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ABSTRACT

The arid and semiarid region in central Asia is sensitive and vulnerable to climate variations. However, the sparse and highly unevenly distributed meteorological stations in the region provide limited data for understanding of the region's climate variations. In this study, the near-surface air temperature change in central Asia from 1979 to 2011 was examined using observations from 81 meteorological stations, three local observation validated reanalysis datasets of relatively high spatial resolutions, and the Climate Research Unit (CRU) dataset. Major results suggested that the three reanalysis datasets match well with most of the local climate records, especially in the low-lying plain areas. The consensus of the multiple datasets showed significant regional surface air temperature increases of 0.36°–0.42°C decade^{-1} in the past 33 years. No significant contributions from declining irrigation and urbanization to temperature change were found. The rate is larger in recent years than in the early years in the study period. Additionally, unlike in many regions in the world, the temperature in winter showed no increase in central Asia in the last three decades, a noticeable departure from the global trend in the twentieth century. The largest increase in surface temperature was occurring in the spring season. Analyses further showed a warming center in the middle of the central Asian states and weakened temperature variability along the northwest–southeast temperature gradient from the northern Kazakhstan to southern Xinjiang. The reanalysis datasets also showed significant negative correlations between temperature increase rate and elevation in this complex terrain region.

1. Introduction

The arid and semiarid region in central Asia covers 5×10^6 km^2, including Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, and Xinjiang province in northwest China. The region is especially sensitive and vulnerable to climate change (UNDP 2005; Parry et al. 2007). Rising air temperatures increase the surface evapotranspiration, stimulate substantial glacial retreats,

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and exacerbate water shortage in the region (UNDP 2005; Siegfried et al. 2012; Sorg et al. 2012). Because of the critical dependence on climate of the water resources, ecosystems, and societies in this massive inland region, it is crucial to understand its climate variation and change in order to support sustainable development policies. Our review has found few studies that examined climate variation in central Asia (e.g., Houghton et al. 2001; Lioubimtseva et al. 2005; Lioubimtseva and Cole 2006; Lioubimtseva and Henebry 2009), especially its temperature variation. The Intergovernmental Panel on Climate Change (IPCC; Houghton et al. 2001) reported that the region's averaged near-surface air temperature rose by 1°–2°C during the twentieth century. However, the report provided no specific information about its temporal (e.g., the time of abrupt temperature changes) or spatial (e.g., areas of substantial temperature rise or fall) variations. Meanwhile, large uncertainties have been noticed existing in these previous studies, arising from either using observational records from a few meteorological stations (e.g., Kharlamova and Revyakin 2006; Mamtimin et al. 2011) or using a single spatially interpolated dataset of the Climate Research Unit (CRU) time series from New et al. (1999, 2000) and Mitchell and Jones (2005) in the region. As pointed out by Lioubimtseva and Cole (2006), the spatial interpolation or extrapolation was particularly prone to errors in this region of very complex terrains with rather sparse and highly skewed spatially distributed meteorological stations. In comparison with other regions, the limited weather stations in central Asia are clustered in and around the oases. Moreover, long-term climatic observations are rare (Lioubimtseva and Cole 2006). Most stations outside China stopped functioning in the 1990s after the dissolution of the former Soviet Union (Chub 2000), losing continuation of data for analysis of regional climate variations in the recent decades (Schiemann et al. 2008). These problems in data pose severe challenges for the study of climate in central Asia and limit our understanding of the spatial and temporal variations in temperatures in the region.

The National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis dataset (Kalnay et al. 1996) provided an alternative data source and helped overcome some of the data issues. While the reanalysis data have been widely used in regional climate studies (e.g., Marshall 2002; Blender and Fraedrich 2003; Bromwich and Fogt 2004; Bordi et al. 2006; Bromwich et al. 2007; Song and Zhang 2007; Grotjahn 2008; Dessler and Davis 2010; Bao and Zhang 2012), the data have rarely been used in climate studies for central Asia except for a few studies on the region's precipitation (e.g., Schiemann et al. 2008), partially because the spatial resolution of the dataset (2.5° × 2.5° of latitude and longitude) was considered too coarse to describe important details in regional climate in central Asia.

In the last few years, a new generation of reanalysis datasets has been developed with improved accuracy and spatial resolution [≤(0.75° × 0.75°) of latitude and longitude]. These new datasets include the NCEP Climate Forecast System Reanalysis (CFSR; Saha et al. 2010), European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim; Dee et al. 2011), and Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al. 2011). These data could be suitable for regional climate studies in central Asia. However, as cautioned by the data producers, few evaluations have been made so far and the suitability and accuracy of these global datasets for regional studies are not yet fully understood (https://climatedataguide.ucar.edu/reanalysis/climate-forecast-system-reanalysis-cfsr). Because of the differences in the models and methods used in these reanalysis projects these datasets may, for example, describe near-surface air temperatures (Pitman and Perkins 2009). Thus, before using them their suitability or accuracy to describe the regional climate features needs to be evaluated against available field observations (Ma et al. 2008).

In this study, we first examine the accuracy of the three relatively high spatial resolution datasets, CFSR, ERA-Interim, and MERRA, in describing the regional temperature variations in central Asia by comparing the reanalysis data with observations from stations in the region. After the evaluation these datasets are used to examine temperature variations in central Asia for the period from 1979 to 2011.

There are three major questions to be addressed in this study. Was there a warming trend in central Asian climate in recent decades? If there was, how does it compare to the temperature changes in the mid- and early-twentieth century, and how does it compare with temperature changes in other regions in the Eurasian continent? Were there changes in seasonal temperature variation in central Asia and which season experienced the strongest temperature change? Were there significant differences in temperature change among different subregions of central Asia and how does the temperature change rate vary with elevation?

2. Study area, data, and methodologies

a. Study area

Our study area consists of Xinjiang Uygur Autonomous Region, China (Xinjiang), and five central Asian states (CAS): Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan,

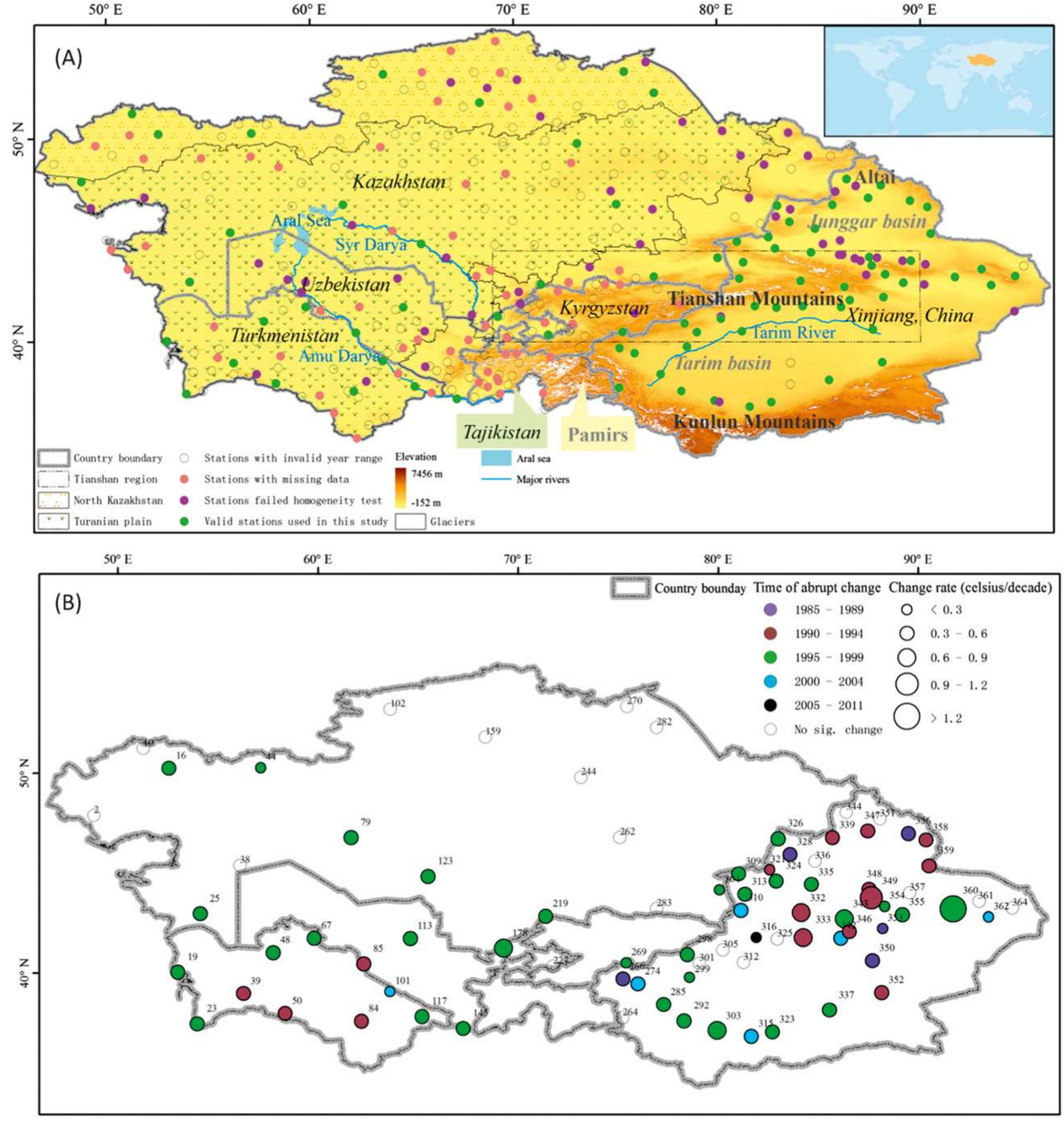


FIG. 1. The study area and distribution of meteorological stations. (a) The location, elevation, country boundary, subregions, and major water and orographic features in central Asia. The dashed-line rectangle delineates the Tian Shan region (40°–44.5°N, 69°–90°E). Climate stations are represented by circles filled with different colors, indicating different data quality. The country boundary and major rivers were drawn with the Environmental Systems Research Institute, Inc. (ESRI) Basemap Services (http://www.esri.com/software/arcgis/arcgis-online-map-and-geoservices/map-services). (b) Distribution of the meteorological stations and their temperature change from 1979 to 2011. The identification (ID) numbers of the stations are labeled (station descriptions are found in Table S1 in the supplementary material). The size of each circle is in proportion to the rate of change. An open circle indicates no significant change at the station. A filled circle indicates significant temperature change, and the color of the filling indicates the turning point (in a time span of 5 yr) of temperature change in 1979–2011 according to the M-K test.

and Uzbekistan (Fig. 1a). We will refer this region as central Asia. There have been discrepancies and discussions about the usage of the term ''central Asia.'' In some publications, central Asia refers to western China and Mongolia (Le Houerou 2005); in others, it refers to the five CAS in the former Soviet Union (e.g., Mayhew et al. 2004). Our definition agrees with Goudie (2002)'s description, in which central Asia consists of two parts separated by high mountains, including the Pamirs, the Tian Shan Mountains, Kunlun Mountains, and Altai Mountains (Fig. 1a): ''To the west lie the deserts of the former Soviet Union and to the east are the deserts of China'' (Goudie 2002).

According to the topography and climate characteristics, the CAS are usually divided into three climatic subregions: the northern Kazakhstan region in the north, the Turanian plain in the central and southeast, and the mountainous region in the southwest [definitions of these climatic subregions also can be found in Schiemann et al. (2008) and Small et al. (1999)]. In addition, Xinjiang consists of two climatic subregions: the northern Xinjiang and the southern Xinjiang. The former consists of the Junggar basin and the Altai Mountains to its north and the northern slope of the Tian Shan Mountains to its south and west. The latter consists of the Tarim basin and the southern slope of the Tian Shan Mountains to its north and the Kunlun Mountains and Pamir Plateau to its south and west (Fig. 1a). To investigate the relationship between elevation and temperature change, we further outline the Tian Shan region (40°–44.5°N, 69°–90°E) (Fig. 1a) according to Chen (2012).

b. Data

Daily observational records of near-surface (2 m above the ground) air temperatures from 365 meteorological stations in the study region were collected in this study. Among them, 295 stations are in the five central Asian states, and their temperature records were obtained from the National Climatic Data Center (NCDC) of the U.S. National Oceanic and Atmospheric Administration (NOAA). The remaining 70 stations are in Xinjiang, China, and their records were obtained from the National Meteorological Center of China Meteorological Administration and from Xinjiang Meteorological Agency. The data history of these stations is shown in Table 1. These data are referred to as OBS in the following sections.

Among the reanalysis data, we used the monthly CRU time series 3.1 (TS3.1) dataset (New et al. 1999; Mitchell and Jones 2005) from 1901 to 2009. We also used the NCEP CFSR, ERA-Interim, and MERRA datasets. Some details of these reanalysis datasets are provided in Table 1. These datasets were first examined by comparisons with observations from the ground stations for their accuracy in describing the near-surface air temperature, and then to aid the analysis of spatial variations in the near-surface temperature. For the analyses that require elevation information (see below), the 30-arc-s resolution digital elevation data (GTOPO30; downloaded from http://eros.usgs.gov) were resampled to match the spatial resolution of each reanalysis dataset. The elevation at each reanalysis data grid was calculated as the mean of the digital elevation data within that grid. To assess the potential impacts of climate change on the dryland ecosystems and water resources in central Asia, we further evaluated changes in temperature in vegetated and glacial areas in central Asia. The glacial and vegetated areas were determined with the 300-m resolution European Space Agency global land cover dataset (GlobCover 2009; Arino et al. 2010), which has been evaluated and used for environmental studies in the study region (Chen et al. 2013). The ''glacier area'' in the GlobCover 2009 includes permanent snow and glacier. Boundaries of northern Kazakhstan and the Turanian plain in the CAS region were digitized based on the maps provided by Small et al. (1999) and Schiemann et al. (2008).

c. Methodologies

Quality control of the OBS involves three steps. 1) Stations whose climate records did not cover the analysis period were excluded. 2) Stations with missing observations for more than 5 consecutive days or with 20% observation missing in any 30-day period were excluded. Otherwise, the missing values in the climate records were filled with 30-day running means. 3) Stations that failed to pass the standard normal homogeneity test were excluded (Alexandersson 1986). This homogenization test aims to preserve the climatic signal and eliminate or reduce the effects on nonclimatic factors from such changes in instrumentations, observing practices, and station locations (Aguilar et al. 2003; Li et al. 2004; DeGaetano 2006). For example, among the 365 meteorological stations under study, only 191 cover the period between 1979 and 2011, among which 59 have too many missing values to pass the quality control (step 2). Of the remaining 132 stations, only 81 stations passed the homogeneity test and were used in climate change analysis for the period of 1979–2011 (Fig. 1a). The longer the study period, the fewer number of stations passed quality control. Compared to the period of 1979–2011, only 62 stations are qualified for climate change analyses for the period of 1960–2011 (Table 1).

The three reanalysis data products are evaluated by comparing their temperatures against the OBS at or near the reanalysis grid points for the 1980s, 1990s, and 2000s+ (2000–11). For each meteorological station, its closest grid in a reanalysis dataset is identified. Then, the temperature of the reanalysis data at that grid is adjusted according to the lapse rate and the elevation difference between the grid and the station. This elevation difference was calculated using the GTOPO30 developed by the U.S. Geological Survey (USGS; http://eros.usgs.gov). Annual and seasonal temperature lapse rates [$°C\,(100\,m)^{-1}$] in central Asia were calculated based on the 1979–2011 mean temperature in the Tian Shan region (40°–44.5°N, 69°–90°E) (Fig. 1a) (see Table S2 in the supplementary material). The seasonal mean lapse rates were then linearly interpolated to derive the daily lapse rate, which was used for the temperature adjustment.

Following Ma et al. (2008) and You et al. (2010), the absolute errors (AE) or bias, two-tailed Pearson correlation coefficients (CC), mean absolute errors (MAE), and root-mean-square error (RMSE) were calculated to measure various aspects of the differences between the observed air temperatures and those from the three reanalysis datasets. The reanalysis products were evaluated separately for mountainous and plain areas. The definition of mountainous area by the United Nations Environment Programme (UNEP) was used; that is, a mountainous area should have elevation >2500 m, or between 1500 and 2500 m and with a slope >2°, or between 1000 and 1500 m and with a slope >5° or local elevation range >300 m (Blyth et al. 2002). Information of topography was derived from the USGS GTOPO30 elevation dataset. For each grid in the USGS GTOPO30 dataset, the local elevation range was derived from a $5 \times 5\,km^2$ buffer around the grid. Areas outside of the mountainous area were treated as plain areas.

