan) before 1991, and then the dramatic economic and institutional upheavals following the collapse of the USSR.

The IPCC defines vulnerability as the extent to which an environmental or social system is susceptible to and unable to cope with adverse effects of climate change, including climate variability and extremes (IPCC and WGII, 2007). Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which the system is exposed, and the sensitivity and adaptive capacity of that system (Adger et al., 2005). A highly vulnerable system would be a system that is very sensitive to modest changes in climate, where the sensitivity includes the potential for substantial harmful effects, and for which the ability to adapt is severely constrained. Ample literature on vulnerability and adaptations suggests that the concept of vulnerability to climate change is multidimensional. The cross-disciplinary nature of vulnerability analysis arises from the intersection of studies on climate and climate change, impacts of and adaptations to climate change, natural hazards and responses to hazards, particularly droughts, storms and floods, famine, and social and environmental indicators of sustainability.

Many global and regional assessments of vulnerability to climate change rely primarily on the global climate change scenarios. They focus on the physical aspects of vulnerability, such as land degradation and changes in agricultural or silvicultural productivity (Mizina et al., 1999; Pilifosova et al., 1997; Smit and Skinner, 2002), and on impacts of the availability of water resources to meet future needs (Alcamo and Henrich, 2002; Arnell, 2004; Shiklomanov and Rodda, 2001). On the other hand, a considerable amount of social science research on global and regional environmental changes suggests that the human aspects of vulnerability to climate change or hazards represent the critical dimension for understanding vulnerability, and that this perspective shifts the focus from proximate to underlying causes of vulnerability (Adger et al., 2005; Handmer et al., 1999; Van Lieshout et al., 2004). Such factors as human behavior, political system, institutional capacity and culture can be far more important than biophysical impacts in identifying and defining the levels of vulnerability and the differential abilities of population groups to adapt to environmental change. This emphasis on human dimensions of vulnerability is particularly prominent in large-scale "place-based" land-change assessments that define a vulnerability framework as a combination of exposure, sensitivity and resilience components of a human-environmental system (Reynolds et al., 2007). Despite some philosophical and methodological divergence between the different approaches, we argue that a regional assessment requires blending a top-down analysis motivated by climate change scenarios with a place-based analysis of vulnerabilities and options for adaptation, in which both physical and social factors contribute to the spectrum of possible adaptations. Monitoring changes in the physical environment is a necessary precondition for an assessment of natural and anthropogenic stressors, vulnerabilities, and adaptive capacities at most geographic scales; however, it is not sufficient. Sensitivity to stressors and the adaptation spectrum is strongly modulated by economic, political, and social factors. The case of arid Central Asia is but one example of this complex dynamical interactivity between human and environmental systems.

2.2. Human dimensions of vulnerability

A complex and multifaceted concept with social, economic, physical and environmental dimensions, vulnerability can be defined and approached in more than one way. Physico-environmental vulnerability to climate change suggests that biophysical impacts of climate change will occur through various mechanisms, and that these may have significant influence on the future viability or integrity of physical resources (Adger et al., 2005). Thus, agricultural and silvicultural productivities will be vulnerable to climate change, if the shifts in weather patterns can impact yields significantly (Fischer et al., 2005). Yet, the role of a variable and changing physical environment should not be overemphasized. In many geographic regions today, the vulnerabilities of the human systems arise less from physical sensitivities of the resource base that supports the human system than from the social, economic and political factors than affect how the human system interacts with the resource base. For example, southern Kazakhstan — where rainfall is very unreliable and soils are poor — is economically more robust due to political stability and rich geological resources; it is thereby less vulnerable to climate change in comparison with neighboring Uzbekistan and Kyrgyzstan. Similarly, Finland or Canada might be more resilient to adverse impacts of climate change compared to those parts of Russia that have a similar physical geography. Attempts have been made to use the level of wealth (typically GDP) as a measure of human vulnerability of a country or region, but this approach has serious limitations. In many cases, social capital, an indicator of equity in income distribution within countries, is a more important factor of vulnerability and resilience than GDP per capita (e.g., Cuba outperforms Brazil in most health indicators); furthermore, political and institutional instabilities can undermine the influence of economic development (e.g., Russia in the mid-1990s).

Human dimensions of vulnerability that involve socio-cultural, political and economic aspects of vulnerability, represent the exposure of groups of people or individuals to environmental stress or hazards. Stress in the social sense encompasses disruption to the livelihoods of individuals or groups and the resulting adaptations forced by the changing physical environment (Adger et al., 2005). Human dimensions include cultural and political characteristics—the strength of civil society, the societal view of nature, measures of a region's economic wealth, equity, and welfare of its citizens, diversity of natural resources and sources of income—and the ability of institutions to cope with environmental stresses and to implement adaptations (Fischer et al., 2005; Handmer et al., 1999).

Human vulnerability to climate variability and change and non-climatic causes of vulnerability are difficult to separate (Parry et al., 2004). Vulnerability analysis therefore requires cross-disciplinary approaches to integrate biophysical and societal indicators.

2.3. Vulnerability to the long-term climate change, vs. short-term events

Societal responses to droughts, floods, and other short-term extreme weather events can provide analogues to the level of human vulnerability and ability to cope with and adapt to climate change (Adger et al., 2005; McMichael and Kovats, 2000). Hazards refer to the nature of extreme events in the environment, defined by the characteristics of intensity, severity, speed, duration, and areal extent. Despite many differences between the cause–effect mechanisms of the short-term hazards and the long-term climate change the societal responses to natural disasters can provide good lessons for planning adaptations to and mitigation of regional climate change. Rapid land use changes caused by human events (e.g., conflicts, economic shocks) represent another group of short-term changes that often determine the resilience and vulnerability of the system (de Beurs and Henebry, 2004).

The extent to which short-term climate variability and, hence, the frequency and intensity of extreme weather events will be altered by climate change remains uncertain, although there is also growing evidence that future climate change is likely to increase the temporal and spatial variability of temperature and precipitation in many regions (IPCC, 2007).

2.4. Adaptive responses to climate change

Analysis and development of adaptations to socio-economic and environmental effects of climate change are inexorably linked to vulnerability analysis at all geographic scales. Here we follow IPCC studies that define adaptation as "adjustments in ecological–social–economic systems in response to actual or expected climatic stimuli, their effects or impacts" (IPCC and WGII, 2007, Ch.17). The capacity of a sector or region to adapt to climatic changes depends on many non-climatic factors, such as level of economic development and investments, access to markets and insurance, social and economic policies, cultural and political considerations, the rule of law regarding private and public properties, including natural resources, etc. Appropriate adaptations can reduce negative impacts of biophysical changes or take advantage of the new opportunities presented by changing climate conditions; thus, adaptation analysis is an important component of any policy response to climate change (Mizina et al., 1999; Smit and Skinner, 2002). The significant role of adaptation as a policy response by government has also been recognized internationally. For example, the Kyoto Protocol Article 10 commits parties to promote and facilitate adaptation and deploy adaptation technologies to address climate change.

2.5. Adaptations and coping strategies

Impact studies on agriculture, water resources, coastal zones, forestry, and human health suggest that numerous adaptation options are available to governments, businesses, communities, and individuals to reduce vulnerability to climate change risks. A typology of coping and adaptation strategies is an important component of any decision-making process necessary to reduce human vulnerability of a region.

McMichael and Kovats (2000) define three modes of adaptations to climate-induced health hazards: biological, behavioral, and social. Biological or passive adaptations include, for example, physiological adaptation of individuals to a change in background temperature and increase of immune activity following exposure to infection. Behavioral adaptation relates to the personal level: individuals take action to reduce their risk from health hazards arising from climate change. Social adaptation occurs at the community level, via collective changes in behavior, institutional practices, and technical interventions, such as housing design, immunization programs, food distribution systems, health care facilities and vector control (McMichael and Kovats, 2000). Patz (2001) has developed a comparable typology of adaptations to climate-induced health hazards that includes legislative, engineering, and personal adaptations. While the first two categories occur at a national or community level, the last category points to behavioral changes by individuals.

Several typologies of adaptation have been developed in the literature on agricultural vulnerability and food production (Fischer et al., 2005; Mizina et al., 1999; Smit and Skinner, 2002). Smit and Skinner (2002, p. 93) define key distinguishing characteristics of adaptation: intent and purposefulness, timing and duration, scale and responsibility, and form. They also identify adaptation pathways using four not mutually exclusive categories: (1) technological development, (2) government programs and insurance, (3) production practices, and (4) financial management. This typology, although developed for food security, provides a useful framework for exploring adaptive strategies and options in other sectors of human vulnerability.

