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Changes of soil thermal regimes in the Heihe River Basin over Western China

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Abstract

Investigation of the changes in soil thermal regimes is essential to the understanding of ecohydrological processes, resource development, and climate change. We use soil temperatures from 12 meteorological stations of the China Meteorological Administration in the Heihe River Basin to estimate soil seasonal freeze depth, the onset and end dates of soil freeze, and the duration of soil freeze. Based on the characteristics of the soil temperature in the seasonal freezing layer, the freeze/thaw processes of this layer were divided into four stages: the winter freezing stage, spring thawing stage, summer warming stage, and autumn cooling stage. Spring, summer, autumn, and winter ground surface temperatures in the basin exhibit significant increasing trends in 1972–2006, of 0.65 °C decade^{-1}, 0.73 °C decade^{-1}, 0.48 °C decade^{-1}, and 0.44 °C decade^{-1}, respectively. Mean annual soil temperature at 0.0–0.20 m depths reveals an increasing trend of 0.58–0.63 °C decade^{-1} in 1972–2006. The onset date of soil freeze, the end date of soil freeze, and the duration of soil freeze in 1972–2006 exhibit a statistically significant trend of +2 days decade^{-1}, –4 days decade^{-1}, and –6 days decade^{-1}, respectively. The maximum thickness of the seasonally frozen ground for 1960–2007 reveals a statistically significant trend of –4.0 cm decade^{-1} and a net change of –19.2 cm for the 48-year period. These are all related to the increase in spring, summer, autumn, and winter air temperature and the mean annual air temperature in the basin, a possible result of global warming.

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Introduction

Soil thermal regimes in seasonally frozen ground and permafrost regions, especially soil temperature and seasonal freeze/thaw processes, play an essential role in ecosystems and ecohydrological processes (Zhang et al., 2003; Frauenfeld et al., 2004; Zhang et al., 2013). They also affect water exchange between the ground surface and atmosphere, which ultimately has impacts on weather and climate systems through changes in surface energy balance (Jin and Li, 2009; Zhou et al., 2013). Soil temperature is linked to climate through the top layer of the soil that freezes and thaws seasonally, vegetation, and snow cover (Lachenbruch and Marshall, 1986). In permafrost regions, degree days of freezing/thawing for air or surface (DDF_a/DDT_a or DDF_s/DDT_s) are used to predict active layer thickness (ALT) (Nelson et al., 1997; Shiklomanov and Nelson, 2002; Zhang et al., 2003, 2005) and spatial distribution of permafrost (Nelson and Outcalt, 1987; Ran et al., 2012). On the other hand, ALT is an indicator of climate change (Nelson et al., 1997; Brown et al. 2000; Zhang et al., 2003, 2007; Osterkamp, 2007; Frauenfeld et al., 2007). Similarly, the thickness of seasonally frozen ground can also be used to investigate long-term climate and environment changes (Frauenfeld and Zhang, 2011).

Permafrost and seasonally frozen ground are well underlain in the Heihe River Basin (Zhou et al., 2000), and permafrost region occupies ~10.5% of the basin (Wang et al., 2013). The snow cover zone and tundra are the main catchment areas for the Heihe River Basin, accounting for ~80% of the basin-wide runoff (Wang et al., 2009). Caused by recent global warming, air temperature increases significantly in the Qilian Mountains (Lan et al., 2001; Zhang and Guo, 2002; Yin et al., 2009). Construction and engineering activities have increased in recent years. These changes necessitate an investigation of the soil thermal regime conditions (such as soil temperature and soil seasonal freeze/thaw processes) in the Heihe River Basin in order to understand ecohydrological processes, resource development, and climate change.

Most research on the freeze/thaw processes in cold regions focuses mainly on permafrost regions. Research on the coastal plain adjacent to the Beaufort Sea in Alaska shows that ALT increased from the coast inland from 1986 through 1993 (Romanovsky and Osterkamp, 1997). Summer precipitation could cause the thaw front to move rapidly in the active layer due to sensible heat carried by the percolating rainwater downward (Hinkel et al., 1997). It is indicated that ALT patterns had primary relationship with physiographic features through affecting surface and subsurface hydrological processes in the Kuparuk River Basin in northern Alaska (Nelson et al., 1998). Compared with air temperatures, ground temperatures in 1979–1999 exhibited a closer relationship with thickness and duration of snow cover at the lower limit of alpine permafrost in the Marmot Basin, Canada (Harris, 2001). ALT showed a decline from 1995 through 2007 on the North Slope of Alaska, which was generally related to the decline in summer air temperature. Streletskiy et al. (2008) found that the maximum values of ALT in the Alaskan Arctic were recorded accordingly in the years with the warmest summers. Changes in ALT and the maximum thickness of seasonally frozen ground (MTSFG) in the Eurasian high latitudes have also been investigated. During the 1956–1990 period, ALT has thickened significantly by ~20 cm, while MTSFG decreased by 34 cm in Russia (Frauenfeld et al., 2004). Evaluating the MTSFG at 387 sites of seasonally frozen ground for the period 1930–2000, Frauenfeld and Zhang (2011) found that the MTSFG significantly decreasd by 31.9 cm at a rate of –4.5 cm decade^{-1}.