Temporal variations of the temperature were compared between the OBS and the CRU, and between the OBS and each of the three reanalysis datasets. In these comparisons, each meteorological station or each grid in the spatial datasets was treated as a sample point, and the mean values for the study region were analyzed and compared. Trends of temperature variation were evaluated using linear trend fit and the nonparametric Mann–Kendall method (or M-K test) (Mann 1945; Kendall 1948). A trend was considered statistically significant when it is at the 95% confidence level. The M-K test also was used to detect the time of significant or abrupt climate changes. Temperature changes in the four seasons, spring [March–May (MAM)], summer [June–August (JJA)], fall [September–November (SON)], and winter [December–February (DJF)], as well as the annual (ANN) change were examined. Furthermore, we analyzed the OBS and the CRU data to examine the temperature variation and trend for the past five decades (1961–2011) and also from 1901 to 2009. These long-term variations in temperature were compared to the variation from 1979 to 2011 to put the recent changes in context. The method used to study temperature change at the turn of the twenty-first century was by comparing and contrasting the differences (DIF) of the change from the 1980s to the 1990s and the change from the 1990s to 2000s+ (i.e., 2000–11):

$$\begin{aligned} \mathrm{DIF}_{1990s\text{-}1980s} &= T_{1990s} - T_{1980s} \\ \mathrm{DIF}_{2000s+\text{-}1990s} &= T_{2000s+} - T_{1990s}\,. \end{aligned} \tag{1}$$

In the above, T (°C) is a decadal mean temperature.

To compare the spatial pattern of surface temperature change derived from the CRU, CFSR, ERA-Interim, and MERRA datasets, we applied empirical orthogonal function (EOF) analyses (Lorenz 1956) to their annual temperature anomalies (from the average of 1979–2011). EOF analysis finds a set of orthogonal variables to describe the observed variance in the data, whereby large-scale variability will be shown in the low-order EOFs while the higher-order EOFs contain low-amplitude spatially incoherent noise. The EOF method can identify the dominant spatial pattern of the variation in temperature and also produces its index time series, the principal component (PC), which explains the magnitude of the variation of each EOF mode of the temperature. Following North et al. (1982), a significance test is applied to distinguish the physical signal from the noise in the EOF.

Dependence of the change in near-surface temperature on elevation is examined for the Tian Shan mountainous region, which is the major mountain area in central Asia (Fig. 1a). Although the Pamirs in Tajikistan are as important for the Amu Darya as the Tian Shan Mountains are for the Syr Darya and other rivers, they are not investigated because no valid stations in the Pamirs are available for this analysis (Fig. 1b). Pepin and Lundquist (2008) suggested that a reliable analysis of the relationship between temperature change and elevation should be based on observations from meteorological stations in the mountain summit or freely draining slopes. To identify such meteorological stations, we overlay the location map of the stations on the topographic maps (relief map and slope map) derived from the USGS GTOPO30 dataset and the high-resolution (about 1–10 m) remote sensing maps retrieved from http://www.google.com/earth (last visited by the authors on 4 July 2013). A visual check showed only three stations meeting the criteria of Pepin

TABLE 1. Near-surface (2 m) air temperature datasets used in this study.

Dataset	Abbreviation	Resolution	Dataset description and data sources	Reference
Observations from metrological stations	OBS	Daily	Climate records from 295 stations in the five central Asian states were obtained from the NCDC (ftp://ftp.ncdc.noaa.gov/pub/data/gsod/). Climate records from 70 stations in Xinjiang, China, were obtained from China Meteorological Administration (http://www.cma.gov.cn /2011qxfw/2011qsjgx/) and Xinjiang Meteorological Agency (http://www.xjqx.cn/ggtz/ggtz.aspx). Among the 295 central Asian stations, 44 are located in northern Kazakhstan, 149 in the Turanian plain, and 102 in the mountainous areas. There are 77 stations in the Tian Shan region (Fig. 1a). Of the 365 climate stations, 107, 112, 114, 81, and 62 cover the periods of 1979–89, the 1990s, 2000–11, 1979–2011, and 1960–2011, respectively. Other stations were not used in the temperature change analyses because of their low data quality (too many missing data or failing the homogeneity test).	
Climate Research Unit time series 3.1	CRU	Monthly, 0.5° × 0.5°	Angular distance–weighted (ADW) interpolation based on records from 275 meteorological stations, with the influence of elevation ignored (New et al. 1999, 2000). The dataset covers the 109 years from 1901 to 2009.	Mitchell and Jones (2005)
National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis	CFSR	Daily aggregated from hourly prediction, 0.31° × 0.31°	Air temperature at 2 m. With three-dimensional variational data assimilation (3DVAR) of satellite radiances by the gridpoint statistical interpolation scheme over the entire period. The CFSR atmospheric model contains observed variations in CO_2 over the 1979–2009 periods, together with changes in aerosols and other trace gases and solar variations. The 2011 climatologies was produced by NCEP's Climate Forecast System version 2 (CFSv2) with unchanged model but a higher spatial resolution (0.2°) (http://cfs.ncep.noaa.gov/)	Saha et al. (2010)

TABLE 1. (*Continued*)

European Centre for Medium-Range Weather Forecasts Interim Reanalysis	ERA-Interim	Daily aggregated from hourly prediction, 0.75° × 0.75°	ERA-Interim was developed based on the 40-yr ECMWF Re-Analysis (ERA-40) with several improvements (e.g., the 12-h 4DVAR assimilation) as introduced in the ECMWF website (http://www.ecmwf.int/research/era/do/get/era-interim)	Dee et al. (2011)
Modern-Era Retrospective Analysis for Research and Applications	MERRA	Daily aggregated from hourly prediction, 0.5° (lat) × 0.67° (lon)	Air temperature at 2 m. A 3DVAR assimilation was implemented with incremental analysis updates (IAU) to slowly adjust the model states toward the observed state, avoiding unrealistic spindown. Also with an improved set of land surface hydrological fields.	Rienecker et al. (2011)

and Lundquist (2008): Turgart (station ID 269), Balgantai (station ID 343), and Akqi (station ID 298). Station information is found in Table S1 of the supplementary material. Because of the lack of qualified stations, in this study only the three reanalysis datasets are used in analyzing the elevation effect on temperature change.

Since these reanalysis datasets have different spatial resolutions, we also resampled the CFSR and MERRA datasets to match the coarser resolution (0.75° × 0.75° in latitude and longitude) in the ERA-Interim dataset to examine, by comparing the results to the original datasets, whether the analysis results could be influenced by scaling or spatial resolution.

3. Results and analyses

a. Evaluating the reanalysis datasets with climate records

We used the observational data to evaluate the reanalysis datasets for their accuracy in describing the near-surface temperature in central Asia. In this evaluation, we first collected data from 365 meteorological stations in our study region. Of the 365 stations, there are 107, 112, and 114 with continuous surface temperature records in the 1980s, 1990s, and 2000s+, respectively. The increasing number of stations in those decades is attributable to new stations added to the network. Although new stations were added, the addition could not compensate for the damages done by stopping observations at some historical stations in the early 1990s after the former Soviet Union disintegrated. There are only 81 and 62 stations that have continuous climate observations in the periods of 1979–2011 and 1960–2011, respectively. The spatial distribution of the stations is shown in Fig. 1a. It should be noted that the long-term stations (covering the 1979–2011 period), from which the climate trend is derived, were not evenly distributed in central Asia (Fig. 1b). Many areas, such as the Pamirs, the deserts in the middle of the Tarim and Junggar basins, and the northern part of the Turanian plain have very low station density. Such poor station coverage makes it difficult to use the station data to investigate climate change in those areas. The gaps in station observations can, however, be filled with information provided by spatially explicit reanalysis products that utilize model simulation outputs. To assure that the model simulations are reasonable in describing the climate in the regions it is necessary to first evaluate the reanalysis datasets using the quality-controlled station records (i.e., OBS).

TABLE 2. Evaluating three reanalysis products using annual mean temperature recorded by meteorological stations in central Asia.

			Statistics			
Period	Region	Reanalysis product	AE (°C)	CC	MAE (°C)	RMSE (°C)
1980s	Plain area (74 stations)	CFSR	0.4	0.93	1.27	1.73
		ERA-Interim	0.25	0.92	1.19	1.9
		MERRA	1.79	0.92	2.08	2.71
	Mountain area (33 stations)	CFSR	−1.19	0.83	2.54	3.44
		ERA-Interim	−2.12	0.68	3.47	4.62
		MERRA	1.59	0.85	3.22	4.03
	All areas (107 stations)	CFSR	−0.09	0.89	1.66	2.37
		ERA-Interim	−0.48	0.84	1.9	2.99
		MERRA	1.73	0.89	2.43	3.16
1990s	Plain area (80 stations)	CFSR	0.37	0.95	1.18	1.65
		ERA-Interim	0.11	0.93	1.2	1.89
		MERRA	1.72	0.92	2.07	2.68
	Mountain area (32 stations)	CFSR	−1.63	0.78	2.85	3.84
		ERA-Interim	−2.43	0.61	3.62	4.80
		MERRA	1.35	0.79	3.23	4.02
	All areas (112 stations)	CFSR	−0.21	0.89	1.66	2.46
		ERA-Interim	−0.61	0.85	1.89	3.00
		MERRA	1.62	0.89	2.4	3.11
2000s	Plain area (81 stations)	CFSR	0.66	0.88	1.78	2.42
		ERA-Interim	0.16	0.85	1.99	2.75
		MERRA	1.97	0.85	2.69	3.47
	Mountain area (33 stations)	CFSR	−2.05	0.75	3.17	4.15
		ERA-Interim	−2.72	0.6	3.82	5.1
		MERRA	0.18	0.69	3.43	4.46
	All areas (114 stations)	CFSR	−0.13	0.84	2.18	3.0
		ERA-Interim	−0.67	0.78	2.52	3.57
		MERRA	1.45	0.81	2.91	3.76
1979–2011 average	Plain area	CFSR	0.48	0.92	1.41	1.93
		ERA-Interim	0.17	0.90	1.46	2.18
		MERRA	1.83	0.90	2.28	2.95
	Mountain area	CFSR	−1.62	0.79	2.85	3.81
		ERA-Interim	−2.42	0.63	3.64	4.84
		MERRA	1.04	0.78	3.29	4.17
	All areas	CFSR	−0.14	0.87	1.83	2.61
		ERA-Interim	−0.59	0.82	2.10	3.19
		MERRA	1.60	0.86	2.58	3.34

Comparisons between the observed and reanalysis results of variations in near-surface air temperature show rather encouraging results: no significant differences in the annual and seasonal temperatures between the OBS and each of the three reanalysis datasets. As shown in Table 2, the surface temperatures in CFSR, ERA-Interim, and MERRA are significantly correlated with the OBS, with high correlation coefficients of 0.82–0.87. Compared to the OBS the average absolute error ranges from −0.59°C for ERA-Interim to 1.6°C for MERRA. As also expected, all three reanalysis datasets show closer match with the OBS in the plains region (with CC of 0.90–0.92) than in mountainous areas (with CC of 0.63–0.79) (Table 2). The CC between the OBS and the three reanalysis datasets decreases slightly from 0.87 in the 1980s and 1990s to 0.81 in the 2000s+. These statistics indicate that the three reanalysis datasets can faithfully describe the temperatures and their variations in central Asia. In particular, the CSFR had the lowest AE, MAE, and RSME and highest CC among the three reanalysis datasets. Noticeably, CSFR also has the highest spatial resolution among all the three datasets (Table 1).

b. *Temporal variation in surface temperature based on multiple datasets*

The OBS, the CRU, and the three reanalysis datasets all show that central Asia has experienced a significant rise in surface temperatures from 1979–2011. Most areas in our study region, about 75%–90% according to linear least squares fitting and 60%–85% according to the M-K test, have experienced a significant (at the 95% confidence level) increase in annual mean temperatures in the period from 1980 to 2011 (Figs. 2a and 2b). Areas experiencing

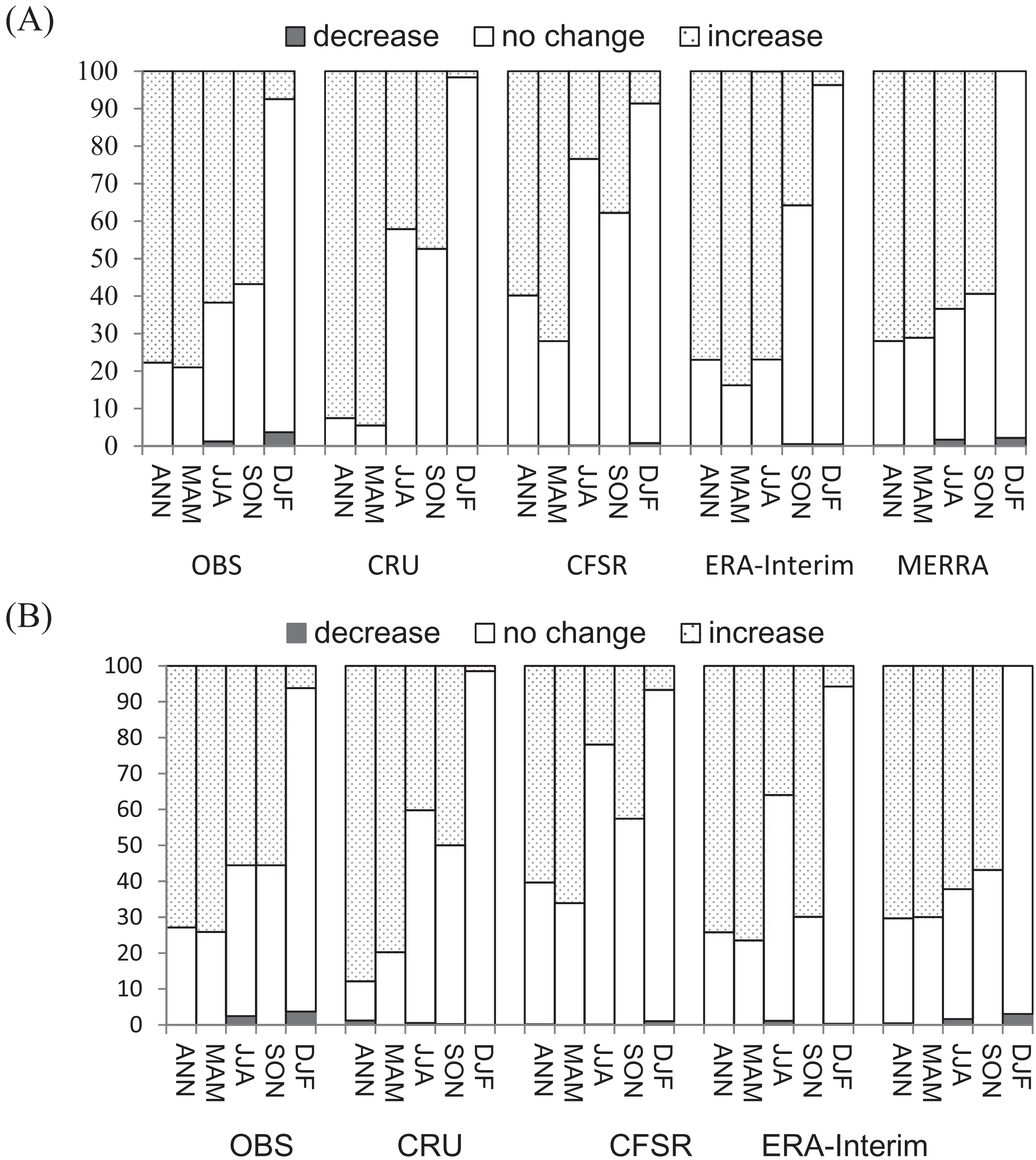


FIG. 2. Percentage of stations and study area (according to the CRU, CFSR, ERA-Interim, and MERRA datasets) showing no change (white) or significant (at the 95% confidence level) warming (stippled) or cooling (gray) in surface temperature during 1979–2011. Results in are derived based on (a) linear trend fit and (b) the M-K test. Along the abscissa, ANN indicates annual, MAM spring, JJA summer, SON fall, and DJF winter.