The distinction between immediate coping strategies and longer term adaptations is somewhat fuzzy. Coping strategies are actions taken by communities or individuals when faced with adverse impacts of climate change or natural hazards. They are, in effect, short-term adjustments to extreme events (Adger et al., 2005). Coping strategies are usually involuntary and lead almost inevitably to a different state of vulnerability. Adaptation may involve broader responses to stress, such as changing income sources, migration or other significant livelihood changes, as well as sustained intervention by government agencies.

3. Climate change and variability in Central Asia

For many countries arising from the ashes of the former USSR, the direct environmental impacts of the manifold political, economic, and social changes will overshadow impacts linked to global climate change for the next decade, at least. Some land changes of the last fifteen years may exacerbate some aspects of vulnerability of arid Central Asia to climate change, while others might enhance the region's resiliency and promote adaptations.

To foresee potential social, economic, and environmental responses of a region to climate change, it is critical to examine the regional climatic variability and change of the past and present as well as future projections. Palaeoclimatic reconstructions, historical meteorological data, and AOGCM scenarios can provide useful information about regional climatic changes across a variety of time scales.

3.1. Climate change in Central Asia in the past and present

Central Asia has a distinctive continental arid and semi-arid climate with hot, cloudless, dry summers and moist, relatively warm winters in the south and cold winters with severe frosts in the north. Precipitation throughout most of the region 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 Mediterranean, migrate north-eastwards, and regenerate over the Caspian Sea. 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.

Palaeoclimatic and archaeological data indicate that the climate of arid and semi-arid Central Asia has experienced many past fluctuations that might be comparable with future climate change. Based on the early-to-mid-Holocene reconstructions, the arid zones of Central Asia may become moister as a result of global warming, due to an expected southward shift and probable intensification of the westerly cyclones (Lioubimtseva et al., 2005).

Meteorological data series available since the end of the 19th century show a steady increase of annual and winter temperatures in this region. Both aggregated temperature data downloaded from the Climate Research Unit dataset (Jones et al., 1999) and our earlier study of individual weather stations across the region (Lioubimtseva et al., 2005) indicate a steady significant warming trend in this region (Fig. 1). Unfortunately, few stations in Central Asia have a period of observations spanning more than a century; most stations have records for 60–65 years with gaps. Steady temperature increases during the past century might be an indication of a general spatial shift in the atmospheric circulation in Central Asia. The recorded increases in both mean annual and seasonal temperature trends are likely to result from the decreasing intensity of the southwestern periphery of the Siberian high in winter and the intensification of summer thermal depressions over Central Asia.

While all available station datasets consistently indicate the warming trend in Central Asia during the past century, the precipitation trends are highly variable, reflecting the region's high diversity of landscapes and land use changes. Precipitation records available in this region since the end of the 19th century show a slight decrease during the past 50–60 years in the western part of the region, little or no change throughout most of the region, and a relatively significant increase in precipitation recorded by the stations surrounded by irrigated lands. This precipitation decrease in the area between the Caspian and Aral Sea mainly occurred since 1960, and it 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 resulted in significant changes in albedo, hydrological cycle, and mesoclimatic changes throughout the western parts of Kazakhstan, Uzbekistan, and Turkmenistan (Varushchenko et al., 2000). While the overall regional trend in this region indicates a small decrease in rainfall throughout the region, data series from the stations located in quasi-pristine ecosystems significantly differ from those reported by the stations located on irrigated lands (Lioubimtseva et al., 2005; Small and Bunce, 2003). Despite the general decrease of precipitation in Central Asia during the past 50 years, the opposite trends have occurred in the vicinity of the major oases of Kazakhstan, Uzbekistan, and Turkmenistan (e.g., Urganch, Bokhara, Toshkent, Murgab, Tedjen, and Ashgabat). This phenomenon is likely linked to the human-induced local climatic change caused by the expansion of irrigated lands (Pielke et al., 2007).

3.2. Projections of climate change in Central Asia

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 greenhouse gas concentrations. Our earlier assessment of the annual, seasonal and monthly AOGCM scenarios for Central Asia

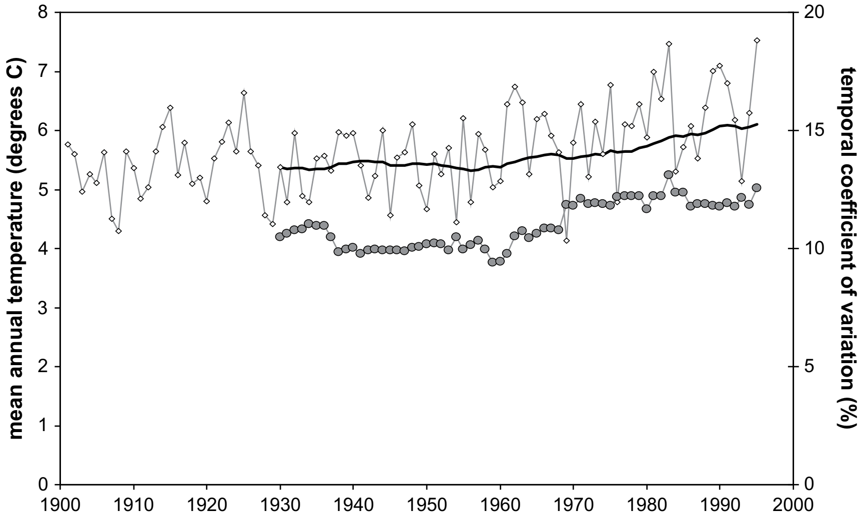

Fig. 1. Inter-annual variability and change in the mean annual temperature over Central Asia during the 20th Century.

and their probabilities used in the Third IPCC Report (IPCC, 2001) indicates a generally good agreement among the models that the current trend of temperature increase in arid Central Asia is likely to continue (Lioubimtseva, 2007; Fig. 3).

We have further examined the regional scenarios derived from four models recently evaluated by IPCC in the Fourth Assessment Report among twenty-three AOGCMs (IPCC, 2007). Annual and seasonal temperature and precipitation scenarios from HadCM3 (UK Meteorological Office), CSIRO-Mk3 (Australia's Commonwealth Scientific and Industrial Research Organization), ECHAM5 (Max-Planck-Institute for Meteorology), and CGCM3 (Canadian Centre for Climate Modeling and Analysis) were examined under different IPCC SRES policy scenarios (Nakicenovic et al., 2000) available from the IPCC Data Distribution Centre. Our comparison of the simulated and recorded baseline climatology for the period 1961–1990 available from the Climatic Research Unit Dataset (Jones et al., 1999) suggests that all four models demonstrate a good level of sensitivity for arid and semi-arid Central Asia. Mean annual temperature and precipitation changes in Central Asia under four emission scenarios are summarized in Tables 1a–d.

The ranges of precipitation projections produced by AOGCMs are still uncertain for Central Asia and elsewhere. The majority of climate models project a slight decrease in precipitation rate over most of the region (~1 mm/day by 2050) with a stronger decrease in the western and southwestern parts of the region and a very slight increase in the northern and eastern part of Central Asia (~1 mm/day). However, given the low absolute amounts of precipitation and high inter-annual, seasonal, and spatial variabilities of precipitation across the region, the changes in precipitation rate projected by the AOGCMs cannot be deemed reliable (Lioubimtseva, 2007). 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 project.

In the IPCC Special Report on Emission Scenarios (SRES), policy scenario families A1, A2, B1, and B2 follow narrative storylines, describing the relationships between the forces driving greenhouse gas and aerosol emissions and their evolution during the 21st century for large world regions and globally. Each storyline represents different demographic, social, economic, technological, and environmental developments that diverge in increasingly irreversible ways (Nakicenovic et al., 2000). Despite the criticism of IPCC SRES for simplification of some economic indicators, several detailed studies have recently demonstrated that the IPCC SRES scenarios remain plausible in most cases (IPCC and WGI, 2007; Van Vuuren and O'Neil, 2006).