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Similar research has been conducted on the Qinghai-Tibetan Plateau (QTP) in China. Soil volumetric water content could strongly influence the spatial distribution of soil temperature and freeze/thaw processes along the Qinghai-Tibetan highway (Yang et al., 2003). Mean annual soil temperature (MAST) at 1.0 m depth had significantly increased by 0.12–1.65 °C during 1996–2006 along the highway in the permafrost regions (Wu and Zhang, 2008). The MTSFG has decreased by 0.1–0.2 m, and the lower limit of permafrost has risen by 50–80 m since the 1980s in the source area of the Yellow River (Jin et al., 2009). ALT increased at a rate of ~7.5 cm yr^{-1} along the Qinghai-Tibetan highway over the period 1995–2007 (Wu and Zhang, 2010). Ground temperatures at the bottom of the active layer warmed by 0.06 °C yr^{-1}, on average, over the period 1999–2008 along the highway (Zhao et al., 2010). MAST at 6.0 m depth was ~0.02 °C yr^{-1} from 2006 to 2010 estimated by linear regression method along the Qinghai-Tibetan railway, and the ALT increased by 6.3 cm yr^{-1} (Wu et al., 2011a). Mean annual ground surface temperature warmed by 0.60 °C $decade^{-1}$ on the central QTP over the period 1980–2007. The DDF_s has decreased at a rate of –111.2 °C-days $decade^{-1}$, while the DDT_s increased by 125.0 °C-days $decade^{-1}$ over the same period (Wu et al., 2013). Generally speaking, all of these changes are fundamentally owing to air temperature warming on the QTP. However, they are not only forced by air temperature, but also affected by precipitation (especially snow cover), vegetation, soil lithology and its physical properties, and water/ice content, and so on.

However, long-term changes of soil thermal regimes in the Heihe River Basin are poorly understood. This study investigates the changes in soil thermal regimes in the basin since the 1950s. Specifically, we investigate soil seasonal freeze/thaw processes, changes in soil temperature, the timing and duration of soil freeze, thickness of seasonally frozen ground, and the response of these changes to regional climate conditions in the basin.

Study Area

The Heihe River originates in the watershed between mountains Zoulangnanshan and Tuolainanshan in the Qilian Mountains. The basin is the second largest inland river basin in Western China, located in the central part of the Hexi Corridor at 98°–101°30′E, 38°–42°30′N (Fig. 1). It can be divided into three parts: the upper reaches (from the Yingluoxia valley upstream), the middle reaches (from the Yingluoxia valley downstream to the Zhengyixia valley), and the lower reaches (from the Zhengyixia valley downstream) (Cheng, 2009) (Fig. 1).

The upper reaches, with elevation of 2000–5500 m a.s.l. (above sea level), belong to the cold semiarid mountain zone, dominated by tundra, shrubs, and trees (Lin, 1981). Mean annual air temperature (MAAT) in the area is less than 2 °C, and mean annual precipitation (MAP) is between ~250 mm and ~500 mm (Chen and Qu, 1992). The middle reaches of the basin belong to the arid temperate zone, controlled by crops such as wheat and corn, with MAAT less than 6–8 °C. With elevation in the middle reaches decreasing from more than 2000 m a.s.l. to 1000 m a.s.l., MAP ranges from 250 mm to less than 100 mm from south to north (Li et al., 2001). The lower reaches of the basin mainly consist of bare gobi (corresponding to the