cooling are rare. Results from linear fitting analysis show that the region's annual mean temperatures have increased at an average rate of 0.39°C decade^{-1} (ranging from 0.36°–0.42°C decade^{-1}) from 1979 to 2011 (Figs. 3 and 4a). This rate is higher than the average warming rates of 0.30° and 0.15°C decade^{-1} in the last 5 decades (1960–2011) and 11 decades (1901–2009), respectively, based on the OBS and CRU datasets (Figs. 3b,c and 4a), as

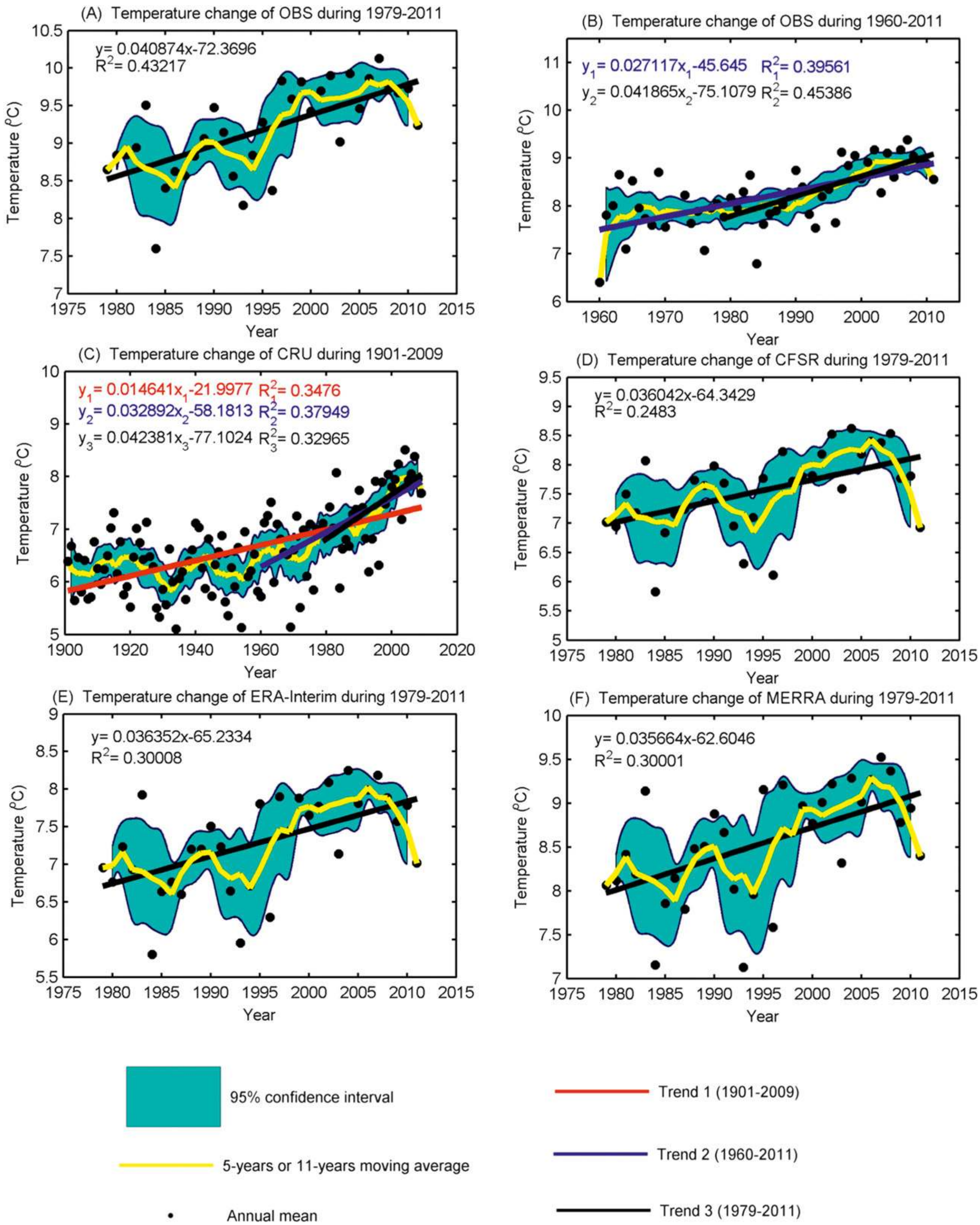


FIG. 3. Trends of temperature change: (a) from 1979 to 2011 based on observational records from 81 meteorological stations; (b) for 1979–2011 and 1960–2011 revealed by records from 62 meteorological stations; (c) for 1901–2009, 1960–2009, and 1979–2009 revealed by the CRU dataset; (d) for 1979–2011 revealed by the CFSR reanalysis dataset; (e) for 1979–2011 revealed by the ERA-Interim reanalysis dataset; and (f) for 1979–2011 revealed by the MERRA reanalysis dataset. In each panel, annual mean temperatures are shown by the dots along with a linear fit to the data to show the trend in temperature variation. The yellow curve is a smoothed depiction using 5-yr moving average to capture the variations in the data. The 95% confidence interval envelope is shown by cyan color (annual values exceed those limits).

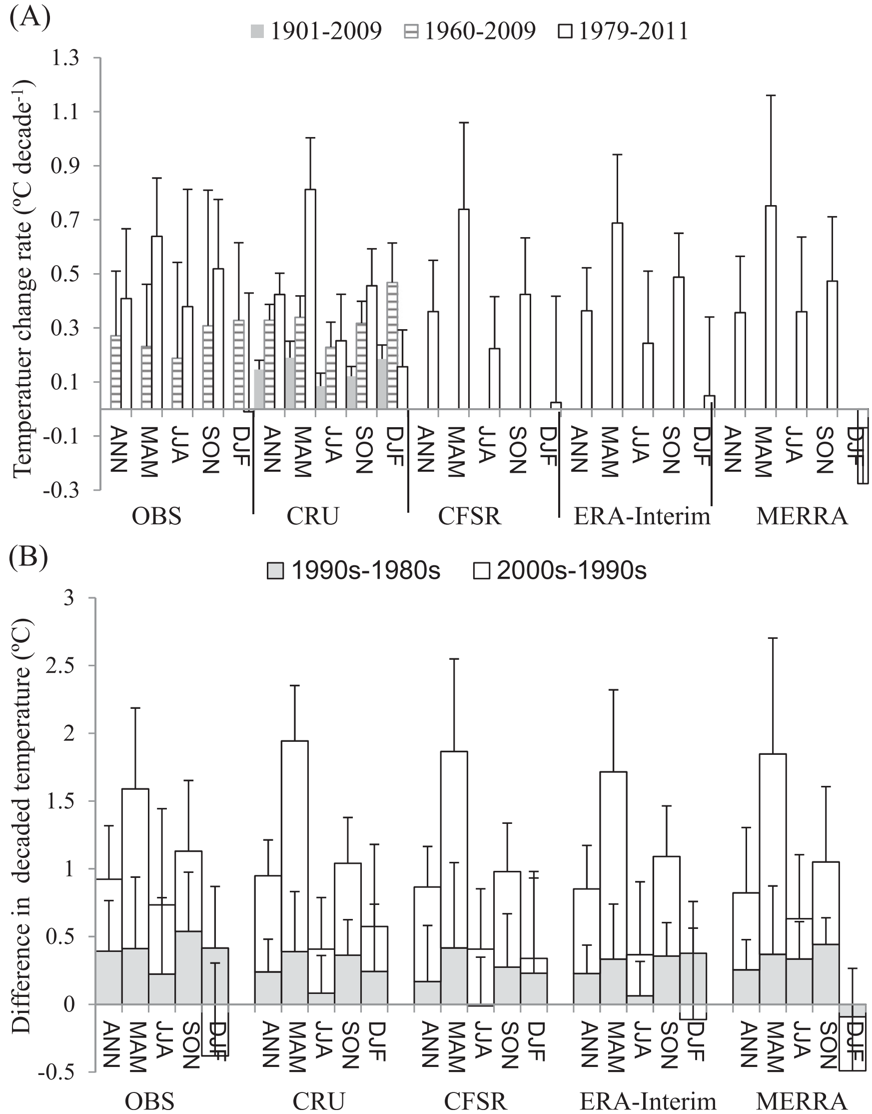


FIG. 4. Annual and seasonal changes in near-surface air temperature (a) for 1979–2011, 1960–2009, and 1901–2009, calculated using linear fitting and (b) from 1980 to 2011 as revealed by decadal differences [i.e., (1990s − 1980s) vs (2000s −1990s); Eq. (1)]. Note that the two periods, 1990s − 1980s and 2000s − 1990s, are stacked in (b). Error bars show 1 standard error in both (a) and (b).

probably anticipated. Moreover, the decadal temperature difference for seasonal and annual mean surface temperatures between the 2000s+ and 1990s is 35%–200% higher than the difference between the 1990s and 1980s, indicating the warming continuing into the twenty-first century (Fig. 4b). The M-K tests indicate that an overwhelming temperature increase took place in the late 1990s and early 2000s, a result again suggesting strong warming near the turn of this century (Fig. 5a).

Figure 4a also shows that the changes in seasonal temperatures are similar among the results from the OBS, the CRU, and the three reanalysis datasets. Warming is most prominent in the spring, at rates ranging 0.64°–0.81°C decade^{-1} from 1979–2011 among the datasets. Figure 4b further shows that the difference of temperatures between the 2000s+ and the 1990s [Eq. (1)] accounts for 75%–83% of the spring warming in the last three decades, a result again indicating strong warming near the turn of this century. Except for winter, the other seasons also show significant warming from 1979 to 2011 (also see Fig. 2). Results from analysis of the OBS and MERRA data show that 3%–4% of the study region has experienced decrease in winter temperatures

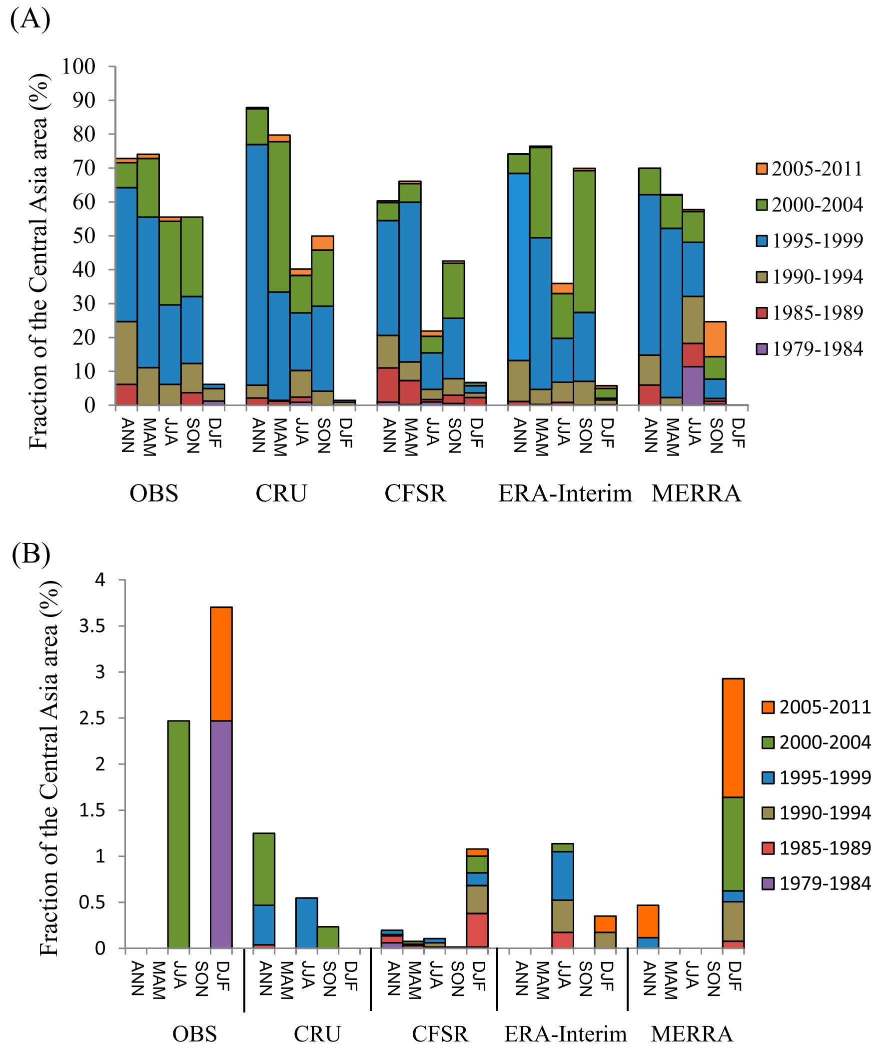


FIG. 5. Turning point (in a span of 5 yr) in temperature trend from 1979 to 2011: (a) temperature increase and (b) temperature decrease.

during the last three decades. A linear fitting result of the MERRA data (Fig. 4a) suggests a cooling rate of 0.27°C decade^{-1} in mean winter temperature from 1979 to 2011. Results from decadal difference analyses [Eq. (1)] of the OBS, ERA-Interim, and MERRA show that the average winter temperature of the 2000–11 is about 0.11°–0.39°C lower than that of the 1990s in central Asia, indicating mild winter cooling near the turn of the century (Fig. 4b). The other two datasets, CFSR and CRU, show a slight increase in winter temperatures (magnitude smaller than one standard error).

c. Spatial variation in temperature changes

Although the analysis of average temperatures in the study region shows similar variations between the OBS and the CRU and the three reanalysis datasets, there are dissimilarities in their spatial patterns. Figures 6b and 6c show that the CFSR and ERA-Interim have similar spatial pattern of temperature change with relatively strong increase in the northern and southwestern Turanian plain and in eastern Xinjiang. This pattern is largely similar to that shown in Fig. 1b from the OBS and Fig. 6a from the CRU data, but different from the result derived from the MERRA dataset (Fig. 6d). The major differences are in Xinjiang, where the MERRA result shows little change in temperature, and in northern and eastern Kazakhstan where there is widespread increase in temperature in the MERRA result.