Temperature changes are projected to increase by 3–5 °C around 2080 and all the four AOGCMs agree that the warming will be accompanied by a further increase of aridity (Tables 1b and d; Fig. 2). While some of the earlier AOGCM runs used in the Second and Third IPCC reports suggested the high likelihood of a modest increase in rainfall (1 mm/day or less) throughout most of the region, most of the models used in the Fourth Assessment do not confirm these projections. ECHAM and CSIRO models suggest a possibility of insignificant precipitation increase only over the eastern part of Central Asia (roughly east from 70°E), while the Hadley and Canadian models suggest that the precipitation will decrease throughout the entire region under all policy scenarios by a very small amount. However, given the very small order of magnitude of the precipitation rate changes projected by all models (<1 mm/day) and high temporal and spatial variability of precipitation, the changes in temperature will be the stronger factor affecting potential vulnerabilities across Central Asia (Fig. 3).

The rates of the projected changes significantly differ across seasons, with much higher temperature changes generally expected during the winter months. Table 2 further illustrates the projected changes in mean temperature, maximum temperature, precipitation, vapor pressure, cloud cover, and wind speed based on the HadCM3 A1F scenario for winter, spring, summer, and fall seasons (Table 2).

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, Pakistan) from Central Asia. 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 towards higher aridity is projected to be more significant west from 70 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 (IPCC, 2007). 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 that 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 vs. mesoclimate changes induced by regional land use change.

There are several sources of uncertainties associated with these scenarios. The 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 (IPCC, 2001). Others uncertainties relate to the simulation of various feedback mechanisms in models concerning, for example, water vapor and

Table 1a
Annual temperature scenarios for 2050, °C relative to 1961–1990.

AOGCM/SRES policy	HadCM3	ECHAM4, 5	CSIRO-Mk3	CGCM3
A1a	2.87–4.55	ND[a]	3.24–5.49	ND
A2a	2.68–3.61	2.87–3.61	2.87–3.99	2.12–4.55
B1a	1.93–2.49	ND	1.93–2.05	ND
B2a	1.93–2.87	2.12–3.24	2.12–3.80	1.93–3.24

[a] No data.

Table 1b
Annual precipitation scenarios for 2050, mm/day relative to 1961–1990.

AOGCM/SRES policy	HadCM3	ECHAM4, 5	CSIRO-Mk3	CGCM3
A1a	(−0.6)–0.59	ND	(−0.43)–(−0.08)	ND
A2a	(−0.49)–0.42	(−0.09)–0.42	(−0.26)–0.08	(−0.26)–0.08
B1a	(−0.43)–0.08	ND	(−0.26)–(−0.08)	ND
B2a	(−0.43)–0.08	(−0.09)–0.45	(−1)–1	(−0.09)–0.08

Table 1c
Annual temperature scenarios for 2080, °C relative to 1961–1990.

AOGCM/SRES policy	HadCM3	ECHAM4, 5	CSIRO-Mk3	CGCM3
A1a	4.92–7.17	NA	3.99–5.86	NA
A2a	2.87–3.80	5.11–6.05	3.80–5.30	4.36–6.42
B1a	2.49–3.24	NA	3.43–4.74	NA
B2a	2.87–3.99	2.87–3.99	3.80–3.99	2.68–4.18

Table 1d
Annual precipitation scenarios for 2080, mm/day relative to 1961–1990.

AOGCM/ SRES policy	HadCM3	ECHAM4, 5	CSIRO-Mk3	CGCM3
A1a	(−0.77)–(−0.09)	NA	(−0.26)–0.08	NA
A2a	(−0.43)–(−0.09)	(−0.26) –0.08	(−0.26)–(−0.09)	(−0.43)–(−0.09)
B1a	(−0.43)–(−0.09)	NA	(−0.26)–(−0.09)	NA
B2a	(−0.26)–(−0.09)	(−0.26) –0.08	(−0.26)–(−0.09)	(−0.26)–(−0.09)

warming, clouds and radiation, ocean circulation and ice and snow albedo (Arnell, 2004; IPCC and WGI, 2007).

3.3. Recent land change in Central Asia

Monitoring land change in a region as large and as sparsely and unevenly populated as Central Asia presents multiple challenges. At over four million square kilometers, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan cover an area larger than India, Pakistan, and Bangladesh combined, and are home to more than 60 million people. There is a dearth of data, including few extant regional land cover/land use maps and global land cover maps that are too broad thematically to be of much use in change analysis. The satellite data record is relatively short and of uneven quality. Yet, it contains valuable synoptic views into the land surface of the recent past.

Much land cover mapping in the past three decades has relied on data that has fine (<100 m) spatial resolution relative to the phenomena of interest and little or no temporal resolution. Change detection and quantification methods used with these classified data focused predominantly on shifts in composition, transitions between specific classes of interest, and changes in spatial pattern occurring between two or more periods of interest. With the emergence of land cover mapping using synoptic sensors that provide imagery at coarser spatial but higher temporal resolutions (e.g., AVHRR, VEGETATION-SPOT, MODIS) and the concomitant improvement in numerical weather prediction models, there has been increasing scientific interest in the interactions between the land surface and the lower portion of the atmosphere (Feddema et al., 2005; Osborne et al., 2007; Pielke et al., 2007).

The spatial resolution of the longest image time series relating to surface vegetation dynamics is 8 km, far coarser than the scale of almost every land use decision. These synoptic pixels thus include a mixture of many land covers. However, the enhanced temporal resolution of these sensors enables seasonal portraits of land surface condition that can provide important insights into functional aspects of land cover. Characterizing these phenologies of the land surface enables linkage of vegetation growth and development to weather, land management, and disturbance (de Beurs and Henebry, 2004). The Normalized Difference Vegetation Index (NDVI) provides a powerful indicator of green vegetation in synoptic imagery. NDVI exploits the differential spectral reflectance that is characteristic of green vegetation; specifically, low in red and high in near infrared. Land surface phenology (LSP) provides an important window onto land surface variability and change, especially in agricultural lands. LSP models track temporal changes in a vegetation index such as NDVI as a function either of calendar time or biometeorological time, such as accumulated growing degree-days (de Beurs and Henebry, 2004).

The agricultural sector has been the principal source of extensive land change in Central Asia in recent decades. A canonical land change event of the 20th century was the Virgin Lands program of Khrushchev that resulted in the rapid transformation of 36 Mha of steppe into croplands for grain production (Douglas Jackson, 1962). Areal expansion of irrigated agriculture was not so dramatic, but the impact of decades of water withdrawals from the Syr Darya and Amu Darya to irrigate cotton in particular have desiccated and polluted the lands bordering in the Aral Sea (Glantz, 2005; Micklin, 2007; Saiko and Zonn, 2000).

In the past two decades since the decline and collapse of the Soviet Union, there have been three significant aspects of land change in Central Asia: (1) land degradation caused by intensive irrigated cotton cultivation and the associated environmental crisis of the Aral Sea Basin; (2) deintensification of agriculture in the rain-fed grain cultivation semi-arid zone across northern Kazakhstan; and (3) the collapse of livestock production within the entire region and the divergent national trajectories on the rebound. As the irrigation-related trends in the Aral Sea basin have been well documented (Glantz, 2005; Micklin, 2007; Small and Bunce, 2003), we will highlight the other land changes.

Socio-political institutions are important for directing and influencing agricultural policies, businesses, and markets, especially in command economies. The dissolution of the Soviet Union and its trade network, the Council for Mutual Economic Assistance (CMEA or Comecon), shocked the agricultural sector of the newly independent Central Asian states. With little or no access to fertilizers, pesticides, subsidies, and markets, a substantial amount

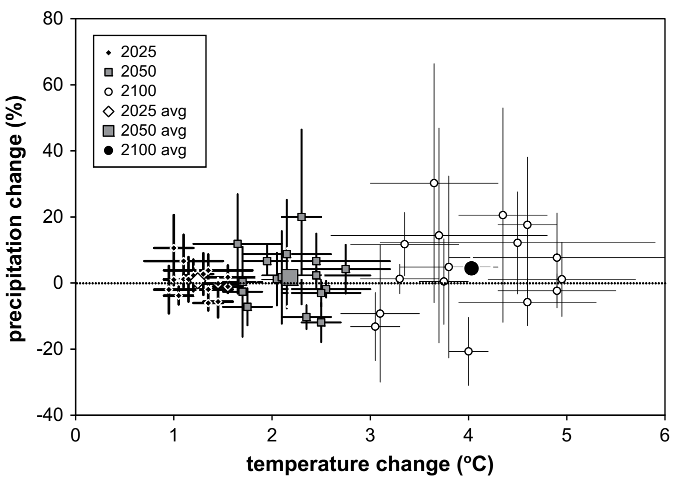

Fig. 2. The range of precipitation and temperature changes in arid Central Asia, predicted by 17 AOGCMs.