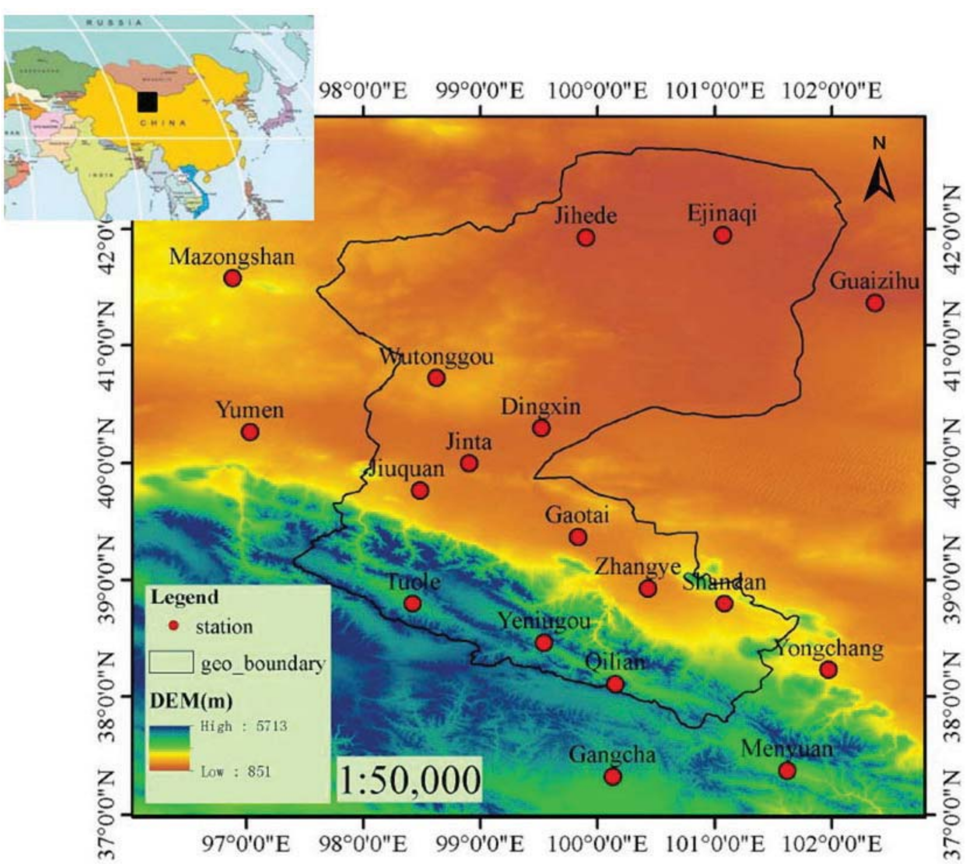

FIGURE 1. Location of Heihe River Basin in China (upper left) and geographical location of China Meteorological Administration meteorological stations (lower right).

extremely arid temperate zone), with a mean elevation of ~1000 m a.s.l., MAAT of 8–10 °C, and MAP less than 50 mm (Qi and Luo, 2005; Li et al., 2012). It has been estimated that the average decrease of MAAT with elevation in the basin is ~–0.80 °C 100 m^{-1}, while the increase of MAP with elevation is ~15 mm 100 m^{-1} (Cheng et al., 2010).

Data and Methods

Data used in this study include daily soil temperatures and monthly air temperatures from 18 meteorological stations of the China Meteorological Administration (CMA) located in the Heihe River Basin and its adjacent areas (Fig. 1 and Table 1). Soil temperatures are measured at depths of 0.0, 0.05, 0.10, 0.15, 0.20, 0.40, 0.80, 1.60, and 3.20 m. Soil temperatures at depths of 0.0, 0.05, 0.10, 0.15, and 0.20 m were measured by angle geothermometers four times per day (at Beijing time 02:00, 08:00, 14:00, and 20:00), and daily mean soil temperature at those depths was calculated as the arithmetic average of these four measurements; while at the other depths, it was measured by tube-type geothermometer once per day (at Beijing time 14:00) and used as the daily mean. Based on daily soil temperature and monthly air temperature, we derived freeze/thaw depth, the onset and end dates of soil freeze, the duration of soil freeze, and the DDF_a.

TABLE 1

Observation records of soil temperature (in roman type) and air temperature (in italic) at China Meteorological Administration meteorological stations in the Heihe River Basin and its adjacent area.

Stations	Latitude (N)	Longitude (E)	Elevation (m)	Observation Records
Qilian (QL)	38.19	100.24	2787.4	1961.07.01–2006.12.31 *956.05–2009.02*
Yeniugou (YG)	38.42	99.58	3320.0	1980.01.01–2006.12.31 *1959.02–2009.02*
Tuole (TL)	39.03	98.01	3367.0	1957.10.01–2006.12.31 *1956.11–2009.02*
Ejinaqi (EJ)	41.94	101.09	940.5	1971.06.04–2006.12.31 *1959.11–2009.02*
Wutonggou (WG)	40.47	98.32	1591.0	1970.09.24–1988.12.31 *965.12–1988.12*
Dingxin (DX)	40.31	99.51	1177.4	1957.10.01–2006.12.31 *1955.01–2009.02*
Jinta (JT)	40.00	98.91	1270.2	1989.01.01–2006.12.31 *1989.01–2009.02*
Jiuquan (JQ)	39.70	98.50	1477.2	1959.01.01–2006.12.31 *1951.01–2009.02*
Gaotai (GT)	39.36	99.79	1332.2	1954.01.01–2006.12.31 *1952.09–2009.02*
Zhangye (ZY)	38.91	100.46	1482.7	1955.01.01–2006.12.31 *1951.01–2009.02*
Shandan (SD)	38.77	101.08	1764.6	1955.08.01–2006.12.31 *1952.10–2009.02*
Jihede (JD)	41.91	99.71	965.6	1972.01.01–1986.12.31 *1958.11–1986.12*
Menyuan (MY)	37.25	101.38	2878	1954.01.01–2006.12.31 *1956.10–2004.12*
Gangcha (GC)	37.25	100.11	3307	1979.05.01–2006.12.31 *957.07–2009.02*
Yongchang (YC)	38.18	101.58	1976.1	1958.04.01–2006.12.31 *1958.04–2009.02*
Yumen (YM)	39.84	97.55	1526	1952.07.01–2006.12.31 *1952.08–2009.02*
Mazongshan (MS)	41.51	97.11	1962.7	1973.01.01–2002.12.31 *1958.01–2009.02*
Guaizihu (GH)	41.37	102.28	929	1970.11.16–2006.12.31 *1959.06–2009.02*

Note: dates are in form yyyy.mm.dd, and yyyy.mm.