We further examined and compared the evolution of the decadal temperature change pattern from the 1980s to 2000s+ derived from all the datasets. The differences of the decadal averaged near-surface air temperatures in

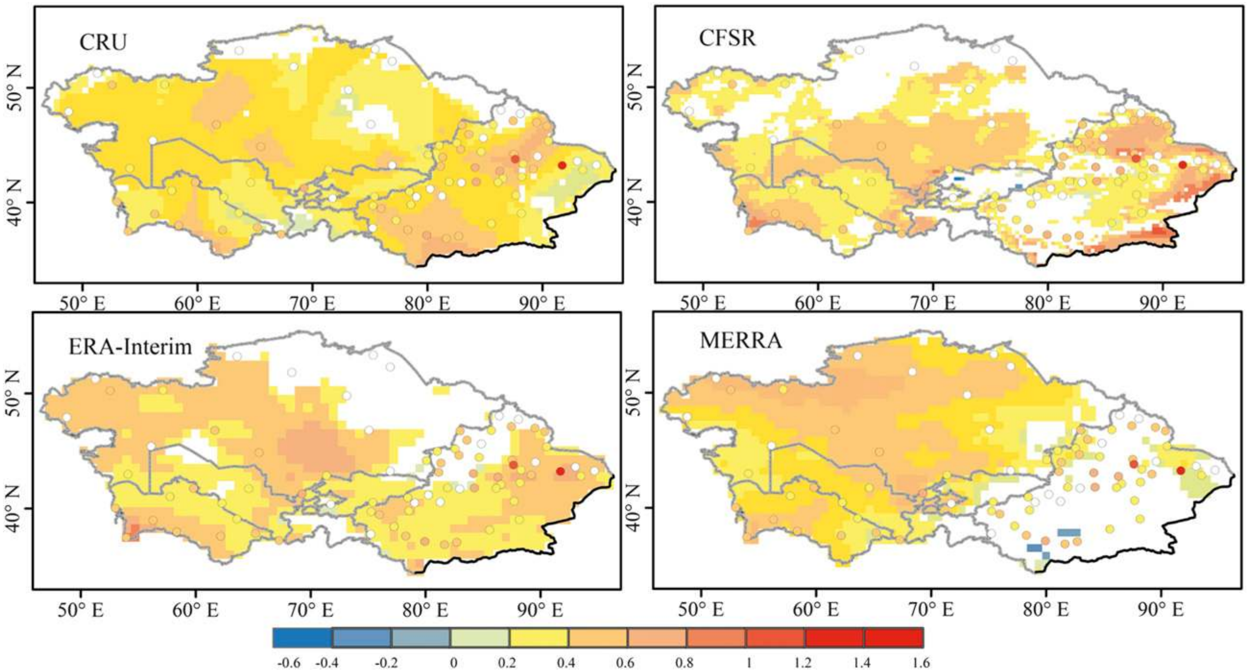


FIG. 6. Spatial pattern of annual temperature change rates (°C $decade^{-1}$) in central Asia from 1979 to 2011 based on linear trend fitting. Circles show the locations of the meteorological stations and the filling color indicates the rate of change from available observational data. Note that the white areas and circles indicate temperature changes that are insignificant at the 95% level.

the study region provide additional temporal details for the 33-yr (1979–2011) temperature trends shown in Fig. 6. The changes in surface temperature from the 1980s to the 1990s for the datasets are shown in Fig. 7. They show that 1) different datasets have yielded similar results in temperature change in those two decades although the MERRA data have some excessive warming in the northern tier of Kazakhstan, and 2) there was cooling from the 1980s to the 1990s in south-central and central CAS region with varying but small magnitudes. The cooling trend reversed in 2000–11 as shown in Figs. 7b,d,f,h when the five central Asian states showed warming at large magnitudes.

Figure 7 also shows big differences in temperature variation in eastern central Asia (Xinjiang, China). The area shows noticeable warming from the 1980s to the 1990s while part of the CAS was experiencing weak cooling in the same period. From the 1990s to the 2000s+ Xinjiang had weaker warming with some locations showing cooling while nearly the entire CAS had substantial warming. Results from the M-K tests suggest that temperature warming in many areas in Xinjiang became noticeable in the 1980s, consistent with and supporting the results in Fig. 7.

The EOF analysis helps encapsulate the information about the spatiotemporal variations in the near-surface air temperature in central Asia previously described. Results of the EOF analysis are summarized in Table 3. Since the first EOF mode (EOF-1) contributes 63%–73% of the spatial variability in the annual temperature variation during 1979–2011, only EOF-1 and its coefficient (PC-1) are shown in Fig. 8. Significant at the 95% confidence level, EOF-1 reaffirms that the temperature changes in CAS and eastern central Asia (i.e., Xinjiang) are different as suggested in Figs. 7 and 8. These results suggest the importance of regional processes in local climate across the arid and semiarid central Asia. The EOF-1 in Figs. 9a,c,g,e further shows that the variability of the surface temperatures in central Asia decreases from the northwest to the southeast. Along this gradient, northern Kazakhstan has large variability in surface temperature whereas southwestern Xinjiang has small variability.

We further extended the analysis of near-surface air temperature change in central Asia to changes in the temperature for the vegetated (VG), nonvegetated (NV), and glacier-covered (GC) areas in the region. The results are summarized in Table 4. Again, the three reanalysis datasets show significant warming in near-surface temperatures for all land cover types. While differences exist among rates of temperature changes for VG, NV, and GC areas, the rates are similar for the CFSR and ERA-Interim datasets. The results from MERRA suggest a higher warming rate in VG areas

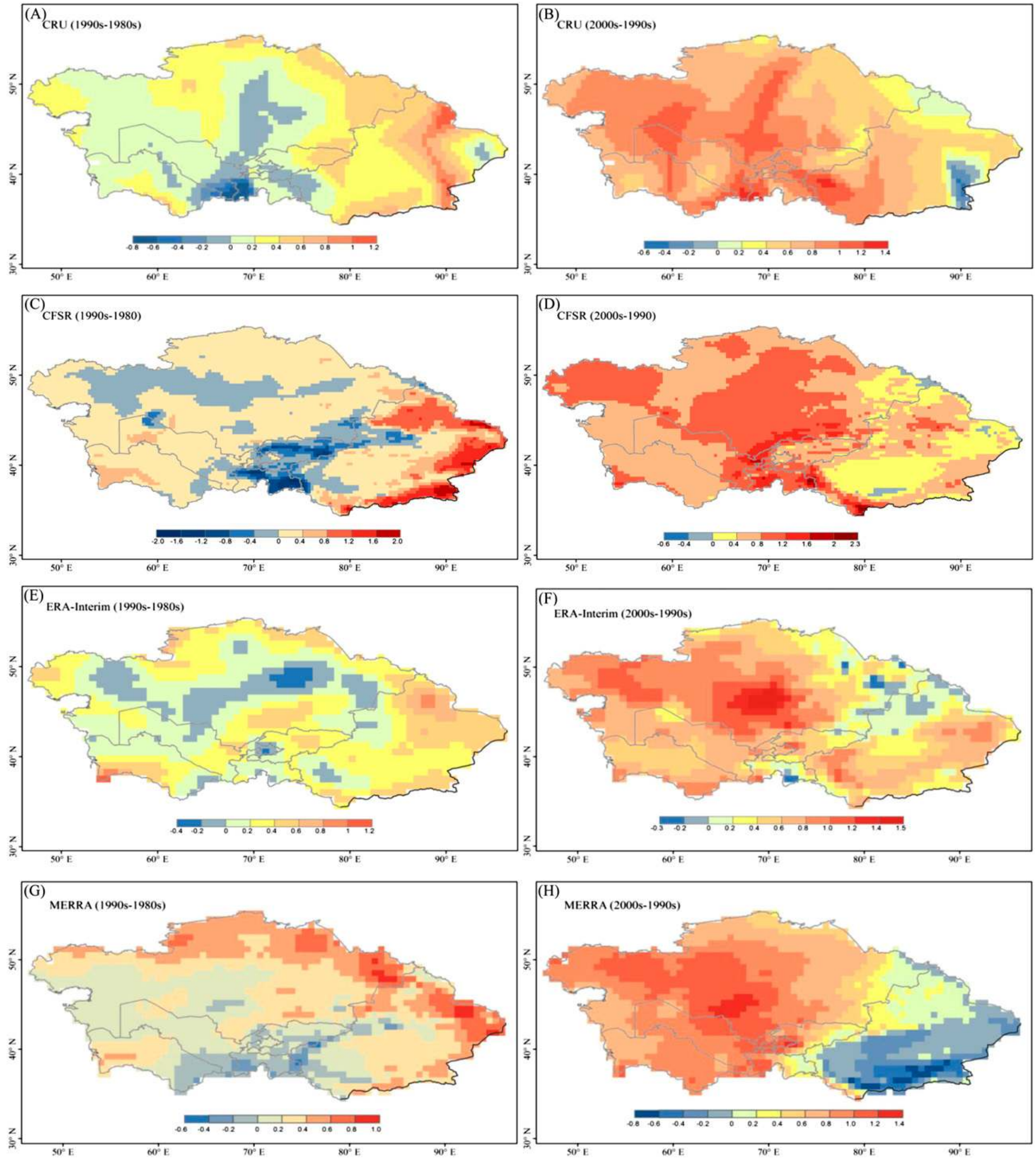


FIG. 7. Spatial pattern of differences in decadal mean temperature (°C) for different datasets: (left) the difference between the 1990s and 1980s and (right) the difference between the 2000s+ (2000–11) and 1990s: datasets (top)–(bottom) CRU, CFSR, ERA-Interim, and MERRA.

than the other two datasets. Additionally, results from MERRA show that the warming rate of 0.41°C decade^{-1} in the VG area is (statistically) significantly higher than the warming rate of 0.24°C decade^{-1} in the glacier-covered areas.

The change in the temperature trend as function of elevation is also examined using the datasets. Figure 9 shows such elevation dependence of the annual and seasonal near-surface air temperature in the Tian Shan mountainous area. In general, the effect of elevation

TABLE 3. The eigenvalues λ and variance contributions R (%) of the EOF analyses. The numeric subscripts indicate the EOF modes 1–4.

Datasets	λ_1	R_1	λ_2	R_2	λ_3	R_3	λ_4	R_4
CRU	1186.55	72.50	145.25	8.88	132.28	8.08	39.34	2.40
CFSR	3490.33	62.99	577.43	10.42	355.58	6.06	280.59	5.06
ERA-Interim	521.21	69.05	77.59	10.28	64.68	8.57	17.82	2.36
MERRA	917.21	70.43	132.36	10.16	82.68	6.35	37.32	2.87

damps the warming in the surface temperature. The results from the CFSR dataset show stronger altitude effects (with correlation coefficients as high as 0.41) than the results from MERRA and ERA-Interim. Our further analysis shows that this difference is not due to the high resolution of CFSR, because even when the CFSR and MERRA were rescaled to match the coarse resolution of ERA-Interim (0.75° × 0.75°) the general pattern is unchanged (see Table S3 in the supplementary material). CFSR always has stronger altitude effects than the other two reanalysis datasets. Also shown in the results of the CFSR data is that the effect of elevation is most prominent in spring, when the decadal mean warming rate is damped by 0.22°C with every 1-km increase in elevation.

4. Discussion

a. Comparison of this study with prior studies

Our results show a strong increase in the near-surface air temperature at 0.39°C decade^{-1} averaged in central Asia during the period from 1979 to 2011. This rate of change is larger than the rate averaged for global land areas (i.e., 0.27°–0.31°C decade^{-1} from 1979 to 2005) (Table 5; Brohan et al. 2006; Smith and Reynolds 2005) and is about twice as large as the warming rate in Europe (Simmons et al. 2004). This rate is comparable to the observed warming trend in China [0.25°–0.34°C decade^{-1} according to Ren et al. (2005) and Li et al. (2011, 2012)] and also is in line with the central Asian averaged warming rate in the 50 years from 1960 to 2009, 0.30°C decade^{-1}. It is worth of noting that this rate is much smaller than the rate averaged over China, 0.52°C decade^{-1}, reported in Wang and Gong (2000). This difference results from different years used in these two studies. Wang and Gong (2000) used data from 1979 to 1998. Because 1998 was an extraordinarily warm year in China, ending the analysis period in that year could have yielded a larger rate of temperature change.

Our extension of the analysis indicates that central Asian temperature has increased at a rate of 0.15°C decade^{-1} from 1901 to 2011, which is comparable to the 0.17°C decade^{-1} temperature increase in Russia (Kattsov et al. 2008) but twice as large as the global mean rate of 0.07°–0.08°C decade^{-1} over the same period (Brohan et al. 2006; Smith and Reynolds 2005). Additional comparisons of the results from our study to some relevant previous studies are summarized in Table 5.

A breakdown of the decadal temperature change in the recent 30 years further suggests an accelerated warming in the past three decades (Table 4; Figs. 3b,c and 7). This strong warming trend agrees with the predictions from global climate model (GCM) simulations, which suggested that central Asia will have a warming rate well above the global mean in the twenty-first century (Trenberth et al. 2007). For example, model simulations with eight GCMs (Pollner et al. 2008) and four coupled atmosphere–ocean GCMs (AOGCMs; Lioubimtseva and Henebry 2009) projected the temperature in central Asia to increase with a rate of 0.29°–0.48°C decade^{-1} in the twenty-first century, comparable to the recent warming rate (0.39°C decade^{-1}) found in this study (Table 5).

b. A shift in seasonal temperature change pattern in recent decades and its impacts

It has been reported that temperature increase in many regions around the world and in central Asian countries has occurred most prominently in the winter months. Winter warming contributed strongly to the annual temperature increase (Zoi Environment Network 2009; Huang et al. 2005; Li et al. 2011; Ren et al. 2005; Trenberth et al. 2007). Climate model projected temperature change in the twenty-first century also suggested that the largest temperature increase would occur in winter in the central Asian states (e.g., Kattsov et al. 2008; Lioubimtseva and Henebry 2009). Our study, however, has revealed a dramatic shift of the largest temperature increase in central Asia from its winter to spring season. During most of the twentieth century, surface air temperature on average has been increasing at larger rate in winter than in other seasons. This situation has changed in the recent 33 years. From 1990s to 2000s+ the largest increase in seasonal temperatures has been found in spring months (Fig. 4b) whereas the winter temperature increase has been leveling off.

Our results further show that large rate of spring temperature increase up to 1.2°–2.2°C decade^{-1} has

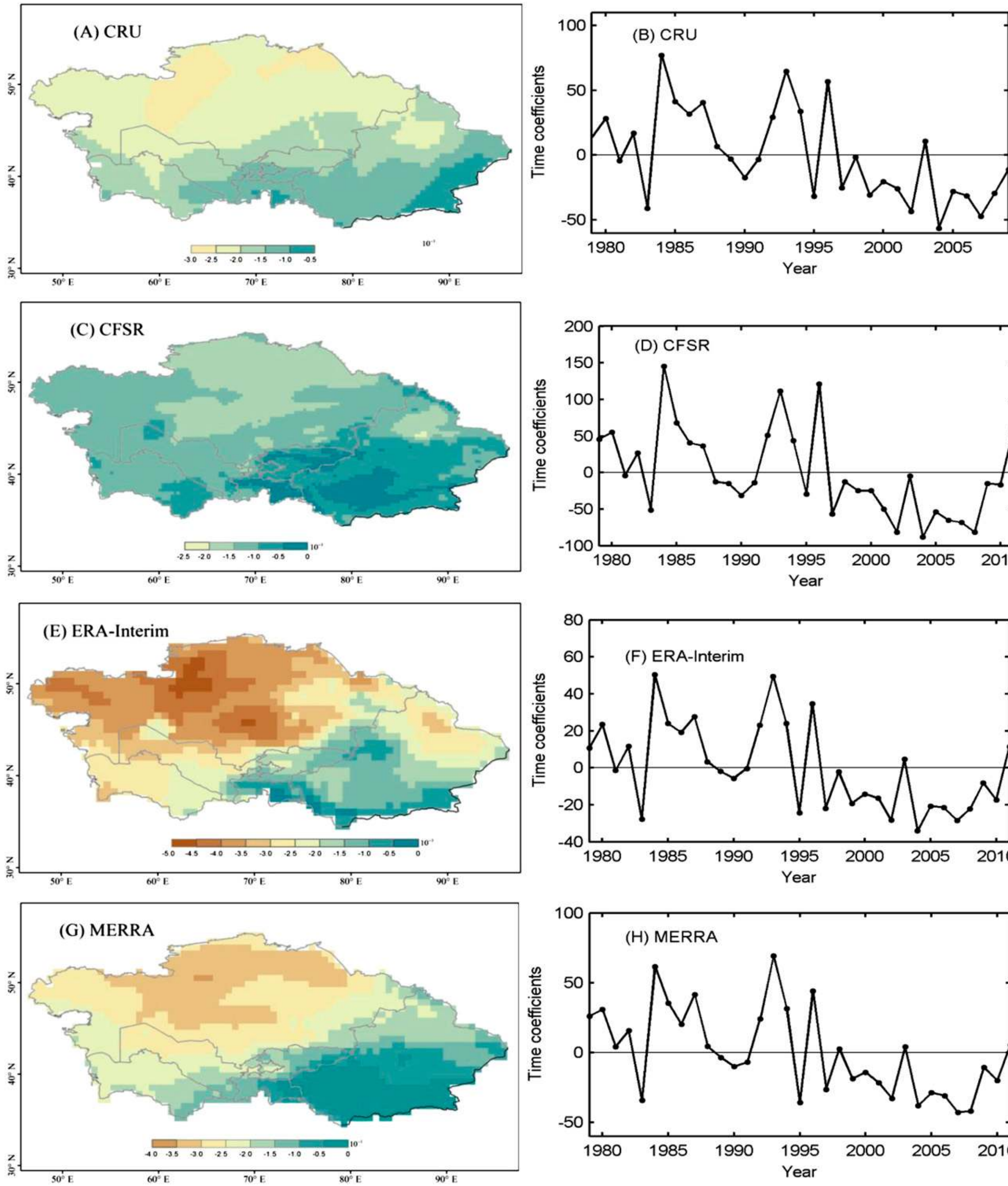


FIG. 8. (left) EOF-1 of the annual temperature anomalies (°C) and (right) the corresponding time series from the four datasets: (a),(b) CRU, (c),(d) CFSR, (e),(f) ERA-Interim, and (g),(h) MERRA.