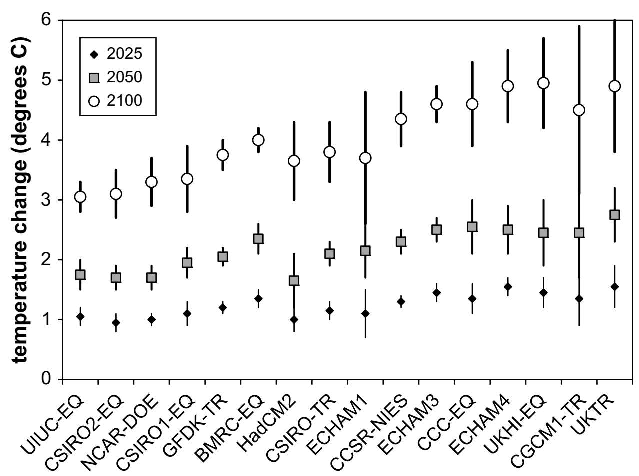

Fig. 3. Temperature changes projected by the AOGCMs for arid Central Asia.

Table 2
HadCM-AF1 climate changes fields scenario for 2050, relative to 1961–1990.

Seasonal changes	Winter	Spring	Summer	Fall
Mean temperature, C	1.56–4.92	2.87–3.99	3.24–7.36	3.05–3.99
Max temperature, C	1.96–4.17	2.33–3.99	2.88–9.33	2.88–3.99
Min temperature, C	1.88–4.92	1.88–3.30	3.99–5.33	2.69–3.91
Precipitation, mm/day	0.43–0.08	−0.26–0.08	−1.11–0.09	−0.7–0.09
Vapour pressure, hPa	−7.55–1.62	−8.29–0.06	−17.5–63.1	−5.33–0.14
Cloud cover, %	−0.07–0.01	−0.5–0.5	−0.25–0.01	−0.09–0.01
Wind speed, m/s	−0.47–0.15	−0.03–0.17	−0.31–0.25	−0.15–0.05

of land was idled with longer fallow periods (Fig. 4a, Appendix B). Furthermore, if the government statistics are held to be reasonably accurate, there were significant shifts in crop composition that differed among the Central Asian states as a result of internal policies regarding land reform and farm restructuring (Sievers, 2003). For example, Turkmenistan increased significantly its cultivation of grain (Fig. 4b, Appendix B) while decreasing production of feed products by half (Fig. 4c, Appendix B). The deintensification of grain production in northern Kazakhstan was sufficiently great to produce significant observable changes in regional LSPs, despite the high climatic inter-annual variability (de Beurs and Henebry, 2004). The form of change in LSP observed in northern Kazakhstan had two aspects. First, a significantly higher NDVI was observed at the start of the growing season. Second, the peak NDVI values occurred at significantly fewer accumulated growing degree-days (calculated using a base temperature of 0 °C), indicating a shift towards an earlier seasonal peak in vegetation. These changes in LSP were interpreted as resulting from increases in fallow area and fewer herbicides available to control weeds during the 1990s (de Beurs and Henebry, 2004). In the irrigated areas of Kazakhstan, there were no significant shifts toward earlier peaks, but there were higher NDVI values at the beginning of the observed growing season, leading de Beurs and Henebry (2004) to speculate that shifts in irrigated areas were due to improvements in efficiencies. A more general interpretation would be changes in land management practices, including crop types and composition.

Another explanation of an observed increase in NDVI throughout arid Central Asia during the past decades can be linked to the accelerated growth of biogenic crusts (microphytic communities formed by desiccation-tolerant mosses, fungi, algae, and cyanobacteria). These crusts are commonly known as "karakharsangs" (black mosses) in Kazakhstan, Uzbekistan, and Turkmenistan. Desert and semi-desert landscapes have a very sparse vegetation cover; as a result more than 65% of the surface reflectance signal captured in very coarse-resolution pixel NDVI data is coming from the soil or, in most cases, from the biogenic crust covering the soil (Lioubimtseva, 2007). Biogenic crusts on the soil surface can vary from a few millimeters to several centimeters in thickness and play a significant role in arid ecosystems controlling such processes as water retention and carbon and nitrogen fixation in soils. However, these crusts are fragile and cannot thrive in areas frequently visited by livestock. In the Kara-Kum and Kyzyl-Kum deserts of Turkmenistan and Uzbekistan, the accelerated growth of such biogenic crusts has been observed during the past 40–50 years and has been attributed to a gradual decrease in grazing pressure on the desert rangelands. This trend has been further accelerated by the livestock reduction after 1991 (Fig. 5a, Appendix B).

Across the Central Asian States, the impact of the transition on the stocks of live animals was severe (Suleimenov et al., 2006). From the perspective of land change, the stock of grazing sheep is of particular interest due to their trampling and close cropping of the surface vegetation. In Kazakhstan, 33.9 million sheep were in stock 1992. By 1999 that number had dropped 74% to 8.6 million, and in 2005 the stock had raised to 11.4 million (FAOSTAT, 2008). In 1992 Kazakhstan had 57% of the sheep in Central Asia; in 2005 that share was only 29%. The total number of sheep in Central Asia in 2005 was 40 million or 67% of what it had been in 1992 (FAOSTAT, 2008). The sheep stock time series indexed to 1992 (Fig. 5a and b, Appendix B) show the divergence among the Central Asian States from collapse and slow recovery in Kazakhstan to steady growth in Turkmenistan. From a 9% share of the regional sheep stock in 1992, Turkmenistan reached a 36% share in 2005 equivalent to 14.3 million sheep (FAOSTAT, 2008). During the Soviet period livestock production in the republics of Central Asia was specialized: Uzbekistan and Turkmenistan focused on breeding Karakul sheep for export; Tajikistan raised goats for fiber; Kyrgyzstan had many sheep for its size; and Kazakhstan was the largest livestock producer, raising much meat for the export market (Suleimenov et al., 2006). The transition to independence required the Central Asian States to adjust policies with an eye to self-sufficiency, leading to a collapse of feed production (Fig. 4c, Appendix B) and a contraction in wool production (Suleimenov et al., 2006). The extent of regional land change induced by a shift from 80 million cattle, sheep, and goats in 1992 down to 44 million in 1999 and up to 63 million in 2005 remains to be seen, due to regional reallocations of grazing pressure that Fig. 5b (Appendix B) suggests. Fewer grazers meant greener pastures and LSPs shifting to earlier and higher peaks (de Beurs and Henebry, 2004).

Lioubimtseva (2007) also speculated that in addition to the decrease of grazing pressure of the past decade the accelerated growth of biogenic crusts observed in many parts of the Kara-Kum and Kyzyl-Kum deserts might be favored by the increasing CO_2 concentrations in the atmosphere. Many global biogeography models and CO_2 enrichment experiments suggest the CO_2 fertilization impacts not only microphytic communities but also higher vegetation. The deserts and semi-deserts of Central Asia are dominated by vegetation with the C_3 photosynthetic pathway with few C_4 and CAM species. Theoretical considerations and modeling experiments suggest that plants using the C_3 photosynthetic pathway will respond more strongly to increased CO_2 availability than species with resource-efficient C_4 pathway (Lioubimtseva et al., 2005). An increased atmospheric CO_2 concentration has direct and relatively immediate effects on two important physiological processes in plants: it increases the photosynthetic rate while decreasing the time that stomata are open, thus reducing the rate of water loss. This combination of 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 CO_2.

4. Major sectors of human vulnerability in Central Asia

Although there are many aspects of human vulnerability of climate change, we focus only on three major aspects of human vulnerability in Central Asia since the collapse of the USSR: food security, water stress, and human health and well being. There are multiple linkages between food production, water use, and health, and these three aspects of human vulnerability are particularly dependent on the regional climate and land use (Table 3).

4.1. Food security

Climate aridity is the primary constraint limiting the portion of land available for agriculture and livestock production in Central Asia. (Terrain is the secondary key constraint.) Most croplands in Turkmenistan, Uzbekistan and southern Kazakhstan are irrigated and agriculture is potentially highly vulnerable to climate change because of degradation of limited arable land. Almost two-thirds of domestic livestock are supported on grazing lands, although in Kazakhstan a significant share of animal fodder also comes from crop residues.