The depth of the 0°C isotherm is calculated through linear interpolation method throughout the 0.0–3.20 m depths, and it is regarded as the freeze/thaw depth. In the best case, the 0°C isotherm appears between a positive and an adjacent negative value. However, if some data throughout the 0.0–3.20 m depths were missing, especially during the period when MTSFG might occur, we excluded the MTSFG of that year from its time series. Based on daily observations of soil temperature, the daily freeze/thaw depth could be obtained through linear interpolation method. The annual MTSFG was determined from the maximum of all daily depths in the cold season.

The onset and end dates of soil freeze were determined by calculating the freeze depth using the daily soil temperature at 0.0–3.20 m depths. According to the specifications of the CMA, the onset date of soil freeze is defined as the first day after 1 July on which the frozen ground thickness is not zero, and the end date of soil freeze is defined as the last day before 30 June on which the frozen ground thickness is not zero. The duration of soil freeze is the days between the onset and end dates of soil freeze. It must be noted that, the MTSFG and the end date of soil freeze are both considered as the last year's in a freeze/thaw process, though they both appear in the beginning of the following year.

Here we use monthly air temperature to estimate the annual DDF_a. Furthermore, the freezing period is defined to be July–June (in the following year) in order to sum the freezing index in a continuous cold season, and the thawing period to be January–December (Frauenfeld et al., 2007; Wu et al., 2013). DDF_a is calculated using the following formula:

$$DDF_a = \sum_{i=1}^{M_F} \left|\overline{T_i}\right| \bullet D_i, \overline{T_i} < 0°\mathrm{C}\,, \tag{1}$$

where DDF_a is the annual degree days of freezing (for air; annual freeze index); M_F is the number of months when the mean monthly air temperature is below 0 °C during the freezing/thawing periods; $\overline{T_i}$ is the mean monthly air temperature; D_i is the number of days in the month(s) of M_F. Therefore, time series of annual DDF_a for each meteorological station were obtained.

The accuracy of using monthly air or ground surface temperature data to calculate the approximate annual DDF and DDT has been discussed in previous studies (Zhang et al., 1996; Frauenfeld et al., 2007; Wu et al., 2011b). It could cause an error of less than 5% at Barrow, Alaska, using monthly air temperature to estimate annual DDF and DDT (Zhang et al., 1996). Frauenfeld et al. (2007) discovered that the relative errors for annual DDF_a and DDT_a were generally less than 5% across the northern hemisphere. The relative errors were less than 2% for the annual DDF_s and less than 3% for the annual DDT_s, using monthly measured data to calculate the annual DDF_s and DDT_s in the central Mongolian Plateau (Wu et al., 2011b).

Although some of the meteorological stations have long continuous records, analyzing soil temperature changes at these individual stations would result in partial conclusions, as most observation records are missing data and some only cover short periods of time. Soil temperatures at 0.0 m depth are missing 51%, 49%, 23%, and 57% at the Wutonggou, Jinta, Yeniugou, and Jihede Stations over the period 1972–2006, respectively. Soil temperatures at 0.05, 0.10, 0.15, and 0.20 m depths are missing 33% at the Jinta Station over the period 1980–2006, while they are all missing at the Wutonggou, Yeniugou, and Jihede Stations. In order to ensure data consistency and comparability at all stations, if possible, any missing data was interpolated based on data at the nearest meteorological station, through the linear regression method with a significance level of $p \leq 0.05$, at least. Then data from all meteorological stations were composited to structure a long-term time series that provided an integrated view in the Heihe River Basin.

A variant of the Stefan solution is usually used to estimate ALT, using the annual DDT. The validity of the relationship between ALT and the annual DDT was proved in northern Alaska (Hinkel and Nicholas, 1995; Romanovsky and Osterkamp, 1997; Nelson et al., 1998; Klene et al., 2001; Hinkel and Nelson, 2003; Zhang et al., 2005).

Similarly, MTSFG can also be estimated from such a formula using the DDF_a in the following manner:

$$Z = \sqrt{2k_t n_t / (L\rho w)}\sqrt{DDF_a}\,, \tag{2}$$

where Z is MTSFG (m), k_t is the thermal conductivity of the frozen soil (W m^{-1} °C^{-1}), n_t is the n-factor, L is the latent heat of fusion (J kg^{-1}), ρ is the soil bulk density (kg m^{-3}), w is the soil water content (by weight). It requires the numerical values of thermal conductivity, the n-factor, soil bulk density, and soil water content in order to estimate MTSFG. These numerical values might be available at some specific meteorological stations, but not for the entire basin or the whole time series. However, Equation 2 can be described as:

$$Z = E\sqrt{DDF_a}\,, \tag{3}$$

where

$$E = \sqrt{2k_t n_t / (L\rho w)}\,. \tag{4}$$

From Equation 3, E can be expressed as

$$E = Z / \sqrt{DDF_a}\,. \tag{5}$$

The "edaphic factor" E can be calculated using Equation 5, and then the mean E factor and MTSFG time series at each station can be calculated.