concentrated in the central part of the central Asian states (Fig. 10). This shift of the largest warming rate of the seasonal temperature from winter to spring may have started affecting the ecosystems in central Asia. Strong spring warming could stimulate early leaf onset, as observed in Europe during the last three decades (Menzel and Fabian 1999; Menzel 2000; Menzel et al. 2006). Propastin et al. (2008) have detected a significant

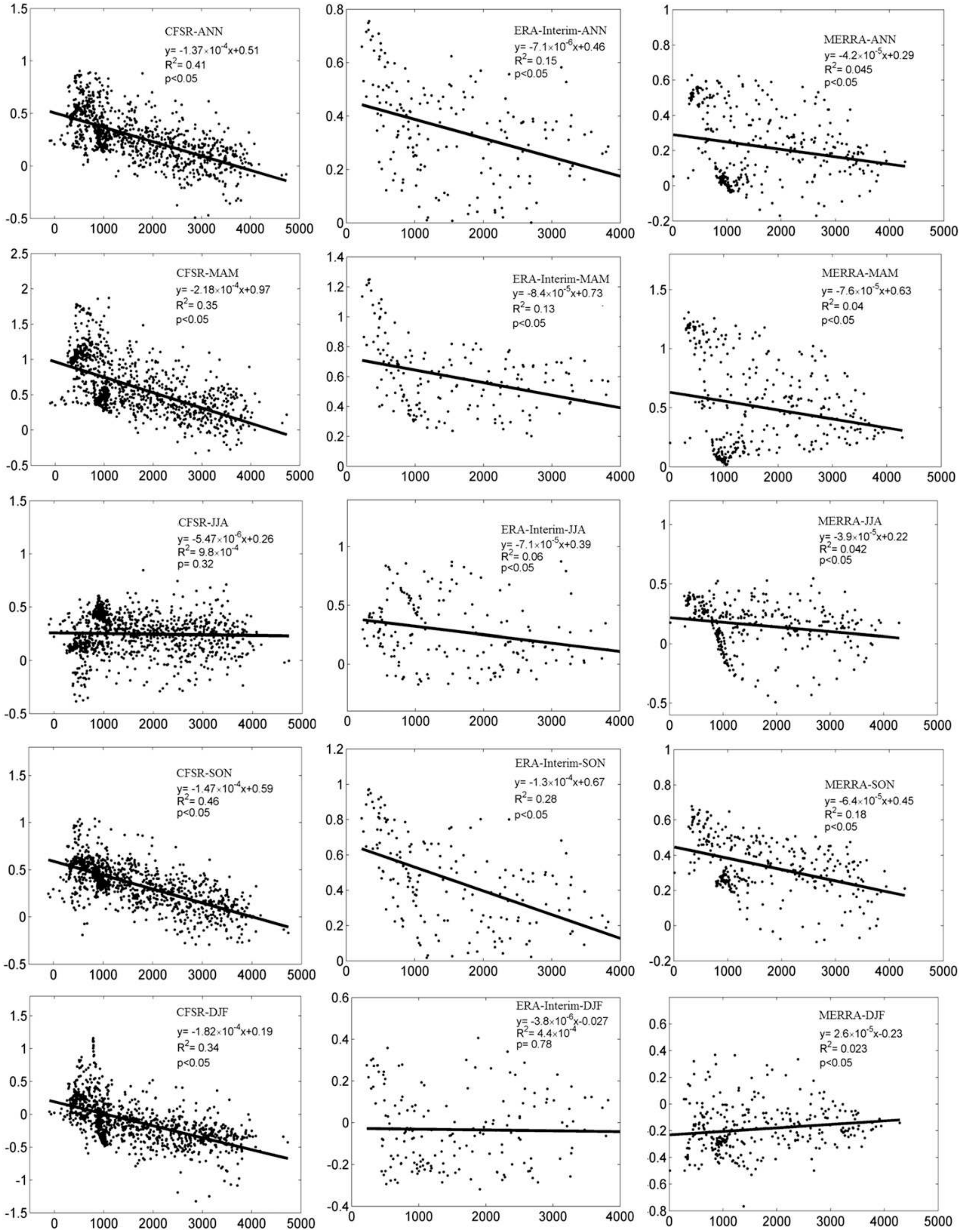


FIG. 9. (top)–(bottom) Annual and seasonal temperature trends from 1979 to 2011 (ordinate, °C decade^{-1}) as function of elevation (abscissa, m MSL) in the Tian Shan mountainous area (see Fig. 1a for the geographical location of this area) based on (left)–(right) CFSR, ERA-Interim, and MERRA datasets. ANN indicates annual, MAM spring, JJA summer, SON fall, and DJF winter.

TABLE 4. Rates of temperature change (°C decade^{-1}) from 1979 to 2011 in central Asia (CA), and in vegetated (VG), nonvegetated (NV), and glacier-covered (GC) areas in central Asia.

Dataset	CA	VG	NV	GC
CRU	0.42	0.42	0.42	0.42
CFSR	0.36	0.37	0.34	0.33
ERA-Interim	0.36	0.36	0.37	0.33
MERRA	0.36	0.41	0.29	0.24

increase (13.58%) in vegetation growth in terms of the normalized difference vegetation index (NDVI) in central Asian states from 1982 to 2003, which they attributed largely to the increase in spring temperatures. Furthermore, the strong spring warming in the central Asian states was reported to have increased risks of natural hazards such as flooding and formation and outburst of ice dams in major rivers (Michael 2011; Siegfried et al. 2012).

c. Elevation dependence of the near-surface air temperature change in central Asia

A recent review by Rangwala and Miller (2012) suggests that elevation dependence in temperature change varies under spatial and temporal conditions. Some prior studies using observational data have shown positive correlations of the elevation with the warming rate in the European Alps (Beniston and Rebetez 1996), Nepal Himalayas (Shrestha et al. 1999), Yunnan Plateau in China (Fan et al. 2011), and the Tibet Plateau (Liu and Chen 2000). The warming is more pronounced at higher elevations in those areas. This positive correlation of the warming rate and elevation is also found in most model simulation results (Giorgi et al. 1997; Chen et al. 2003). However, our analysis shows significant negative correlations (up to $R^2 = 0.41$) between elevation and the warming rate in the Tian Shan mountainous area of central Asia during 1979–2011 (Fig. 9). A similar negative correlation also was found in the tropical Andes in Vuille and Bradley (2000) and Vuille et al. (2003).

According to Liu and Chen (2000), a decrease in spring snow cover at higher elevations could lower the surface albedo and initiate a positive feedback on the surface and near-surface air temperatures, leading to more pronounced warming at high altitudes. This mechanism has been confirmed by model simulations (Chen et al. 2003) and was used to explain the observed positive correlation between the warming rate and elevation in the Tibetan Plateau (Liu and Chen 2000). However, it is difficult to explain why in Tian Shan, a region not far from the Tibetan Plateau, we found a completely opposite pattern with warming rate decreasing with elevation. Some possible factors attributing to these differences could include the effectiveness of the feedback as the elevation increase (into the permafrost elevation or higher) and regional atmospheric circulation. A conclusive understanding of this relationship will require a more comprehensive network of climate monitoring in mountainous regions and detailed modeling (Rangwala and Miller 2012).

d. Effects of land-use changes

Although the temperature change in central Asia well matched the recent warming in the North Hemisphere, it could also be influenced by land-use changes such as irrigation and urbanization at local scales (Lioubimtseva et al. 2005). It has been widely observed that the oases in our study region have lowered temperature comparing to the surrounding desert (i.e., oasis cooling effect), mainly due to the evaporative cooling caused by plant transpiration and irrigation (Kai et al. 1997; Han 1999). According to the statistics in Dukhovny et al. (2009), both the intensity and total water of irrigation in the five central Asian states decreased from 1994 to 2008 (Fig. 11a), possibly due to deintensification of agriculture following the collapse of the former Soviet Union (Lioubimtseva and Henebry 2009). Therefore, the observed temperature rise could be partially caused by local climate effect from declining irrigation intensity in the CAS. To investigate this possibility, we first identified all the meteorological stations located in or within 5 km of the irrigated land in CAS based on the United Nations Food and Agriculture Organization (FAO) global map of irrigated land (Siebert et al. 2007). We then paired them to the closest stations in nonirrigated land (Fig. 11b). Although the advective effect of oases on local climate fades rapidly with distance (Taha et al. 1991), there has been evidence that the effects could still be considerable within 1–10 km from the vegetated areas (DeVries 1959; Zhang and Zhao 1999), and the typical width of the oasis–desert ecotone in the temperate desert of central Asia is about 4 km (Han 1999). Therefore, we used a 5-km buffer around the irrigated land to identify the meteorological stations where local conditions or observations may have been influenced by changes in irrigation intensity since the early 1990s. Comparisons between the temperature change rates of those "oasis stations" and the control sites (i.e., the selected stations outside the irrigated land) are shown in Table 6. Although the mean warming rate of the oasis stations was slightly higher than the mean rate of the control sites (0.38° versus 0.34°C decade^{-1}), the difference was not significant (p value > 0.05; $N = 14$) according to a paired t test. There was also no significant difference between the mean warming rates of the oasis stations and all other stations in central Asia according

TABLE 5. Comparison of decadal temperature change rate (°C decade^{-1}) in central Asia from 1979 to 2011 derived from this study to rates reported in other studies. CAS: central Asian states; OBS: observations; CRU: Climate Research Unit (http://www.cru.uea.ac.uk/cru/data/temperature); NCDC: National Climatic Data Center.

Studies	Study area	Study period	Data and methods	Annual	Spring	Summer	Fall	Winter
Aizen et al. (1997)	Tian Shan mountain	1940–91	Observations from 110 stations	0.10				
Li et al. (2011)	Xinjiang	1961–2005	Observations from 65 stations	0.28		0.12		0.45
Li et al. (2012)	Northwest China	1960–2010	Observations from 74 stations	0.34				
Pollner et al. (2008)	CAS	from 1980–99 to 2030–50	Model simulations with 8 GCMs	0.38		0.48		0.32
Lioubimtseva and Henebry 2009	CAS	from 1961–90 to 2080	Model simulations with 4 AOGCMs	0.29–0.48				
Ren et al. (2005)	China	1951–2004	Observations from 740 stations	0.25		0.15		0.39
Jones et al. (1997); Wang and Gong (2000)	China	1979–98	Area weighted observations in 10 climatic subregions in China	0.52				
Simmons et al. (2004)	Europe	1958–2001	CRU	0.17				
Kattsov et al. (2008)	Russia	1980–2006	Observations from meteorological stations in Russia	0.43				
		1907–2006		0.13				
Easterling et al. (1997)	Globe	1950–93	Observations from 4100 stations			0.05–0.11		0.11–0.25
Solomon et al. (2007)	Globe	1901–2005	Multiple global land temperature reconstructions based on multiple historical climate records from CRU, NCDC, and Goddard Institute for Space Studies (GISS) (Lugina 2006)	0.07–0.08				
		1979–2005		0.19–0.32				
This study	CAS and Xinjiang	1979–2011	Observations from 81 stations	0.41	0.64	0.38	0.52	−0.01
			CRU	0.42	0.81	0.25	0.46	0.16
			CFSR	0.36	0.74	0.22	0.42	0.02
			ERA-Interim	0.36	0.69	0.24	0.49	0.05
			MERRA	0.36	0.75	0.36	0.47	−0.28
		1960–2009	CRU	0.33	0.34	0.23	0.32	0.47
		1960–2011	Observations from 62 stations	0.27	0.23	0.19	0.31	0.33
		1901–2009	CRU	0.15	0.19	0.09	0.12	0.19

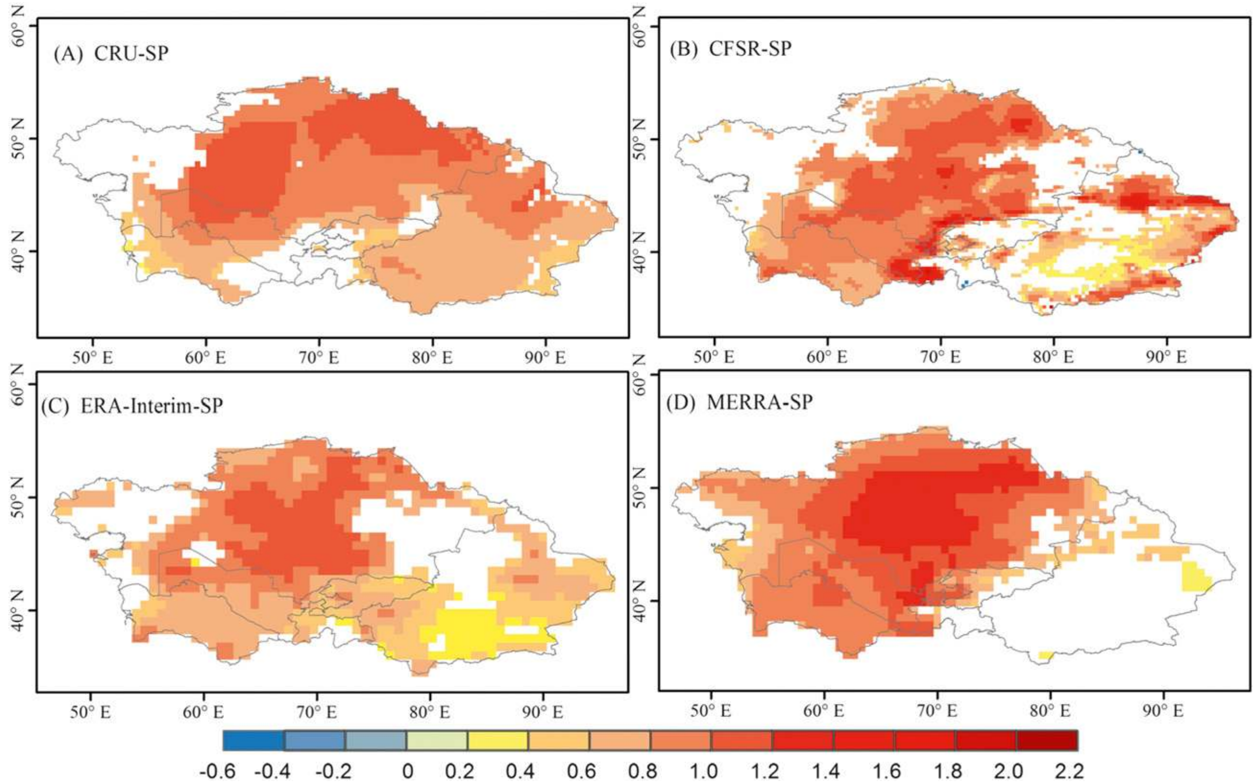


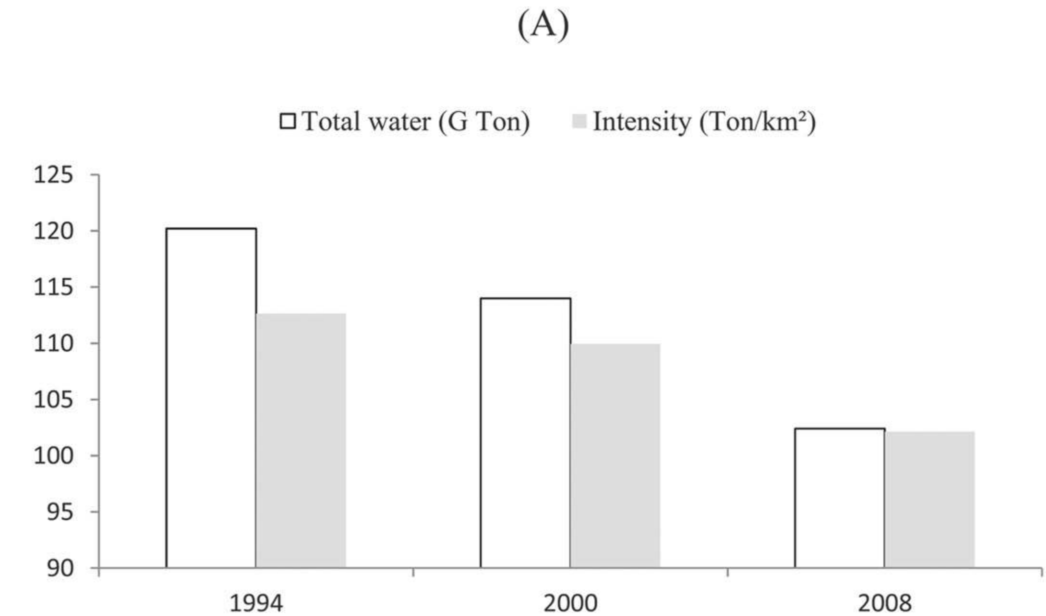
FIG. 10. Spatial pattern of spring warming rate (°C decade^{-1}) from 1979 to 2011 in central Asia according to the four reanalysis datasets: (a) CRU, (b) CFSR, (c) ERA-Interim, and (d) MERRA.

to unpaired t tests. Finally, when comparing the mean temperatures between the early 1990s (1990–95) and late 1990s (1995–2000), we found that the warming in the oasis stations was actually smaller than that in the other stations (0.66° versus 0.84°C). Our analysis, therefore, detected no significant positive effect from de-intensification of agriculture following the collapse of the former Soviet Union in the early 1990s on the observed temperature increase in central Asia.