Climate change can affect food production in Central Asia in several ways. Changes in temperature and precipitation regimes are likely to impact agro-ecological potential and constraints, including (1) changes in the area suitable for growing rain-fed production of cereals and other food crops, (2) changing sustainable stocking rates, and (3) modifying crop irrigation requirements.

The results of modeling studies suggest that the Central Asian region as a whole is likely to benefit from the increase in winter temperatures and a longer growing season, CO_2 fertilization effect and projected increase in the water-use efficiency by agricultural crops, and probably also winter rainfall increase in the eastern part of the region (Fischer et al., 2005; Parry et al., 2004). According to an agro-ecological zoning study by IIASA (International Institute for Applied Systems Analysis), almost 90% of land in this region has constraints for rain-fed crops: almost 76% of the area is too arid, 4% too steep, and about 7% have insufficient soils. Out of the total 414 million hectares approximately 45 million hectares are currently used for cultivation of food and fiber crops and more than 14 million hectares require irrigation (Fischer et al., 2005). The IIASA Basic Linked System models driven by the HadCM3-A1FI scenario suggest that, due to the regional climate changes by 2080, the total area with constraints will decrease to 84% and only 60% of the region would be too arid for rain-fed agriculture. On the other hand, the area in Central Asia deemed unsuitable for agriculture due to insufficient soils is projected to reach 17% by 2080 (Fischer et al., 2005). The same studies suggest that the potential for rain-fed cultivation of major food and fiber crops in this region could increase by 2080 due to climate change (primarily due to the CO_2 fertilization effect on C_3 plants). However, this later projection is not well supported by the majority of the recent AOGCM experiments used in the IPCC-AR4 that suggest that most of the region is likely to become more — not less — arid and probably more variable. A crop suitability index — ranging from not suitable (0) to very suitable (≥75) — is projected to increase based on the scenarios of all 12 AOGCM scenarios used in the IIASA study. The current suitability index for Central Asia is 13. However, the degree of such increase is highly uncertain, ranging from 9% based on the CCC-A2 scenario to 60% based on HADCM3-A1F1 (Fischer et al., 2005).

AOGCM scenarios also revealed substantial geographic differences across the region. The major differences in the magnitude of projected temperature changes, however, result from the wide range of the SRES socio-economic pathways. The climate change scenarios discussed in Section 2 project some temperature increase between 2.4 and 4.7 °C under B1 scenario and from 3.9 to 7.1° under A1 by 2080 with a particularly notable increase in winter temperatures. Precipitation scenarios vary, suggesting a slight increase in the eastern part of the region and a decrease in the west. However, even the wettest scenario (ECHAM 4), projecting a precipitation increase of 0.08–0.45 mm/day, does not seem to be sufficient to offset the aridity caused by elevated temperatures, especially in the southern and western sectors of the region (Turkmenistan, Uzbekistan and southwestern Kazakhstan). CGCM3 and HadCM3 scenarios suggest a risk of even higher levels of aridity in the southwestern part of Central Asia and a very insignificant increase in the northeast under all socio-economic scenarios, and the greatest increase of aridity throughout the entire region is projected by the CSIRO model. The recent IPCC multi-model assessment also points out that the median precipitation change in Central Asia by the end of the 21st century is −3% in the annual mean, with −13% in summer (dry season) and +4% in winter (IPCC and WGI, 2007, Ch.11). These findings are consistent with the earlier multi-model study of Meleshko (2004). Combination of elevated temperatures and decreased precipitation in the deserts and semi-deserts of Central Asia could sharply increase potential evapotranspiration, leading to very severe water stress conditions with dramatic impacts on agriculture and livestock production. Climate models agree that the western part of the region (deserts of Turkmenistan and Uzbekistan and the Caspian coast) would be particularly vulnerable to the increase in potential evapotranspiration. Yet, perhaps of bigger concern in estimating impacts from temperature and precipitation changes on food production are the potential changes in variability and extreme events, such as frosts, heat waves, droughts, and heavy rains. Extreme events are responsible for a disproportionately large part of climate-related damages and sensitivity of extremes to climate change may be greater than one would assume from simply shifting the location of the climatological distribution. The global-scale study of Tebaldi et al. (2006), based on analysis of ten indicators of temperature and precipitation-related extremes computed by nine AOGCMs used in the IPCC-AR4, suggests that agricultural production in the Central Asian region could benefit from the fewer frosts and an increasing length of the growing season. It could also be negatively affected by the increasing variability of precipitation and number of dry days,

Table 3
Aspects of human vulnerability in the context of different land changes.

Land changes / *Aspects of human vulnerability*	Changes in irrigated agricultural landscapes in arid zones & the Aral Sea degradation	Changes in rain-fed agricultural landscapes in semi-arid zones (Virgin Lands)	Changes in livestock and pastoral landscapes in arid & semi-arid zones
Food security	Malnutrition High dependence on imports of food	Dramatic increase of cereal production in the 1950s followed by its decline in the 1980s	Disruption of traditional semi-nomadic systems in the 1920s Dramatic decline of livestock in the 1990s
Water stress	Deterioration of water quality and quantity Shortage of drinking water in the region	Increased water consumption	Decrease of water consumption on arid rangelands (1990s)
Human health	Increase in water-borne diseases, massive exposure to pesticides and fertilizers. Increase in infant mortality, decrease in life expectancy	Massive exposure to pesticides and fertilizers	Deterioration of traditional diet

particularly at higher elevations and for rain-fed crops and orchards (Tebaldi et al., 2006).

Another factor that is likely to affect productivity agriculture in the Aral Sea basin and adjacent areas is increasing surface runoff in the adjacent mountain systems of Tien-Shan and Pamir-Alaj. The projected increase in runoff could potentially accelerate soil erosion, especially in case of increasing frequency of catastrophic precipitation. Several multi-model assessments (Arnell, 2004; Shiklomanov and Rodda, 2001), suggest that the volume of runoff from glaciers in Central Asia may increase three-fold by 2050, leading to significant changes in the regional pattern of water and land use.

4.2. Water stress

Water issues take on special importance in Central Asia. With the rapidly shrinking Aral Sea, transgression of the Caspian Sea, an immense cotton industry, huge deserts, advancing desertification, and concerns over potable water Central Asia's water problems are complex and compelling. What would be the impact of climate change on this highly vulnerable area? Growing demand for water for irrigation, high levels of water pollution, and frequent droughts and widespread land degradation are among the key water-related issues for the region that already threaten human development and security. Overall water withdrawals in the Central Asia States have increased from 37 km^3/year in 1950 to 102 km^3/year in 2000 and are projected to reach 122 km^3/year by 2025 (Shiklomanov and Rodda, 2001). The core regional problem, however, is not the lack of water resources but rather their management and distribution. In fact, parts of Central Asia have a great amount of water: Kazakhstan, for example, claims more than 85,000 rivers and streams, and 56% of its 100 km^3 annual river flow is formed on the territory of Kazakhstan itself (Sievers, 2003). A lack of coordination among irrigation systems, pervasive soil degradation, and inter-basin transfers are the persistent water problems in the region.

Although differences in water stress at the country level are considerable, these are smaller compared to the differences among the geographic regions within the countries. The Aral Sea states of Kazakhstan and Uzbekistan are impacted by local climate change caused by the reduction of water volume in the Aral Sea and the resulting toxic salt and dust-storms. The desiccation of the vast body of water has changed the local climate and has impacted the hydrometeorology of the entire Aral Sea basin, far beyond the limits of the lake area. The salt content of the Southern Aral Sea now ranges between 100 and 150 g/L, which is more than triple the salinity of the open ocean (Micklin, 2007; Small and Bunce, 2003). The quality of water for human consumption is poor in many parts of Central Asia. The same processes that contributed to the Aral Sea degradation—excessive irrigation and mismanagement of water—have also resulted in the rise of groundwater table, contaminating the groundwater with high levels of salts and other minerals (Saiko and Zonn, 2000). Groundwater quality ranges in the region from a minimum of l.5 g/L TDS (total dissolved solids) to 6 g/L TDS and drinking water reaches levels of up to 3.5 g/L TDS. In Karakalpakstan (an autonomous republic of Uzbekistan adjacent to the Aral Sea) about 65% of drinking water samples tested did not meet national standards of 1 g/L TDS (AQUASTAT, 2007). There is a growing concern that water stress in Central Asia may lead to open conflicts over water, weakening the states to such an extent that they lose their capacity to address other threats to stability and development (Glantz, 2005; Sievers, 2003).