Results

SOIL SEASONAL FREEZE/THAW PROCESSES

Based on the measured soil temperature in Wudaoliang in the permafrost region on the QTP, freeze/thaw processes of the active layer are divided into four stages: summer thawing stage, autumn freezing stage, winter cooling stage, and spring warming stage (Zhao et al., 2000). The summer thawing stage ranges from the onset date of soil thaw (from the ground surface downward) to the date on which the active layer reaches the maximum depth in mid-September. The autumn freezing stage is the period of time between the date when the active layer reaches its maximum depth and the date on which the entire active layer becomes frozen. The winter cooling stage extends from the end of active layer freeze through the middle or late January of the following year. The spring warming stage consists of the time between the end of the winter cooling stage and the onset date of soil thaw.

Here we only pay attention to the soil seasonal freeze/thaw processes in seasonally frozen ground regions. The seasonal freezing layer is the portion of the soil that thaws and freezes seasonally in nonpermafrost regions (Zhou et al., 2000). The seasonal freezing layer begins to freeze from the ground surface, and freezing progresses downward. After reaching MTSFG, the layer thaws both from the bottom upward and from the ground surface downward, which is unique in seasonally frozen ground regions. Providing that we use 0 °C as the freezing point, that is, choosing the 0 °C isotherm as the location of the freezing front, ground surface in the Heihe River Basin begins to freeze in late November. MTSFGs are reached in late January at all meteorological stations. After this, the freezing layer begins to slowly thaw from the bottom layer upward, and quickly converges with the downward thawing from the ground surface in late February.

Similarly, based on soil thermal regimes at 0.0–3.20 m depths between July 2004 and August 2005 at the 9 meteorological stations (Yeniugou, Wutonggou, and Jihede excluded) of the CMA in the Heihe River Basin, soil freeze/thaw process of the seasonal freezing layer can be divided into four stages: autumn cooling stage, winter freezing stage, spring thawing stage, and summer warming stage.

Autumn Cooling (AC) Stage: The AC stage begins at the end of summer and ends with the stable freeze of the ground surface in late October to mid-November. With decreasing air temperatures in August, soil temperature begins to decrease gradually in the seasonal freezing layer. The threshold of soil temperatures at 0.0, 0.05, 0.40, 1.60, and 3.20 m depths was 25.4–37.6 °C, 21.1–35.4 °C, 16.0–32.3 °C, 9.8–22.6 °C, and 6.6–16.5 °C, respectively, at the 9 stations during this stage (Fig. 2). For example, soil temperatures at 0.0, 0.05, 0.10, 0.15, 0.20, 0.40, 0.80, and 1.60 m depths at the Ejinaqi Station decreased by 36.5, 32.4, 29.6, 27.4, 25.6, 24.0, 16.0, and 8.0 °C from 1 August through 9 November at the AC stage in 2004, respectively, while it changed little at 3.20 m depth. Mean soil temperature at 0.0–3.20 m depth was ranging from 9.5 to 20.2 °C (Table 2).