We used a similar approach to investigate whether urbanization in the study region may have affected the observed temperature change. First, all urban stations in central Asia were identified with the 500-m-resolution global urban land map developed by Schneider et al. (2009). Then, these urban stations were paired to the closest rural stations in central Asia (Fig. 12a; Table 7). In Fig. 12, the crosses mark the 22 meteorological stations located in urban areas. Although the population increased by about 45.7% in those cities in 1980–2000 (Fig. 12b), paired t test showed no significant differences in temperature change rates between the urban and rural stations (p value > 0.05; $N = 22$). Unpaired t test values also indicated no significant difference in temperature change rates between the urban stations and all the other stations in the study region. These test results thus suggest no significant effect from urbanization on the observed temperature change in central Asia.

5. Conclusions

Temperature observations at meteorological stations, the CRU dataset, and three recently developed high-resolution reanalysis datasets, CSRF, MERRA, and ERA-Interim, were used in this study to evaluate the near-surface air temperature change in central Asia from 1979 to 2011. The reanalysis datasets of CSRF, MERRA, and ERA-Interim were first examined for their accuracy in describing the temperature variations in the study region. Comparisons of these datasets with quality-controlled in situ observations showed that the datasets are fairly accurate by several statistical measures, although minor differences exist among these datasets and the observations. While these test results are important for validation of the datasets they justify the use of these datasets in our analysis of the temperature variation in central Asia. Their high-resolution spatial coverage overcomes the difficulty of the ground observations from sparse stations in the region and allows us to examine and understand central Asian temperature variations (Lioubimtseva et al. 2005; Lioubimtseva and Cole 2006).



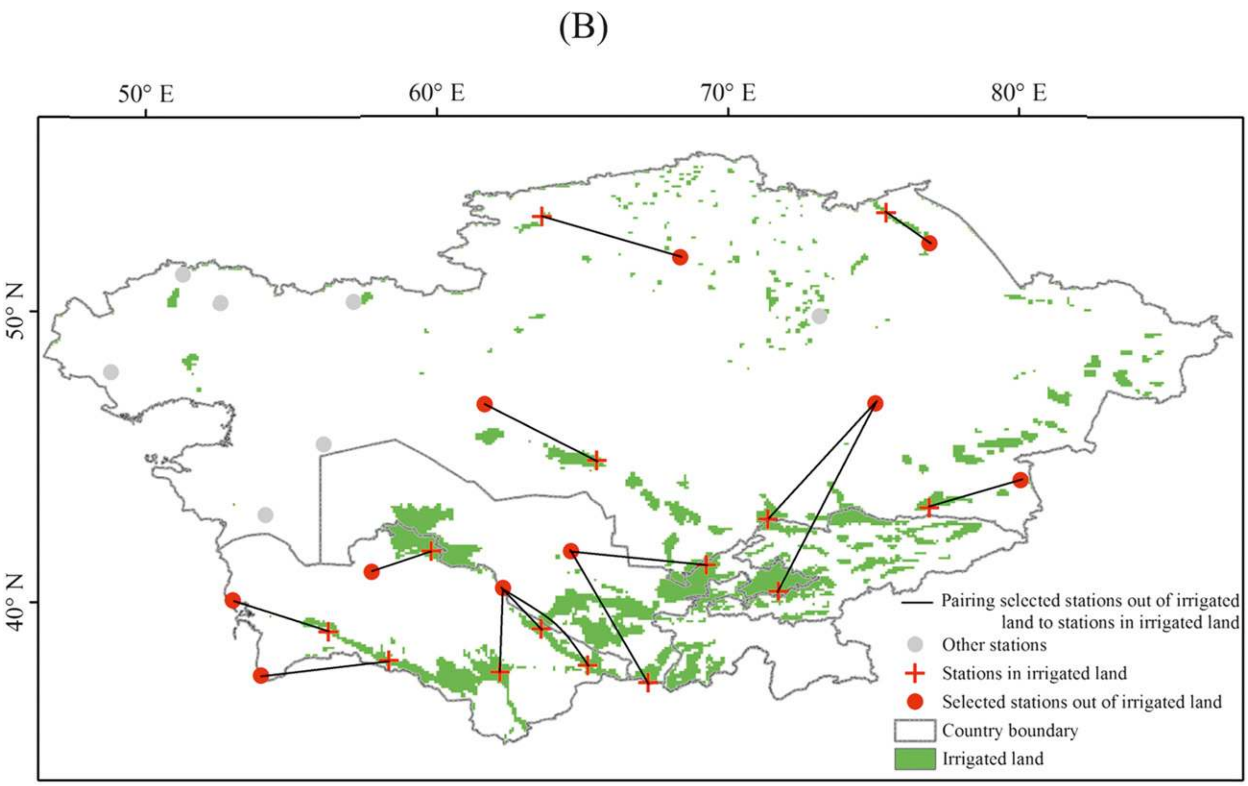


FIG. 11. (a) Changes in total water for irrigation and irrigation intensity in the five central Asian states from 1994 to 2008 (Dukhovny et al. 2009) indicating a declining irrigation in the region. (b) Pairing of meteorological stations located in the irrigated land with the closest stations outside the irrigated land.

TABLE 6. Comparison of the observed temperature change rates from 1979 to 2011 between stations in irrigated land and the selected stations out of irrigated land in the five central Asian states.

Stations in irrigated land		Selected stations outside of irrigated land	
ID	Warming rate (°C decade^{-1})	ID	Warming rate (°C decade^{-1})
12	0.33	23	0.31
7	0.24	19	0.10
176	0.11	151	0.28
261	0.16	106	0.20
138	0.50	109	0.41
193	0.30	106	0.20
223	0.52	241	0.37
236	0.68	224	0.34
299	0.27	260	0.39
305	0.46	273	0.42
334	0.52	350	0.57
346	0.41	260	0.39
338	0.44	260	0.39
356	0.41	224	0.34

The consensus of these datasets and available in situ observations indicates accelerated warming at the average rate of 0.39°C decade^{-1} in central Asia from 1979 to 2011, which is stronger than the mean rate of temperature change for global land areas (e.g., Brohan et al. 2006; Smith and Reynolds 2005) and other regions (Simmons et al. 2004; Ren et al. 2005; Li et al. 2011, 2012). Moreover, the warming rate in central Asia in the first 12 years of the twenty-first century is larger than that of the previous decades. This increase rate in central Asia in the early twenty-first century is comparable to that averaged for Russia and for China (Brohan et al. 2006; Smith and Reynolds 2005) and is larger than that averaged for Europe (Simmons et al. 2004). In addition to showing the spatial pattern of the temperature change we further identified that the maximum rate of temperature increase in central Asia occurred in the central areas of the central Asian states.

We also found that the seasonal pattern of the rise in near-surface air temperature has changed in central Asia in the recent decades. While winter warming was most prominent among all the seasons during the most part of the twentieth century (Zoi Environment Network 2009; Huang et al. 2005; Li et al. 2011; Ren et al. 2005; Trenberth et al. 2007), the winter warming has weakened and even reversed in some areas over time. Mean winter temperature in the early twenty-first century is cooler than in the 1990s. Meanwhile, the spring temperature has been steadily increasing from 1979 to 2011, with a larger increase rate in the early twenty-first century. The spring warming has replaced the winter warming as the major contributor to the annual temperature rise. This shift of the strong warming from the dormant winter season to the germination spring season could result in changes in phenology of plants in the region and also raise the risk of spring flooding (Michael 2011; Siegfried et al. 2012).

The magnitude of temperature increase is found shrinking significantly with elevation, a result different from the results of some previous studies in regions surrounding central Asia (Beniston and Rebetez 1996;

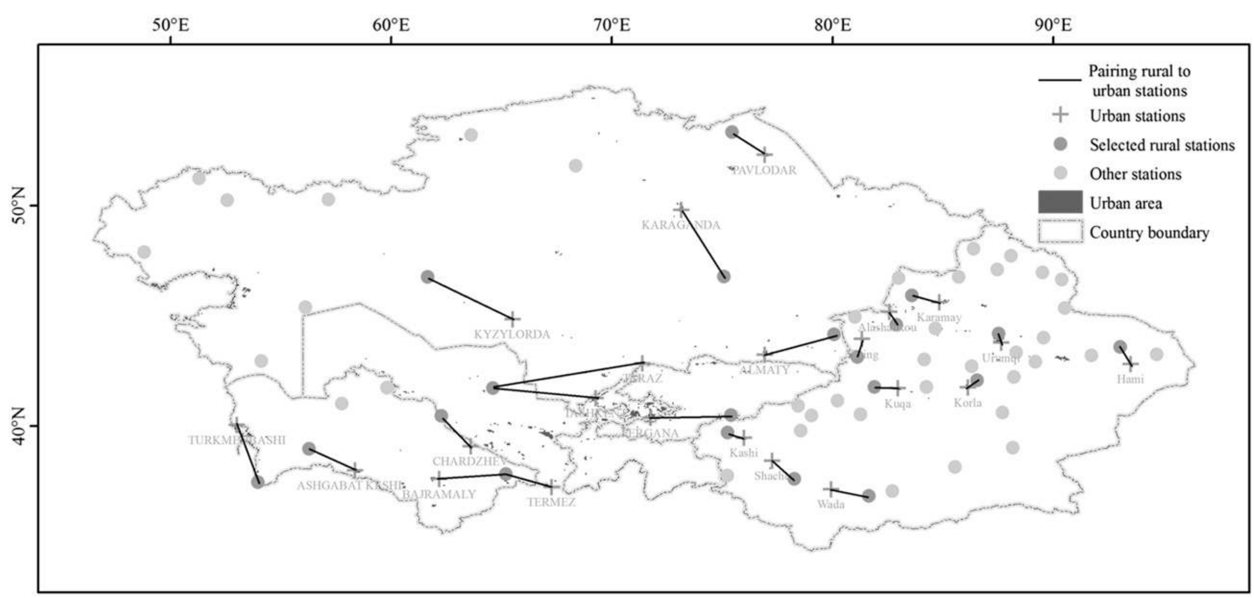


FIG. 12. Pairs of meteorological stations located in the urban areas and the closest rural stations.

TABLE 7. Comparison of the observed temperature change rates from 1979 to 2011 between urban station and the closest rural station in central Asia.

Urban station		Rural station	
ID	Warming rate (°C decade^{-1})	ID	Warming rate (°C decade^{-1})
273	0.42	350	0.57
334	0.52	305	0.46
346	0.41	338	0.44
299	0.27	260	0.39
138	0.50	109	0.41
356	0.41	338	0.44
236	0.68	224	0.34
193	0.30	224	0.34
261	0.16	258	0.27
54	0.03	106	0.20
287	0.55	279	0.36
19	0.10	7	0.24
176	0.11	151	0.28
319	0.32	345	0.49
357	0.64	360	0.40
159	0.45	179	0.41
131	0.30	144	0.45
225	−0.11	219	0.29
125	0.20	120	0.55
220	0.39	212	0.37
162	1.01	150	0.43
196	0.21	167	0.95

Shrestha et al. 1999; Fan et al. 2011; Liu and Chen 2000) and from most model simulations (Giorgi et al. 1997; Chen et al. 2003). This different result and further understanding of underlying mechanisms for the observed temperature change and its spatial heterogeneity in central Asia will continue to elude us in the absence of comprehensive networks of climate monitoring in this vast arid and semiarid region (Rangwala and Miller 2012).

It has been suggested that the de-intensification of agriculture following the collapse of the Soviet Union in early 1990s and urbanization may be influencing the observed temperature change in irrigated or urban areas (Zhou et al. 2004; Ren et al. 2008; Lioubimtseva and Henebry 2009). Our analysis, however, did not find significant contributions from urbanization or declined irrigation to temperature change in the study region. This finding assures the relevance of our results in describing the surface temperature variations in central Asia.

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Supplementary Material

Table S1. Information for climate stations used in this study

ID	Station Name	Country[&]	Latitude (degree)	Longitude (degree)	Elevation (m)	Time in function (YYYMMDD)		Quality control[#]
						Start	End	
1	URDA	KZ	48.767	47.433	4	19590101	19981009	0
2	NOVYJ USHTOGAN	KZ	47.900	48.800	-10	19590101	20111231	3
3	GANJUSHKINO	KZ	46.600	49.267	-23	19590101	20111231	2
4	ZHALPAKTAL	KZ	49.667	49.483	10	19590101	20111231	1
5	KULALY ISLAND	KZ	45.017	50.033	-22	19590101	20020319	0
6	FORT SHEVCHENKO	KZ	44.550	50.250	-25	19320201	20111231	1
7	DZHANGALA	KZ	49.217	50.300	7	19881001	20040731	0
8	SEVCENKO	KZ	43.583	51.083	-15	19601201	20110125	1
9	CHAPAEVO	KZ	50.200	51.167	17	19590101	20111231	1
10	URALSK	KZ	51.250	51.283	37	19320102	20111231	3
11	ATYRAU	KZ	47.117	51.817	-22	20040706	20111231	0
12	TAIPAK	KZ	49.050	51.867	2	19361231	20111231	1
13	ATYRAU	KZ	47.117	51.917	-22	19320101	20111231	2
14	TUSCIKUDUK	KZ	44.733	51.967	56	19590101	20110125	1
15	KARABOGAZKEL	TX	41.050	52.917	-22	19590101	20090414	0
16	DZHAMBEJTY	KZ	50.250	52.567	32	19480101	20111231	3
17	OGRYDA	TX	39.100	53.100	-26	19590101	20070306	0

18	TURKMENBASHI	TX	40.050	53.000	82	19320101	20111231	3
19	TURKMENBASHI	TX	40.050	53.000	85	20040706	20111231	0
20	KULSARY	KZ	46.800	53.917	18	19340102	19991218	0
21	BYGDAILI	TX	38.533	54.300	-1	19600216	20051114	0
22	DUKEN	KZ	44.317	54.600	143	19590101	20030612	0
23	ESENGYLY	TX	37.467	53.967	-22	19320101	20111231	3
24	NEBITDAG	TX	39.500	54.333	-8	19591102	20061019	0
25	AKKUDUK	KZ	42.967	54.117	78	19570701	20111231	3
26	UIL	KZ	49.067	54.683	128	19320401	20111231	1
27	GYZYLETREK	TX	37.617	54.783	29	19591102	20060816	0
28	SAGIZ	KZ	48.200	54.933	73	19730101	19990318	0
29	ZAMBIKE	KZ	47.033	55.133	45	19590101	20030303	0
30	BEKIBENT	TX	38.617	55.183	206	19600111	20090520	0
31	CHAGYL	TX	40.783	55.333	115	19570710	20111231	1
32	GAZANDZHYK	TX	39.250	55.517	31	19591102	20111231	1
33	JASGA	TX	39.683	55.567	-9	19591102	20021006	0
34	NOVOALEKSJEVKA	KZ	50.133	55.700	142	19590110	20000829	0
35	KARAKAPALKIJA	UZ	44.850	56.333	126	19590101	20050104	0
36	MARTUK	KZ	50.750	56.533	178	19530216	20020810	0
37	GARRYQALA	TX	38.433	56.300	312	19591103	20061019	0
38	SAM	KZ	45.400	56.117	88	19570701	20111231	3
39	GYZYLARBAT	TX	38.983	56.283	92	19320101	20111231	3
40	TEMIR	KZ	49.150	57.117	234	19480103	20111231	1
41	JASLYK	UZ	43.883	57.517	128	19740421	20111231	2
42	DAVALY	TX	40.067	57.383	47	19591101	20051015	0
43	BAKHERDEN	TX	38.433	57.417	159	19590801	20111231	2