The temporal and spatial availability of water is expected to be highly sensitive to projected climate change (Alcamo and Henrich, 2002; Arnell, 2004; Shiklomanov and Rodda, 2001). Assessment of the water stress can be depicted as the current average annual withdrawals-to-availability ratio, where stress is indicated by a ratio of withdrawals-to-availability is greater than 0.4. The WaterGAP modeling study (Alcamo and Henrich, 2002) indicates severe water stress already occurring in all Central Asian countries of the former USSR and the adjacent parts of Russia from the Caspian lowland to the border with Mongolia. Water stress is a useful measure of human vulnerability to climate change as it measures the degree of demand on water resources by the users of these resources, including agriculture, industries, and municipalities. A larger increase in water stress represents a greater sensitivity of the water resources to global change. The future impacts of climate change on water resources are strongly dependent on the current conditions of existing water supplies and water control systems. Given already very high level of water stress in many parts of Central Asia, projected temperature increases and precipitation decreases in the western part of Kazakhstan, Uzbekistan, and Turkmenistan are very likely to exacerbate the problems of water shortage and distribution.

Since 2000, a series of droughts has affected Turkmenistan, Uzbekistan, Tajikistan, Iran, Afghanistan, and Pakistan. These droughts have amply demonstrated the very high human vulnerability of this region to precipitation deficits. Agriculture, animal husbandry, water resources, and public health have been particularly stressed across the region as a result of the recent drought.

The surface resources of Central Asia are primarily generated in the mountain glaciers. Significant temporal variability in the runoff of the trans-boundary rivers is largely controlled by hydrometeorological changes in the adjacent mountainous areas of Pamir, Tien-Shan, and Altai. Changes in the climatic and hydrological process in the mountains of Kyrgyzstan and Tajikistan are well documented and indicate a steady increase of precipitation during the past decades (Meleshko, 2004), but also a decrease of glacial volume and area. The regional modeling study driven by five AOGCMs under a business-as-usual scenario conducted by Uzhydromet (Hydrometeorological Service of Uzbekistan) suggests that by 2030–2050 the temperature in mountains of southeastern Uzbekistan will increase by 1.5–2.5 °C, causing higher runoff of the Amu Darya, Zeravshan, and Syr Darya due to accelerated melting of the mountain glaciers and precipitation will increase by 100–250% (Miagkov, personal communication, 2006). Glacial melt in the Pamir and Tien-Shan ranges is projected to increase, initially increasing flows in the Amu Darya, Syr Darya, and Zeravshan systems for a few decades, followed by a severe reduction of the flow as the glaciers disappear (Glantz, 2005). Field data indicate that significant changes in the seasonality of glacial flows have already occurred as a result of warming (Braithwaite, 2002). Rapid melting of glaciers and particularly the Zerafshan glacier has increased runoff, which has led to an increase in the frequency of glacial lake outbursts that can cause devastating mudflows and avalanches in the mountainous regions of Tajikistan, Uzbekistan, Kazakhstan, and Kyrgyzstan.

In summary, regional processes—such as land use change and ineffectual water management systems—have stronger direct links to human vulnerability in Central Asia than global climate change. However, the projected effects of climate changes on regional hydrometeorology and hydrology are very likely to increase vulnerability by reducing the region's water supply.

4.3. Human health and vector-borne diseases

Climatic and ecological changes in Central Asia caused by the global and regional factors are likely to have profound impacts on human population health. Theoretically, changes in the regional climate and climate variability might both increase or reduce the risk of some infectious diseases (particularly water-borne and vector-borne infections). Increase of temperature and climate variability can also increase the exposure of populations to heat stress, extreme weather events, such as droughts, dust-storms and floods, contribute to the already existing water stress, and also stress the existing institutional systems of public health.

Rapid economic decline in the 1990s, combined with political instability in many parts of the region (especially Tajikistan), brought back epidemic typhus, tuberculosis, diphtheria, meningitis, and other infectious diseases to the Central Asian States and some other countries of the former Soviet Union (Elpiner, 2003; Small and Bunce, 2003). Deteriorating public health infrastructure, as well as socio-economic instability and population movement, were major contributing factors to disease resurgence (McMichael and Kovats, 2000). Malaria was nearly eradicated in the USSR by the end of the 1950s as a result of the comprehensive campaigns involving widespread of application of insecticides, anti-malarial therapy, land reclamation, water management, public health education, and many other measures. However, since the early 1990s, epidemic malaria—including the deadliest form of malaria caused by *Plasmodium falciparum*—has returned to Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan, as well as Armenia and Azerbaijan. Malaria has become endemic in southern Tajikistan during the past decade and locally transmitted cases of this vector-borne disease have been also frequently reported in Russia, Ukraine, Georgia, and Kazakhstan (WHO, 2008). Kyrgyzstan had an epidemic of malaria in 2002 and the first cases of the deadlier *falciparum* malaria were reported there in 2004. According to World Health Organization the total estimate cases in Tajikistan alone may exceed 400,000 (WHO, 2008; Fig. 6). The situation here is complicated by the drug-resistant type of malaria caused by *P. falciparum* usually restricted to tropical regions.

Many non-climatic factors contributed to this regional health crisis, including political instability in Tajikistan and massive migrations caused by civil unrest in Afghanistan and Tajikistan, deterioration of the national health system, economic decline, reduction of the use of pesticides, and land use changes. At the same time, the recent climate changes, such as winter temperature increases and shifts in precipitation, may augment the regional vulnerability to malaria by creating more favorable mesoclimatic conditions for vectors, parasites, or both. A particularly high numbers of cases of locally transferred malaria occurred in Tajikistan in 1995–1998 and 2001–2003, coinciding with unusually warm and wet years in this area. The MIASMA model links AOGCM climate scenarios with submodels of transmission and impact of vector-borne infections, such as malaria, dengue fever, and schistosomiasis (Martens et al., 1999; Van Lieshout et al., 2004). We have examined MIASMA scenarios found that under winter temperature increases projected by the AOGCMs: MIASMA projects significantly higher risks of malaria in Central Asia. Climate warming will cause not only conditions more favorable for the malaria plasmodium but will also increase the number of days favorable for reproduction of mosquitoes which, in turn, increases the possibility of infection turnover by 6–7 times. According to the study by Kayumov and Mahmadaliev (2002), the zone of potential malaria development in Tajikistan will increase both in the lowlands and highlands up to an elevation of more than 2000 m.

Land use is a very important modifier of regional and local climates. In irrigated areas, the temperatures at ground level can be lower than in adjacent non-irrigated areas and the levels of humidity many hundreds times higher. Open irrigation canals, cisterns, pit latrines, sewage-polluted ditches, discarded rubber tires, and other man-made containers can be productive breeding grounds for *Anopheles* species that transmit malaria. Mosquitoes can take advantage of the timing and location of such anthropogenic microclimates for reproduction. In addition to the threat of vector-borne diseases, infectious diseases with oral-fecal mechanisms of transmission (e.g., typhoid, paratyphoid, salmonellas, dysentery, amebiasis, helminthiasis) are associated with warm weather. Flies play an important role in their transmission. Rising temperatures may lead to higher reproduction rates of flies and thus higher incidence rates and longer disease seasons. Where communal water supplies are inadequately managed, higher temperatures, combined with flooding and occasional heavy rainfall, can significantly increase the risk of many infectious diseases.

4.4. Towards multidimensional assessment of vulnerability

Human vulnerability is a concept that spans multiple scales, interrelated variables, contingent relationships, and many disparate disciplines, making it difficult to articulate, let alone monitor. A multidimensional framework for the integrated assessment of vulnerability is an appealing notion, as it could provide useful information for developing "win–win" adaptations that would target several sectors of vulnerability at the national and macro-regional scale. Spatial modeling with GIS can provide a useful tool in a simplified vulnerability assessment for computing geographic distribution of various sector-specific indices of human vulnerability, e.g., a cumulative index of the regional food security based on multiples factors and constraints of agricultural productivity and demographic data, indices of water availability and stress, and multiple spatial epidemiological indices. A first step in this direction is the development of cumulative vulnerability indices based on combination of multiple sector-specific quantitative indicators (Table 4).