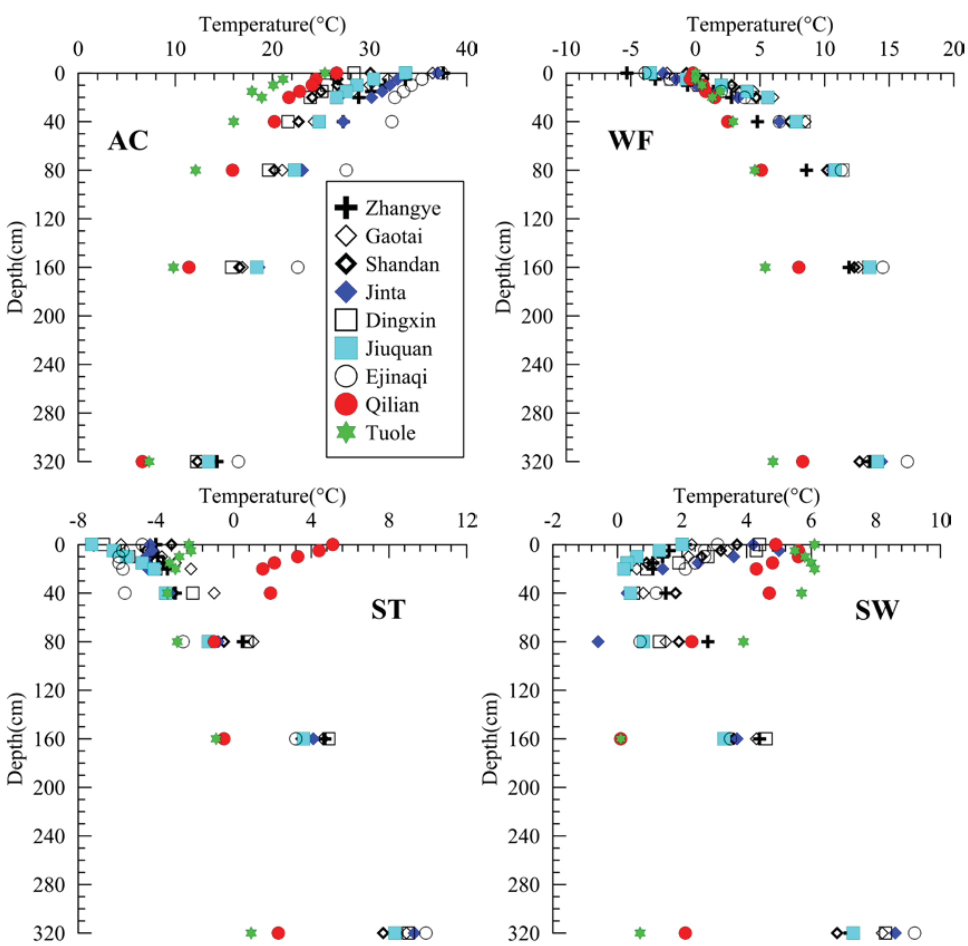

FIGURE 2. The threshold of soil temperatures at autumn cooling (AC) stage, winter freezing (WF) stage, spring thawing (ST) stage, and summer warming (SW) stage at 0.0–3.20 m depths between July 2004 and August 2005 at 9 meteorological stations in the Heihe River Basin.

TABLE 2

The mean soil temperature at 0.0–3.20 m depth at autumn cooling stage (AC), winter freezing stage (WF), spring thawing stage (ST), and summer warming stage (SW) between July 2004 and August 2005 at 9 meteorological stations, including Qilian (QL), Tuole (TL), Ejinaqi (EJ), Dingxin (DX), Jinta (JT), Jiuquan (JQ), Gaotai (GT), Zhangye (ZY), and Shandan (SD) Stations in the Heihe River Basin.

	QL	TL	EJ	DX	JT	JQ	GT	ZY	SD
AC	10.8	9.5	20.2	17.9	17.8	17.6	16.8	16.4	15.5
WF	–2.3	–5.4	–1.5	0.5	0.0	0.0	1.3	0.0	0.2
ST	4.1	2.8	0.4	–0.7	–1.1	–0.2	–0.1	0.2	–0.2
SW	12.5	9.5	19.3	15.3	17.3	16.8	14.8	17.0	15.3

Winter Freezing (WF) Stage: This stage extends from the date on which the freezing layer begins to freeze (downward from the ground surface) in late autumn or early winter through the date on which the MTSFG is reached in late winter. The threshold of soil temperatures at 0.0, 0.05, 0.10, 0.40, and 3.20 m depths was –5.3–0.0 °C, –3.1–0.6 °C, –0.6–2.8 °C, 2.5–8.5 °C, and 8.3–16.4 °C, respectively, at the 9 stations during this stage. With increasing elevation, the date on which the MTSFG is reached becomes later (Fig. 3). This date at the Qilian and Tuole Stations was to be 24–54 days later than at other lower-elevation stations during 2003–2005. The MTSFG increased by 7.7, 7.0, and 6.7 cm with every 100 m of elevation in 2003, 2004, and 2005, respectively (Fig. 3).

The seasonal freezing layer is exothermic. Soil temperature gradually increases with depth in the seasonal frozen layer at this stage. Mean soil temperature at 0.0–3.20 m depth during the WF stage was –2.3, –5.4, and –1.5 °C at the Qilian, Tuole, and Ejinaqi Stations, respectively, while they were all greater than or equal to 0.0 °C at other stations (Table 2).

Spring Thawing (ST) Stage: This stage extends from the date when MTSFG is reached until the date on which the freezing layer is completely thawed. The threshold of soil temperatures at 0.0–0.40 m depths at the Qilian Station was 1.5–5.1 °C, while it was all less than 0.0 °C at the other eight stations. At 0.80, 1.60, and 3.20 m depth, it was –2.9–1.0 °C, –0.9–4.9 °C, and 0.9–9.9 °C, respectively (Fig. 2). After the seasonal freezing layer reaches the MTSFG, with increasing air temperatures in the spring, the frozen soil starts to thaw slowly upward from the bottom of the layer. This thaw front then converges with the rapid thawing from the ground surface downward. For example, the seasonal freezing layer began to thaw upward on 12 February in 2005 and downward on 23 February at the Ejinaqi Station, and it was completely thawed four days later.