44	AKTOBE	KZ	50.283	57.150	219	19320101	20111231	3
45	BOKYRDAK	TX	38.750	58.467	84	19591101	20001027	0
46	KOS-ISTEK	KZ	50.733	57.900	340	19590628	20090621	0
47	MUGODZARSKAJA	KZ	48.633	58.500	398	19570701	20111231	1
48	EKEZHE	TX	41.033	57.767	62	19590101	20111231	3
49	DEVERZE	TX	40.183	58.483	84	19550703	20101219	0
50	ASHGABAT KESHI	TX	37.987	58.361	211	19320101	20111231	3
51	ERBENT	TX	39.317	58.600	87	19590109	20111231	1
52	SHASENEM	TX	41.583	58.717	62	19600207	20090414	0
53	MUJNAK	UZ	43.750	58.733	55	20021124	20021124	0
54	KUNGRAD	UZ	43.083	58.933	64	19480101	20111231	2
55	KENEURGENCH	TX	42.300	59.133	71	19591101	20090414	0
56	AYAK-KUM	KZ	46.717	59.167	114	19570710	20020319	0
57	TALDYK	KZ	49.250	59.550	260	19590101	19941202	0
58	CELKAR	KZ	47.850	59.617	176	19361231	20020319	0
59	NUKUS	UZ	42.450	59.617	77	19591101	20111231	2
60	NUKUS/KARAKALPAKS	UZ	42.483	59.633	77	20040713	20111231	0
61	KAKA	TX	37.350	59.633	308	19590810	20101008	0
62	TEDZHEN	TX	37.383	60.517	186	19480101	20111231	1
63	DASHKHOVUZ	TX	41.750	59.817	82	19480101	20111231	3
64	DASHOGUZ	TX	41.750	59.833	83	20050724	20111231	0
65	BARSAKELMES ISLAND	KZ	45.683	59.917	80	19600101	19970318	0
66	AKMOLLA	TX	39.583	59.950	108	19730102	20051114	0
67	CHIMBAJ	UZ	42.950	59.817	66	19320602	20111231	2
68	URGENCH	UZ	41.567	60.567	101	19480101	20111231	1
69	URGENCH	UZ	41.583	60.633	98	20040713	20111231	0

70	CHESHME	TX	38.683	61.200	147	19570703	19980225	0
71	SARAGT	TX	36.533	61.217	275	19460403	20111231	1
72	IRGIZ	KZ	48.617	61.267	114	19320401	20041003	0
73	ZABELOVKA	KZ	52.300	61.317	279	19600101	20000105	0
74	TAMABULAK	KZ	49.983	61.483	221	19600109	20030218	0
75	KAZALINSK	KZ	45.767	62.117	68	19340201	20111231	2
76	MARY	TX	37.617	61.900	222	20050722	20111231	0
77	CABANKAZGAN	KZ	43.600	61.933	64	19600101	20021101	0
78	TAUP	KZ	48.250	62.000	74	19590101	19951113	0
79	ARALSKOE MORE	KZ	46.783	61.650	62	19480101	20111231	3
80	BUZAUBAJ	UZ	41.750	62.467	98	19600101	20111231	1
81	TOBOL	KZ	52.683	62.600	208	19530216	20020319	0
82	GYSHGY	TX	35.283	62.350	625	19320101	20111231	1
83	ELOTEN	TX	37.300	62.417	259	19590818	20050127	0
84	BAJRAMALY	TX	37.600	62.183	240	19370731	20111231	3
85	DARGANATA	TX	40.467	62.283	142	19480101	20111231	3
86	ARALKOL'	KZ	51.083	62.700	230	19630302	19981009	0
87	APPROXIMATE LOCALE	KZ	50.450	62.800	183	19820102	19820428	0
88	UCHADZHY	TX	38.083	62.800	185	19530216	20111231	2
89	CIRIK-RABAT	KZ	44.067	62.900	88	19480101	20060923	0
90	TAGTABAZAR	TX	35.950	62.917	349	19570710	20090910	0
91	FYODOROV SOVKHOZ	KZ	53.750	63.167	184	19590101	19631218	0
92	REPATEK	TX	38.567	63.183	185	19320101	20081101	0
93	DJACHEV	TX	39.317	63.200	182	20081101	20081101	0
94	KUL-KUDUK	UZ	42.533	63.283	333	19591120	19940430	0
95	DZANGELDY	UZ	40.850	63.333	208	19590901	20070306	0

96	TORGAI	KZ	49.633	63.500	136	19320101	20111231	1
97	DZHUSALY	KZ	45.500	64.083	103	19480102	20111231	1
98	SHUMEKTY	KZ	50.267	64.217	76	19600317	20020830	0
99	LEKKER	TX	36.267	63.700	787	19600101	20011007	0
100	KARAKUL	UZ	39.500	63.850	196	19591101	20020814	0
101	CHARDZHEV	TX	39.083	63.600	190	19480101	20111231	3
102	KUSTANAI	KZ	53.217	63.617	156	19351231	20111231	3
103	ZARAFSHAN	UZ	41.617	64.233	425	20061110	20061110	0
104	AK-BAJTAL	UZ	43.150	64.333	234	19570201	20111231	2
105	BYRDALYK	TX	38.467	64.367	212	19591102	20111231	1
106	BUKHARA	UZ	39.767	64.467	229	20040706	20111231	0
107	AYAKAGITMA	UZ	40.683	64.483	219	19590801	20040215	0
108	BISARY	KZ	48.817	64.617	122	19630302	20050824	0
109	CARSANGA	TX	37.517	66.017	265	19590801	20111231	1
110	BUHARA	UZ	39.717	64.617	226	19361231	20111231	1
111	KUSMURUN	KZ	52.467	64.667	110	19590101	20000807	0
112	KARA-KUM	KZ	46.883	64.667	79	19570711	20020726	0
113	TAMDY	UZ	41.733	64.617	237	19591110	20111231	3
114	AMANGELDY	KZ	50.133	65.233	142	19530216	20090612	0
115	MASHIKUDUK	UZ	41.050	65.283	200	19590930	20050804	0
116	NAVOI	UZ	40.133	65.349	341	19600101	20111231	1
117	KERKI	TX	37.833	65.200	240	19320101	20111231	3
118	KYZYLORDA	KZ	44.850	65.500	130	19320101	20111231	3
119	URICKY	KZ	53.317	65.550	210	19530216	20111231	1
120	NURATA	UZ	40.550	65.683	485	19480106	20111231	2
121	KARSHI	UZ	38.800	65.717	376	19590804	20111231	2

122	KARSHI KHANABAD	UZ	38.833	65.917	416	20070101	20111231	0
123	KARASUL	KZ	52.667	65.500	209	19590101	19741025	0
124	SENBER	KZ	49.750	66.150	229	19600401	20020319	0
125	GUZAR	UZ	38.617	66.267	524	19480101	20090612	0
126	ESIL	KZ	51.883	66.333	221	19530216	20111231	1
127	TORUK	KZ	41.800	66.717	202	19590101	20021212	0
128	KARSAKPAJ	KZ	47.833	66.750	508	19351231	20020920	0
129	CIILI	KZ	44.167	66.750	153	19480101	20111231	2
130	SHAHRISABZ	UZ	39.033	66.783	599	20080724	20111231	0
131	ARKALYK	KZ	50.217	66.833	343	19690102	20060114	0
132	AKRABAT	UZ	38.250	66.833	1601	19600817	20040319	0
133	MINCHUKUR	UZ	38.650	66.933	2121	19600101	20030429	0
134	SAMARKAND	UZ	39.567	66.950	724	19480101	20111231	1
135	BLACOVESCHENKA	KZ	54.367	66.967	153	19480101	20111231	1
136	RUZAEVKA	KZ	52.817	66.967	227	19531101	20111231	2
137	SHIRABAD	UZ	37.667	67.017	410	19590811	20050713	0
138	ZLIKHA	KZ	45.250	67.067	138	19530216	20111231	1
139	CARDARA	KZ	41.367	68.000	275	19730101	20111231	2
140	KIJMA	KZ	51.600	67.567	272	19850702	19971128	0
141	PENDZHIKENT	TI	39.500	67.600	1015	19600117	20031130	0
142	ZHEZKAZGAN	KZ	47.800	67.717	346	19480102	20111231	1
143	DZIZAK	UZ	40.117	67.833	345	19480101	20111231	1
144	DENAU	UZ	38.267	67.900	520	19590811	20020829	0
145	TERMEZ	UZ	37.233	67.267	310	19480101	20111231	3
146	ALGABAS	KZ	48.883	68.083	506	19810101	19970209	0
147	VOLODARSKOE	KZ	53.317	68.100	319	19590101	20020319	0

148	SHAARTUZ	TI	37.317	68.133	380	19600602	20040611	0
149	TURKESTAN	KZ	43.267	68.217	207	19320104	20111231	1
150	ISAMBAJ	TI	38.050	68.350	563	19600102	20111231	1
151	DUSHANBE	TI	38.550	68.783	800	19320101	20111231	1
152	ISKANDERKUL	TI	39.100	68.383	2204	19751101	20050115	0
153	GANDZHINA	TI	37.950	68.567	752	20101214	20111231	0
154	SHAHRISTANSKIJ PEREV	TI	39.567	68.583	3143	19610107	20080131	0
155	JETI-KONUR	KZ	46.583	68.617	276	19570710	20020730	0
156	SONGISTON (MTN STN)	TI	39.383	68.617	1507	19610119	20050126	0
157	SYR-DARJA	UZ	40.817	68.683	264	19600101	20111231	1
158	BALKASINO	KZ	52.533	68.750	399	19590101	20111231	2
159	ATBASAR	KZ	51.817	68.367	304	19480101	20111231	3
160	KURGAN-TYUBE	TI	37.817	68.783	429	19600101	20111231	1
161	JANGIER	UZ	40.217	68.833	317	19530216	20050402	0
162	ANZOBSKIJ PEREVAL	TI	39.083	68.867	3373	19610201	20080602	0
163	ACHISAJ	KZ	43.550	68.900	822	19611203	20111231	1
164	URA-TYUBE	TI	39.900	68.983	1005	19600102	20070303	0
165	PYANDJ	TI	37.233	69.083	363	19480101	20040408	0
166	TASTY	KZ	44.800	69.117	190	19530216	20030121	0
167	PETROPAVLOVSK	KZ	54.833	69.150	136	19320101	20111231	1
168	SANGLOK	TI	38.250	69.233	2239	19730101	20111231	1
169	KYZYLZHAR	KZ	48.300	69.650	361	19550301	20111231	1
170	DANGARA	TI	38.100	69.317	660	19591102	20111231	1
171	NUREK	TI	38.417	69.350	549	19830701	19970106	0
172	KOKSHETAY	KZ	53.283	69.383	229	19320101	20111231	1
173	PARKHAR	TI	37.483	69.383	448	19591030	20111231	1

174	TASHKENT VOSTOCNY	UZ	41.317	69.400	466	20050411	20111231	0
175	BERLIK	KZ	49.883	69.517	349	19530216	20080328	0
176	BARSHINO	KZ	49.683	69.517	349	20090203	20111231	0
177	KOKSHETAU AIRPORT	KZ	53.317	69.600	263	20050724	20111231	0
178	TASHKENT	UZ	41.267	69.267	466	19320101	20111231	3
179	MADRUSHKAT	TI	39.433	69.667	2234	19591029	20111231	1
180	KHUDZHAND	TI	40.217	69.683	442	20040706	20111231	0
181	SHYMKENT	KZ	42.317	69.700	604	19480101	20111231	1
182	KHUDJAND	TI	40.217	69.733	427	19360101	20111231	1
183	KULYAB	TI	37.917	69.783	659	19600101	19950405	0
184	ZHALTYR	KZ	51.617	69.800	305	19590101	20111231	1
185	KAJRAKKUMSKOE	TI	40.267	69.817	347	20101214	20111231	0
186	HOVALING	TI	38.367	69.983	1468	20090929	20111231	0
187	KURGALJINO	KZ	50.583	70.000	330	19600223	20020804	0
188	BETPAK-DALA STEPPE	KZ	46.000	70.000	325	19570706	20020607	0
189	DEHAVZ	TI	39.450	70.200	2561	19751101	20111231	1
190	SUCINSK	KZ	52.950	70.217	384	19530216	20111231	2
191	AUL TURARA RYSKULOV	KZ	42.483	70.300	808	19590101	20111231	2
192	RASHT	TI	39.000	70.300	1316	19591124	20020507	0
193	PSKEM	UZ	41.900	70.367	1258	19600208	20111231	2
194	ISFARA	TI	40.133	70.600	873	19480101	19970510	0
195	TERS	KG	41.667	70.717	1759	19591222	19960416	0
196	OLGAING	UZ	42.167	70.883	2151	19630610	19981009	0
197	DARVAZ	TI	38.467	70.883	1288	19590901	20100605	0
198	KOKTAS	KZ	47.517	70.900	471	19590101	20090220	0

199	VOZVISHEN SOVKHOZ	KZ	54.433	70.917	127	19590102	20080905	0
200	UJUK	KZ	43.783	70.933	366	19590101	20090612	0
201	AKKOL	KZ	52.000	70.950	384	19590101	20111231	1
202	KOKAND	UZ	40.550	70.950	499	19590913	20101029	0
203	ULANBEL'	KZ	44.800	71.067	266	19590101	20040104	0
204	APPROXIMATE LOCALE	KZ	50.833	72.183	411	19810101	19860605	0
205	HUMRAGI	TI	38.283	71.333	1737	19730101	20080229	0
206	CATKAL RIVER	KG	41.900	71.350	1937	19591101	20020411	0
207	ASTANA	KZ	51.133	71.367	350	19320101	20111231	2
208	TARAZ	KZ	42.850	71.383	655	19480101	20111231	3
209	KHOROG	TI	37.500	71.500	2077	19571011	20111231	1
210	NAMANGAN	UZ	40.983	71.583	474	19480101	20111231	1
211	KAZGORODOK	KZ	49.950	71.583	422	19630601	20030216	0
212	NAMANGAN	UZ	40.983	71.583	474	20040706	20051110	0
213	ISHKASHIM	TI	36.717	71.600	2523	19591108	20080131	0
214	ATASU	KZ	48.700	71.633	488	19590102	20101130	0
215	OSH	KG	40.533	72.800	875	19591102	20031003	0
216	LAHSH	TI	39.283	71.867	1198	19730312	20111231	1
217	KZYL-TAU	KZ	47.850	72.083	810	19570710	20050704	0
218	FEDCENKO GLACIER	TI	38.917	72.167	4169	19370104	20050827	0
219	TARAZ	KZ	42.850	71.300	666	20070827	20111231	0
220	TALAS	KG	42.517	72.217	1218	19480101	20111231	1
221	ANDIZAN	UZ	40.733	72.333	477	19591205	19840218	0
222	KZIL-TUS SOVKHOZ	KZ	53.633	72.367	138	19630602	20030223	0
223	ANAR	KZ	50.617	72.433	437	19530216	19800322	0
224	IRHT	TI	38.167	72.633	3276	19590101	20020608	0