5. Adaptation options to climate change in Central Asia

Many adaptation measures could potentially reduce human vulnerability of the Central Asian States to climate change; yet, the capacity to implement them today is limited by geographic, historical, political, and economic factors. There is compelling evidence from many other parts of the world that future vulnerability depends on development pathway, as well as projected climate change: "Sustainable development can reduce vulnerability to climate change, and climate change could impede nations' abilities to achieve sustainable development pathways" (IPCC and WGII, 2007, Ch.20).

Non-climatic stresses are likely to increase vulnerability of arid Central Asia to climate change and reduce adaptive capacity because of resource deployment to competing needs. For example, current stresses on the Aral Sea basin include salinization, water loss due to inadequate irrigation practices, chemical runoff from agriculture as well as increases in surface temperature and precipitation variability. The recent outbreaks of malaria in Tajikistan and Kyrgyzstan are another example of stress on health care systems deteriorated by the economic shocks of the 1990s. If we attempt to see the Central Asian region as a complex system exposed to myriad physical and societal stresses, its vulnerability would arise from contingent interactions among thousands of processes acting at different temporal and spatial scales, and many thousands (or millions) of feedbacks, both positive and negative.

5.1. Short-term vs. long-term adaptation strategies

Development of "no regrets" adaptation measures and "win–win" strategies in Central Asia or elsewhere requires also careful balancing of the long-term and short-term, proactive and reactive, planned and spontaneous adaptation options. In the context of the fragile arid ecosystems of Central Asia already affected by human-induced land degradation, any short-term, unplanned, and reactive adaptations may provide an immediate solution for a limited group

Table 4
Examples of potentially useful indicators that would be relevant for an integrated regional assessment of vulnerability to climate change in arid and semi-arid Central Asia.

Sector of vulnerability	Possible metrics of vulnerability	
Food security	*Exposure indices*	• Exposed population • Exposed crops • Exposed livestock • Rainfall variability • Temperature change • Precipitation change • Soil moisture change
	Sensitivity indices	• Area with agro-ecological constraints for rain-fed agriculture • Area with agro-ecological constraints for irrigation • Area with agro-ecological constraints for livestock • Total area suitable for rain-fed cereal production • Total area suitable for irrigated cereal production • Production • Cereal production suitability indices
	Adaptive capacity indices	• Wealth • Equity • Access to technology and information • Agricultural policies • Institutional structures • Level of Central Asian cooperation
Water stress	*Exposure indices*	• Exposed population • Surface runoff • Precipitation change • Temperature change • Infiltration rate • Evaporation rate
	Sensitivity indices	• Water consumption • Surface water availability • Groundwater availability • Surface water quality • Groundwater quality
	Adaptive capacity indices	• National and international institutional structures • Access to technology • Political stability • Trans-boundary agreements relations with neighbours (Russia, Afghanistan, Iran, China)
Vector-borne diseases	*Exposure indices*	• Population density • Population exposed to infection • Length of transmission season
	Sensitivity indices	• Life expectancy • Infected population • Mortality • Number of cases of each infection assessed • Number of the local transmissions • Presence of pressure groups (e.g., NGOs)
	Adaptive capacity indices	• Immune population • Level of education • Availability of preventive measures • Availability of pesticides • Access to medical care • Infrastructure

of the population at risk, but are also likely to exacerbate the problem over the longer term. Unfortunately, the history of Soviet and post-Soviet development in Central Asia is replete with examples of short-term adaptations to climate and climate change. The Virgin Lands program in Kazakhstan, the forced settlement and collectivization of nomads in Kazakhstan, Kyrgyzstan, and Turkmenistan, the construction of the Kara-Kum Canal and associated massive irrigation introduced in southern Turkmenistan, engineering measures attempting to control the level of the Caspian Sea and Kara-Bogaz-Gol are all examples of shorter-term adaptations that were not sustainable in the longer term.

Spontaneous adaptations focus on effect rather than cause. These reactive adaptations frequently aggravate adverse environmental changes in the longer term, rather than ameliorating human vulnerability. For example, a study conducted in Karakalpakstan showed that 49% of the respondents indicated that they wanted to leave their homes because of the severe drought in 2000 (Small and Bunce, 2003). At a Commonwealth of Independent States conference on refugees and migrants in 1996, the estimated number of displaced people due to the environmental disaster in the Aral Sea region was more than 100,000 (Akiner, 2000). The recent drought that started in 2001 doubled the net emigration from Karakalpakstan from over 3000 to over 6000 persons per year. The prospect for the long-term resolution of the drought remains doubtful: precipitation levels are normally low, and trans-boundary water disputes preclude the upstream release of more water for downstream uses. Temporary labor out-migration has recently also become very common, with about 10% of working-age population leaving home to work every year (Elpiner, 2003). These environmental refugees are usually individuals who had the skills, opportunity, and psychological aptitude to migrate and adjust to different lifestyles in other regions or countries. The concern arises that the population left behind might have lower capacity, skills, and potential to respond effectively to the regional environmental crisis. A prolonged drought could make Karakalpakstan and parts of Kazakhstan in the vicinity of the Aral Sea uninhabitable, resulting in a massive flow of environmental refugees.

5.2. Towards an integrated assessment of adaptations

To cope with the multiple regional stresses in the context of increasing stresses caused by climate change, land use, political, and socio-economic changes of the past decades, the Central Asian nations will need to develop and implement sustainable adaptive strategies. Sustainable adaptation to climate change in the context of their continuous economic transition would require consideration of many environmental, social, and economic criteria. To be plausible, adaptive strategies should be (a) appropriate from an environmental perspective, (b) cost-effective from an economical perspective, (c) acceptable from social and cultural perspectives. In other words, adaptive strategies need to meet a "triple bottom line" (TBL) criteria that place equal importance on environmental, social, and economic considerations. Table 5 illustrates how these criteria can help to assist the assessment of potential sector-specific adaptations. In this example, three sector-specific adaptation measures provide examples of how the TBL criteria can be used to assess suitability of each adaptive strategy to the impacts of a 1 °C increase in summer temperature.

It is obvious that development of almost any adaptation strategy involves inevitable trade-offs. In fact, the potential trade-offs between the TBL criteria represent an objective limitation of sustainability of any adaptation option. As several impact assessment studies suggest, the risk of "win–lose" scenarios caused by trade-offs, can be reduced by incorporating of minimum acceptability thresholds for each criteria into the TBL model and requiring that any adaptation initiative at least meets these minimum thresholds. At the regional scale, GIS-based multi-objective multi-criteria evaluation algorithms, such as ordered weighted averaging and weighted linear combination can be particularly useful for assessing potential risks and trade-offs involved in the TBL assessment of adaptations.

Consideration of multiple objectives, criteria, associated risks and trade-offs is necessary to balance the impacts of different sector-specific adaptations and prevent or mitigate secondary environmental impacts. For example, irrigation projects can reduce water stress and increase food security but also have significant negative effects on the local transmission of diseases, such as malaria, lymphatic filariasis, and schistosomiasis (Kovats et al., 2001). Improved water supply in many parts of semi-arid Asia has resulted in a dramatic increase in mosquito breeding sites and consequently higher risks of transmission of malaria (McMichael and Kovats, 2000). On the other hand, increased vector control measures involving high doses of insecticides have side effects impacting human health both directly and indirectly through food chains and food webs with repercussions for ecosystem goods and services (Kovats et al., 2001; Martens et al., 1999).

Many adaptation strategies aiming to improve food security and increase crop yields may require increased use of pesticides, insecticides, and chemical fertilizers. These energy subsides can pose serious hazards to human and ecosystem health. Irrigation projects, such as the infamous Kara-Kum Canal, which has caused immense environmental and health crisis in Central Asia, were initially intended as adaptations to arid climate and meant to improve agricultural productivity and water supply. While the relative importance of various aspects of human vulnerability can be assessed using sets of quantitative indicators and multi-criteria factor analysis, qualitative expert evaluation is equally important to reconcile multiple adaptation priorities.

Various aspects of human vulnerability must be considered to make sure that an adaptation to one impact does not increase the exposure to others. Some adaptation strategies, such as conventional air conditioning or deep tillage, also contribute to the deterioration of the regional carbon budget and potentially contribute to climate change. While some adaptations will depend on adoption of innovative technologies or products (e.g., new crops or crop varieties or crop-rotation techniques, new irrigation technologies, new drugs), others might require re-evaluation and re-adoption of the traditional land management systems that were abandoned during the Soviet period (e.g., traditional terracing techniques).