The onset date of upward thaw from the bottom generally starts earlier than that from the ground surface downward (Zhou et al., 2000). The onset date of upward thaw was on 8 February, 9 February, 6 February, 12 February, 9 February, 9 February, and 3 February in 2005 at the Dingxin, Jinta, Gaotai, Jiuquan, Zhangye, Shandan, and Tuole Stations, while the onset date of thaw from

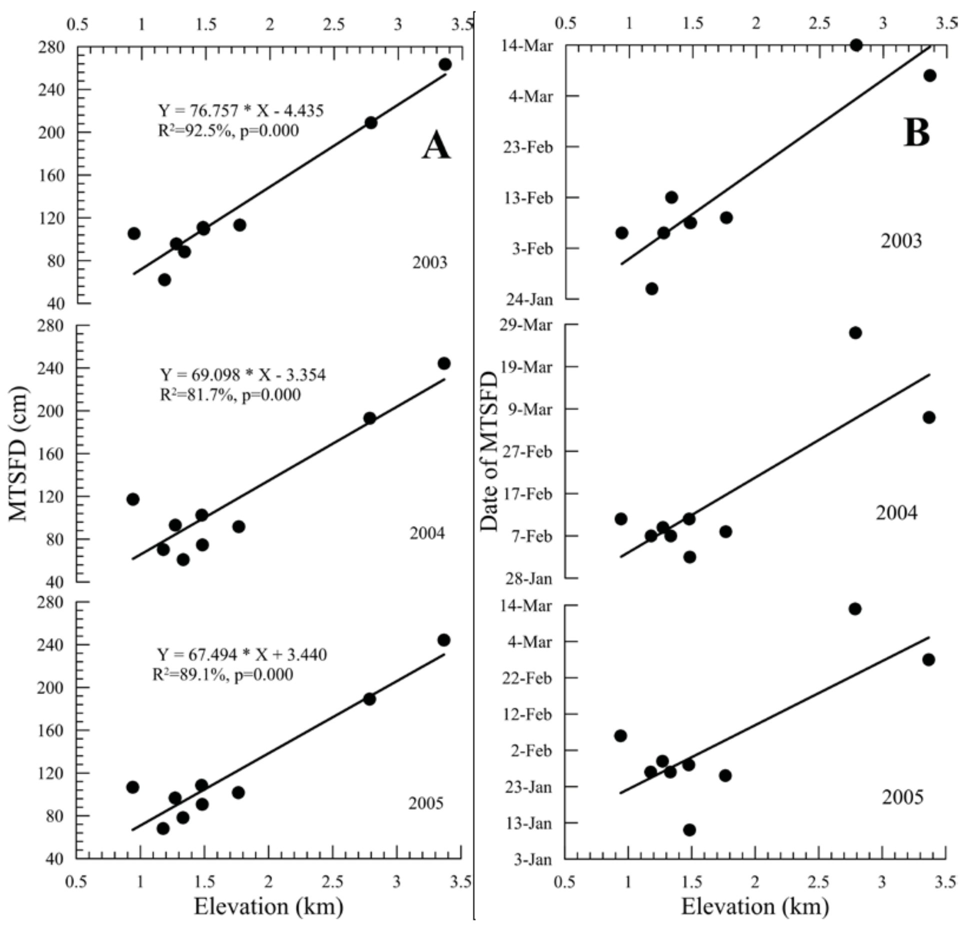

FIGURE 3. (A) Correlation of the maximum thickness of the seasonally frozen ground (MTSFG) and (B) the date of MTSFG with elevation in 2003, 2004, and 2005 in the Heihe River Basin.