225	KOOLAN	KZ	42.950	72.750	683	19590101	20111231	1
226	OSH AIRPORT	KG	40.617	72.800	892	20070825	20111231	0
227	FERGANA	UZ	40.367	71.750	577	19480101	20111231	3
228	ZHARYK	KZ	48.850	72.867	656	19530216	20111231	1
229	KARA-SUU	KG	40.700	72.900	868	19980301	20111231	0
230	DZHALAL-ABAD	KG	40.917	72.950	765	19570702	20111231	1
231	BULUN-KUL	TI	37.700	72.950	3744	19591111	20050223	0
232	MANAS	KG	43.067	74.483	637	19950101	19980115	0
233	JERMENTAU	KZ	51.633	73.167	397	19590116	19990203	0
234	SARY-TAS	KG	39.733	73.267	3155	19591101	20010303	0
235	MOINTY	KZ	47.200	73.350	581	19370119	20020915	0
236	KARAKUL LAKE	TI	39.083	73.417	3930	19591102	20020618	0
237	GULCA	KG	40.317	73.550	1555	19591102	20020511	0
238	KARAKUL	TI	39.017	73.550	3940	19570722	20010528	0
239	TOLE BI	KZ	43.700	73.783	456	19590101	20111231	2
240	CIGANAK	KZ	45.100	73.967	349	19590101	20090810	0
241	MURGAB	TI	38.167	73.967	3576	19591118	20050224	0
242	SUSAMYR	KG	42.150	73.983	2092	19591102	20020826	0
243	BELOVODSKOE	KG	42.850	74.100	726	19590812	20020405	0
244	KARAGANDA	KZ	49.800	73.150	553	19480101	20111231	3
245	MANAS	KG	43.067	74.483	627	20040713	20111231	0
246	BISHKEK MANAS ARPT	KG	43.067	74.483	637	19870204	20111231	0
247	BISHKEK	KG	42.850	74.533	760	19460103	20111231	1
248	BEKTAUATA	KZ	47.450	74.817	620	19530217	20111231	2
249	AKTOGAJ	KZ	48.300	74.967	780	19590102	19980526	0
250	NARYN	KG	41.433	76.000	2041	19370102	20111231	2

251	AUL	KZ	45.633	75.117	353	19570701	20020319	0
252	BAKANAS	KZ	44.833	76.267	396	19590114	20111231	2
253	ALGAZY OSTROV	KZ	46.550	76.867	349	19630502	20111231	2
254	WUQIA	XJ(CN)	39.717	75.250	2176	19550101	20111231	3
255	TOKMAK	KG	42.833	75.283	817	19590630	20111231	1
256	EKIBASTUZ	KZ	51.700	75.367	234	19590102	20010928	0
257	COLPON-ATA	KG	42.650	77.100	1645	19730104	20080618	0
258	AK-SYJRAK	KG	41.817	78.733	3540	19591101	19981008	0
259	KARKARALINSK	KZ	49.383	75.517	812	19320106	19940725	0
260	BAJANAUL	KZ	50.800	75.700	504	19570710	20090612	0
261	DARHAN	KG	42.317	77.900	1700	19600102	20000107	0
262	BALHASH	KZ	46.800	75.083	350	19480101	20111231	3
263	PRUDKY	KZ	43.167	76.050	992	19630302	20010629	0
264	TAXKORGAN	XJ(CN)	37.767	75.233	3090	19570101	20111231	3
265	MIKHAILOVKA	KZ	53.817	76.533	114	19590102	20111231	2
266	OTAR	KZ	43.533	75.250	743	19530216	20111231	1
267	ZHANGIZTOBE	KZ	49.217	81.217	455	19480101	20111231	2
268	BARSHATAS	KZ	48.167	78.417	643	19590101	20090612	0
269	TURGART	XJ(CN)	40.517	75.400	3504	19580101	20111231	3
270	ERTIS	KZ	53.350	75.450	94	19480101	20111231	3
271	OGIZTAU	KZ	48.267	77.317	699	19590101	19970622	0
272	KAJNAR	KZ	49.200	77.367	842	19570706	20100514	0
273	KARAKOLKA	KG	41.483	77.400	3080	19600102	19981226	0
274	KASHI	XJ(CN)	39.467	75.983	1289	19510101	20111231	3
275	BOLSAJA KZYL	KG	42.200	78.200	1719	19591124	19970529	0
276	TIAN-SHAN	KG	41.883	78.233	3639	19590101	20111231	1

277	AKSU	XJ(CN)	41.167	80.233	1104	19530101	20111231	3
278	MULALY	KZ	45.450	78.333	564	19890513	20020820	0
279	SEMIJARKA	KZ	50.867	78.350	149	19480101	20111231	2
280	KYZYL-SUU	KG	42.350	78.350	1769	20071001	20071001	0
281	TALDY-KURGAN	KZ	45.000	78.383	602	19590101	20040731	0
282	ALMATY	KZ	43.233	76.933	851	19320101	20111231	3
283	PAVLODAR	KZ	52.300	76.933	122	19320102	20111231	3
284	YUMIN	XJ(CN)	46.200	82.933	716	19600101	20111231	2
285	SHACHE	XJ(CN)	38.433	77.267	1231	19530101	20111231	3
286	URDZHAR	KZ	47.117	81.617	491	19530216	20111231	2
287	KARAUL	KZ	49.000	79.333	618	19610313	20060830	0
288	KATON-KARAGAJ	KZ	49.183	85.617	1081	19570701	20060531	0
289	SEMONAIHA	KZ	50.633	81.917	320	19530216	20051013	0
290	LUOPU	XJ(CN)	37.083	80.167	1348	19710101	20111231	2
291	UZYNBULAK	KZ	45.850	82.183	362	19731109	20030213	0
292	PISHAN	XJ(CN)	37.617	78.283	1375	19590101	20111231	3
293	SEMIPALATINSK	KZ	50.417	80.300	196	19320101	20111231	2
294	AJAGUZ	KZ	47.967	80.450	655	19570701	20020105	0
295	UC-ARAL	KZ	46.167	80.933	397	19530216	20090612	0
296	UST-KAMENOGORSK	KZ	49.967	82.633	292	19570710	20010504	0
297	ULKEN NARY	KZ	49.200	84.517	401	19530216	20111231	2
298	AKQI	XJ(CN)	40.933	78.450	1985	19570101	20111231	3
299	BA CHU	XJ(CN)	39.800	78.567	1117	19530101	20111231	3
300	SHANSHAN	XJ(CN)	42.850	90.233	399	19550901	20111231	2
301	KE PING	XJ(CN)	40.500	79.050	1162	19590101	20111231	3
302	RIDDER	KZ	50.333	83.550	811	19590102	20111231	2

303	WADA	XJ(CN)	37.133	79.933	1375	19530101	20111231	3
304	ZHARKENT	KZ	44.167	80.067	645	19460114	20111231	3
305	WENSU	XJ(CN)	41.267	80.233	1133	19660201	20111231	2
306	KOKPEKTY	KZ	48.750	82.367	512	19480101	20111231	2
307	UST KAMENOGORSK	KZ	50.033	82.500	286	20070827	20111231	0
308	MOSUOWAN	XJ(CN)	45.017	86.100	348	19580110	20111231	2
309	WEN QUAN	XJ(CN)	44.967	81.017	1358	19570101	20111231	3
310	ZHAO SU	XJ(CN)	43.150	81.133	1851	19540101	20111231	3
311	FUKANG	XJ(CN)	44.167	87.917	547	19710101	20111231	2
312	ALAR	XJ(CN)	40.550	81.267	1012	19580101	20111231	3
313	YINING	XJ(CN)	43.950	81.333	663	19510101	20111231	3
314	PAOTAI	XJ(CN)	44.850	85.250	338	19540101	20111231	2
315	YU TIAN	XJ(CN)	36.850	81.650	1422	19550101	20111231	3
316	BAICHENG	XJ(CN)	41.783	81.900	1229	19580101	20111231	3
317	EMIN	XJ(CN)	46.550	83.650	524	19590901	20111231	2
318	ANDEHE	XJ(CN)	37.933	83.650	1263	19600101	19981231	0
319	TA ZHONG	XJ(CN)	39.000	83.667	1099	19990101	20111231	0
320	KURCUM	KZ	48.550	83.683	427	19590121	19981009	0
321	ALASHANKOU	XJ(CN)	45.183	82.567	336	19560101	20111231	3
322	MUQIZHAN	XJ(CN)	43.320	87.380	1929	19780101	20111231	2
323	MINFENG	XJ(CN)	37.067	82.717	1410	19560101	20111231	3
324	JINGHE	XJ(CN)	44.617	82.900	320	19530101	20111231	3
325	KUQA	XJ(CN)	41.717	82.967	1082	19510101	20111231	3
326	TACHENG	XJ(CN)	46.733	83.000	535	19560101	20111231	3
327	KATUN	KZ	49.733	86.550	1800	19600427	19941231	0
328	TUOLI	XJ(CN)	45.933	83.600	1078	19561001	20111231	3

329	HUTUBI	XJ(CN)	44.133	86.817	523	19601001	20111231	2
330	JIMUNAI	XJ(CN)	47.433	85.867	984	19600801	20111231	2
331	SHIHEZI	XJ(CN)	44.317	86.050	443	19520101	20111231	2
332	BAYINBULUKE	XJ(CN)	43.033	84.150	2458	19570101	20111231	3
333	LUNTAI	XJ(CN)	41.783	84.250	976	19580101	20111231	3
334	MANASI	XJ(CN)	44.317	86.200	473	19610101	20111231	2
335	WUSU	XJ(CN)	44.433	84.667	479	19530101	20111231	3
336	KARAMAY	XJ(CN)	45.617	84.850	450	19561201	20111231	3
337	QIEMO	XJ(CN)	38.150	85.550	1247	19530101	20111231	3
338	TIEGANLIKE	XJ(CN)	40.633	87.700	846	19570101	20111231	3
339	HOBOKSAR	XJ(CN)	46.783	85.717	1292	19560101	20111231	3
340	BUERJING	XJ(CN)	47.700	86.867	474	19600101	20111231	2
341	CHANGJI	XJ(CN)	44.010	87.100	577	19530301	20111231	2
342	KORLA	XJ(CN)	41.750	86.133	932	19580101	20111231	3
343	BALGANTAI	XJ(CN)	42.733	86.300	1739	19570101	20111231	3
344	HABAHE	XJ(CN)	48.050	86.400	533	19570101	20111231	3
345	RUOQIANG	XJ(CN)	39.033	88.167	888	19530101	20111231	3
346	YANQI	XJ(CN)	42.083	86.567	1055	19510101	20111231	3
346	KUMUX	XJ(CN)	42.233	88.217	922	19580101	20111231	3
347	FU HAI	XJ(CN)	47.117	87.467	501	19600101	20111231	3
348	CAIJIAHU	XJ(CN)	44.200	87.533	441	19580101	20111231	3
349	URUMQI	XJ(CN)	43.783	87.650	935	19510101	20111231	3
349	JIMUSAER	XJ(CN)	44.017	89.167	736	19610101	20111231	2
350	TURPAN	XJ(CN)	42.933	89.200	35	19510101	20111231	3
351	ALTAY	XJ(CN)	47.733	88.083	735	19600101	20111231	3
353	QITAI	XJ(CN)	44.017	89.567	794	19510101	20111231	3

354	DABANCHENG	XJ(CN)	43.350	88.317	1104	19560101	20111231	3
355	MULEI	XJ(CN)	43.833	90.283	1272	19581001	20111231	2
356	FUYUN	XJ(CN)	46.983	89.517	808	19610101	20111231	3
358	QINGHE	XJ(CN)	46.667	90.383	1218	19571001	20111231	3
359	NORTH TASHAN	XJ(CN)	45.367	90.533	1654	19570101	20111231	3
360	QIJIAOJING	XJ(CN)	43.217	91.733	721	19520101	20111231	3
361	BARRY TONG	XJ(CN)	43.600	93.050	1677	19560101	20111231	3
362	HAMI	XJ(CN)	42.817	93.517	737	19510101	20111231	3
363	HONGLIUHE	XJ(CN)	41.533	94.667	1574	19520101	20111231	2
364	YIWU	XJ(CN)	43.267	94.700	1729	19580101	20111231	3

& Country code: XJ(CN)- Xinjiang, China; KZ- Kazakhstan; KG- Kyrghyz; UZ- Uzbekistan; TI- Tajikistan; TX- Turkmenistan.

Definition for quality control flags:

0 - the functional time of climate station did not cover the period of 1979-2011;

1 - stations with missing observations for more than 5 consecutive days or with 20% observation missing in any 30-day period;

2 - stations not passing the Standard Normal Homogeneity Test;

3 – stations that passed quality control and cover the period from 1979-2011. Observations from these stations were used in temperature change analysis.

Table S2. Annual and seasonal temperature lapse rates (℃100m^{-1}) in Central Asia based on the long-term (1979-2011) mean temperature in the Tianshan region (40º-44.5ºN, 69º-90 ºE) (Fig 1a). The correlations (R^2) are significant (p-value<0.05) for all reanalysis datasets.

Datasets	Statistics	Annual	Spring	Summer	Fall	Winter
CFSR	Laps rate	-0.38	-0.38	-0.50	-0.37	-0.26
	R^2	0.54	0.49	0.70	0.56	0.29
ERA-Interim	Laps rate	-0.30	-0.30	-0.45	-0.30	-0.17
	R^2	0.40	0.36	0.66	0.43	0.12
MERRA	Laps rate	-0.32	-0.34	-0.49	-0.30	-0.16
	R^2	0.40	0.41	0.67	0.40	0.10

Table S3. Annual and seasonal temperature trend (ºC $decade^{-1}$) from 1979-2011 as function of elevation in Tien Shan Mountain area for CFSR，MERRA, ERA-Interim and OBS. Statistics for the correlation (p-value and R^2) are showed. Because the spatial resolution of CFSR and MERRA are finer than that of the ERA-Interim, to assess the scaling effects on the analysis, we also resampled the CFSR and MERRA datasets to match the resolution of ERA-Interim (0.75º×0.75º), and compared the results side by side with that from the original resolution.

Dataset	Season#	Original resolution			CFSR and MERRA resampled to 0.75º×0.75º		
		Temperature trend	Sig.	R^2	Temperature trend	Sig.	R^2
CFSR	ANN	-1.37×10^{-4}	$p<0.05$	0.41	-1.09×10^{-4}	$p<0.05$	0.27
	MAM	-2.18×10^{-4}	$p<0.05$	0.35	-1.67×10^{-4}	$p<0.05$	0.19
	JJA	-5.47×10^{-6}	$p=0.32$	0.001	1.34×10^{-5}	$p=0.32$	0.0058
	SON	-1.47×10^{-4}	$p<0.05$	0.46	-1.10×10^{-4}	$p<0.05$	0.27
	DJF	-1.82×10^{-4}	$p<0.05$	0.34	-1.60×10^{-4}	$p<0.05$	0.27
MERRA	ANN	-7.10×10^{-6}	$p<0.05$	0.15	-3.33×10^{-5}	$p<0.05$	0.026
	MAM	-8.40×10^{-5}	$p<0.05$	0.13	-4.39×10^{-5}	$p=0.14$	0.013
	JJA	-7.10×10^{-5}	$p<0.05$	0.06	-3.83×10^{-5}	$p<0.05$	0.041
	SON	-1.30×10^{-4}	$p<0.05$	0.28	-5.11×10^{-5}	$p<0.05$	0.092
	DJF	-3.80×10^{-6}	$p<0.05$	0.0004	1.19×10^{-5}	$p=0.39$	0.0043
ERA-Interim	ANN	-4.2×10^{-5}	$p<0.05$	0.045			
	MAM	-7.6×10^{-5}	$p<0.05$	0.04			
	JJA	-3.9×10^{-5}	$p<0.05$	0.042			
	SON	-6.4×10^{-5}	$p<0.05$	0.18			
	DJF	2.6×10^{-5}	$p<0.05$	0.023			
OBS	ANN	3.49×10^{-5}	$p=0.64$	0.0084			
	MAM	1.08×10^{-5}	$p=0.84$	0.0015			
	JJA	-5.78×10^{-5}	$p=0.49$	0.0189			
	SON	-3.87×10^{-5}	$p=0.64$	0.0085			
	DJF	2.40×10^{-4}	$p=0.10$	0.1005			