Adaptations that are likely to be successful and sustainable should target multiple aspects of human vulnerability and remain useful regardless the existing uncertainties about climate change projections. For example, diversification of agriculture and growing legumes and climate-appropriate fruits and vegetables along with application of conservation tillage practices could increase food security while improve soiling through nitrogen fixation, decreasing water use, and reducing net carbon flux to the atmosphere. The replacement of the existing network of open irrigation canals by more efficient drip irrigation systems could significantly reduce evaporative water loss, while simultaneously improving crop productivity, reducing soil salinization, and decreasing risks of water contamination and transmission of vector-borne and water-borne diseases. However, such extensive renovation would be expensive and necessitate the large-scale introduction of technologically advanced management techniques. To be truly integrated, the interactions among the three bottom lines of impact assessment must be considered, since both positive and negative synergies may occur.

Development of early warning systems, such as drought forecast, pest and epidemic disease forecasts, and water quality monitoring systems, should also be considered an important adaptation strategy (Kovats et al., 2001; Mizina et al., 1999). Such early warning systems should integrate surveillance systems and

Table 5
TBL considerations for assessing adaptations to potential impacts of the hypothetical 1° temperature increase in summer.

Area of vulnerability	Agriculture & food security	Water resources	Human health
Adaptation sector			
Risks	Yield reduction due to higher temperature and aridity	Higher evaporation; higher water consumption	Higher risk of malaria in irrigated areas caused by the longer transmission season
Adaptation measure	Change planting date to effectively use the prolonged growing season and irrigation	Modernisation of existing irrigation systems	Use of pesticides
TBL criteria			
Environmental Appropriateness	Minor or no environmental impact	Reduction of water losses; salinization; water pollution by pesticides	Negative impact on ecosystems and health
Economic cost-effectiveness	Cost-effective, does not require additional investments	Increased water efficiency; significant investments are required	Relatively cost-effective; additional investments are required
Social/cultural Acceptability	Acceptable	Reduction of water-related conflicts	May have adverse impact on health

provide forecasts at subnational scale to capture the spatial heterogeneity of risks and hazards across Central Asia.

Economic, social, and environmental equity have been an enduring challenge in many parts of Central Asia, even prior to the collapse of socialism. Economic inequalities among the regions, republics, and individual groups of the population, especially between the urban and rural population have skyrocketed after independence in all countries of the former USSR and particularly in Central Asia. Several urban areas have shown a positive increase in the quality of life; whereas, in most rural areas, the quality of life, food security, water quality and the level of health are profoundly poor and continue to deteriorate. Kazakhstan is the only country in Central Asia whose economic growth has been accompanied by redistribution of wealth in the population; it has also the lowest levels of poverty in the region. The proportion of people living below the minimum subsistence level of US$31 per month still constitutes more than a quarter of population even in this relatively well developing economy (UNDP, 2008). Reduction of socio-economic vulnerability to climate change can be only achieved through income redistribution, full employment, better housing, and improved public health infrastructure. Improved environmental management—upon which health, food security and freshwater resources depend—is critical for adaptations at the national or community scale to succeed.

Public education and communication of environmental risks to all groups of the population are important components of long-term adaptive strategies. Education and public awareness, extension projects, and environmental advocacy can play a very important role in the recognition of existing links among social, environmental and economic components of vulnerability and the need for such integrated approach in regional or national policies.

6. Conclusions

Vulnerability to climate change is a product of multiple factors: “Vulnerability to specific impacts of climate change will be most severe when and where they are felt together with stresses from other sources” (IPCC and WGII, 2007, Section 17.3.3). Central Asia represents an area where various environmental, social, and economic stresses coincide at multiple temporal and spatial scales: noticeable temperature increase, increase of rainfall variability, recent drought, poor irrigation practices, degradation of the Aral Sea, rapid institutional changes after independence, changes in livestock and agricultural crops, water stress, population growth, increase of economic inequality, and increasing disruption of the mutual economic interdependence. Central Asia represents, therefore, a particularly interesting case study providing many useful insights on interrelations between the current and projected climatic impacts, land changes, and development issues.

Central Asia is projected to become warmer during the coming decades. Aridity is expected to increase across the entire region, especially in the western parts of Turkmenistan, Uzbekistan, and Kazakhstan. The ability of this western subregion to adapt to hotter and drier climate is limited by the current water stress and the regional disaster caused by the Aral Sea degradation and poor irrigation practices. The temperature increases are projected to be particularly high in summer and fall, but lower in winter. Significant decrease in precipitation is projected for summer and fall. At the same time, a modest increase in precipitation is expected for winter across the region, especially in the eastern part of Kazakhstan and in Kyrgyzstan and Tajikistan. These seasonal climatic shifts are likely to have profound implications for agriculture when some parts of the region can be winners (cereal production in northern and eastern Kazakhstan can benefit from the longer growing season, warmer winters and slight increase in winter precipitation), while others can be losers (particularly western Turkmenistan and Uzbekistan, where frequent droughts will negatively affect cotton production, increase already extremely high water demands for irrigation, and exacerbate the already existing water crisis and human-induced desertification). The recent and ongoing drought, particularly severe during 2001–2003 and 2007–2008, has already resulted in multiple water disputes and increased tensions among the states of the Aral Sea basin. Knowing that the aridity and water stress are likely to increase, new political and economic mechanisms are necessary to ease such tensions in future.

Central Asia inherited many environmental problems from the Soviet times. Now, 18 years after independence, many land and water-use related problems remain unresolved and they exacerbate the region's vulnerability to climate change. Deintensification of agriculture after following independence, well documented by agricultural statistics, was sufficiently extensive to produce a significant signal in the time series of remote sensing data. The transformation of the agricultural sector had extremely high social costs; agricultural reforms and transition to market economics remain problematic in most of the region. Increasing rural poverty and unemployment (particularly among women), growing economic inequality, and shortage of adequate living conditions, medical care, and water management infrastructure have significantly increased human vulnerability of the majority of the region's population.

All five countries of Central Asia are signatories to the UNFCCC (United Nations Framework Convention in Climate Change) and the Kyoto Protocol. All have developed greenhouse gas mitigation assessments and national climate change action plans in recent years[1–7]. However, the focus of all recent national vulnerability and adaptation assessments is typically limited to sector-specific responses to the biophysical dimension of climate change. Scant attention is paid to the socio-economic aspects of vulnerability. Factors such as social inequality, uneven access to health care and education, rural poverty, crisis in the land tenure system, and ethnic conflicts are usually not considered by the national and local decision makers as aspects of human vulnerability to climate change. The National Action Plans of the Central Asia States hardly mention the connections between economic development, social welfare, and vulnerability to climate change. Neither have they acknowledged that the economic situation of the majority of people, especially in rural areas, translates into high vulnerability and low adaptive capacity to adverse impacts from climate change.

In the separate National Plans, there is no or little consideration of multiple connections and feedbacks in the complex macro-

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[2] Kyrgyzstan State of the Environment, 2001. National Report of the Ministry of Environmental Protection, Bishkek, Kyrgyzstan, 157 pages (in Russian).

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[4] State of the Environment in Kazakhstan, 2004. Ministry of the Environment of Kazakhstan (in Russian), http://www.nature.kz/obsuzhdenie/national_doklad/doklad_2.htm, last access November 2007.

[5] National Environmental Action Plan of the Republic Uzbekistan, 2001. Ministry of Environmental protection, Tashkent (in Russian), 190 pages.

[6] National Action Plan of the Republic Kazakhstan for Climate Change Mitigation, 2003. The Chief Administration for Hydrometeorology, Republic of Kazakhstan (in Russian), 53 pages.

[7] National Action Plan for Climate Change Mitigation, 2003. Ministry for Nature Protection of the Republic Tajikistan, Dushanbe. http://unfccc.int/resource/docs/nap/tainap01e.pdf, last access October 2008.

regional system that they represent together due to their common environmental, political, and economic legacy. Yet, development of effective and realistic adaptation strategies requires consideration of these factors: adaptation measures must be embedded in ongoing activities such as land use planning, water resource management, drought warning, desertification control, health care programs, and diversification of agriculture. Finally, it is critical to approach most adaptation strategies at subnational and international levels simultaneously in order to consider the local and regional variations in resources and to address and coordinate trans-boundary management issues.

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Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jaridenv.2009.04.022.

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