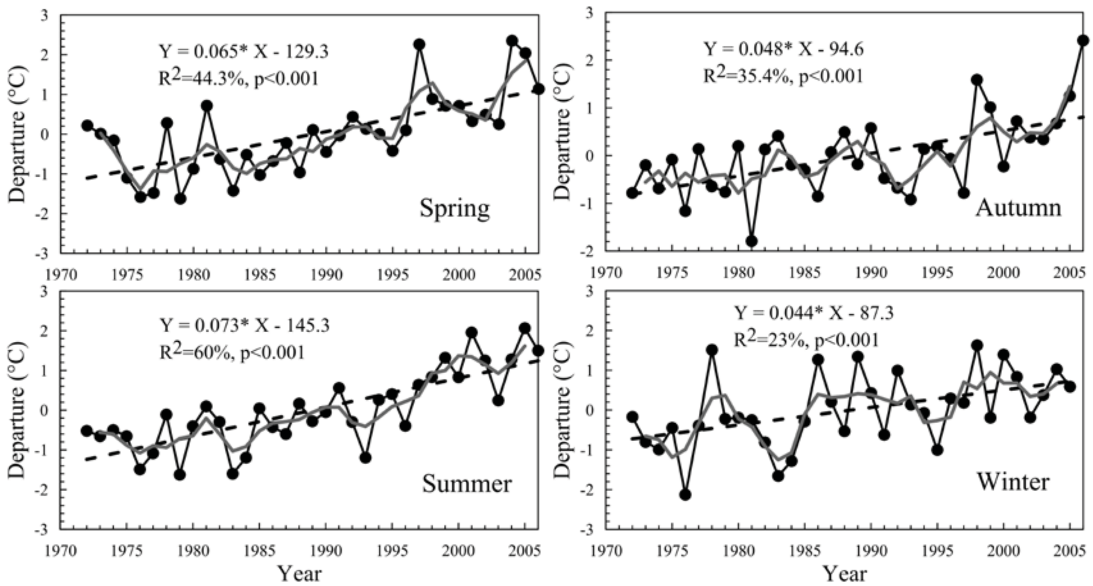

FIGURE 4. Time series of ground surface temperature in spring, summer, autumn, and winter between 1972 and 2006 in the Heihe River Basin. Gray bold line represents the 3-yr moving line. Black dotted line represents the linear least squares regression line.

the ground surface downward was 14, 13, 16, 10, 5, 16, and 20 days later, respectively. However, the onset date of thaw from the ground surface downward is 33 days earlier than that from the bottom of the MTSFG upward at the Qilian Station in 2005. Mean soil temperature at 0.0–3.20 m depth during the ST stage was 4.1, 2.8, 0.4, and 0.2 °C at the Qilian, Tuole, Ejinaqi, and Zhangye Stations, respectively, while they were all less than 0.0 °C at other stations (Table 2).

Summer Warming (SW) Stage: This stage lasts from the end of the ST stage through July, or even early August. The threshold of soil temperatures at 0.0, 0.05, 0.40, and 3.20 m depths was 2.0–6.1 °C, 1.3–5.6 °C, 0.3–5.7 °C, and 0.7–9.2 °C, respectively, at the 9 stations during this stage (Fig. 2). Soil is endothermic, and generally soil temperatures from 0.0 m to 3.20 m depths gradually increase at this stage. Mean soil temperature at 0.0–3.20 m depth was between 9.5 °C and 19.3°C at this stage (Table 2).

SOIL TEMPERATURE CHANGES

Soil temperature, especially ground surface temperature, is a sensitive indicator of climate change as it integrates meteorological factors and the processes occurring at/above the ground surface. It is crucial for monitoring the sensible and latent heat flux exchange between the ground surface and atmosphere (Oku et al., 2006; Wu et al., 2013). In addition, soil temperature may influence the physical, biological, and microbiological processes occurring in the soil (Zhang et al., 2005).

Spring, summer, autumn, and winter ground surface temperatures in the Heihe River Basin exhibit significant increasing trends of 0.65 °C decade^{-1}, 0.73 °C decade^{-1}, 0.48 °C decade^{-1}, and 0.44 °C decade^{-1} between 1972 and 2006, respectively (Fig. 4). It is clear that the rise of ground surface temperature in winter is smaller than in other seasons. This might be a result of the geographical location at the edge of anomalous atmospheric circulation. MASTs at 0.0 m through 0.20 m depths show an increasing trend of 0.58–0.63 °C decade^{-1} between 1972 and 2006 (Fig. 5). The averaged time series at other depths could not be constructed, because there are too many missing soil temperature data points.

TIMING AND DURATION OF SOIL FREEZE

We constructed a composite time series of the onset and end dates of soil freeze, and duration of soil freeze, in the Heihe River Basin between 1972 and 2006 (Fig. 6).

The time series of the onset date of soil freeze shows a positive trend in 1972–2006, while that of the end date of soil freeze and the duration of soil freeze both exhibit a negative trend in 1976–2005. The onset date of soil freeze from 1972 through 2006 advanced 2 days decade^{-1} (Fig. 6, part A), implying that the onset of soil freeze in autumn started 2 days later each decade. The end date of soil freeze from 1976 through 2005 retreated by 4 days decade^{-1} (Fig. 6, part B), meaning the thawing of frozen soil in spring started 4 days earlier each decade. As a result, the duration of soil freeze for 1976–2005 was 6 days shorter per decade (Fig. 6, part C), or soil freeze period becomes shorter by 6 days per decade.

The late onset and the earlier end of soil freeze in the basin in 1972–2006 might be related to the concurrent increase in autumn and spring air temperatures, respectively, while the shorter duration of soil freeze is closely related to the increase in winter air temperatures.

CHANGES IN MTSFG

The *E* factor at 9 meteorological stations in the Heihe River Basin is shown in Figure 7. And the MTSFGs at the 9 stations were averaged into a time series for the period 1960–2007. Evaluating the MTSFG time series for 1960–2007 in the basin reveals a statistically significant trend of –4.0 cm decade^{-1}, and a net change of –19.2 cm for the 48-year period (Fig. 8).

Summary and Discussion

The changes of soil thermal regimes play a vital role in the understanding of ecohydrological processes, resource development, and climate change, especially in the context of global warming. Nevertheless, changes in freeze/thaw processes in the Heihe River Basin, especially changes in soil temperature, the timing and dura-

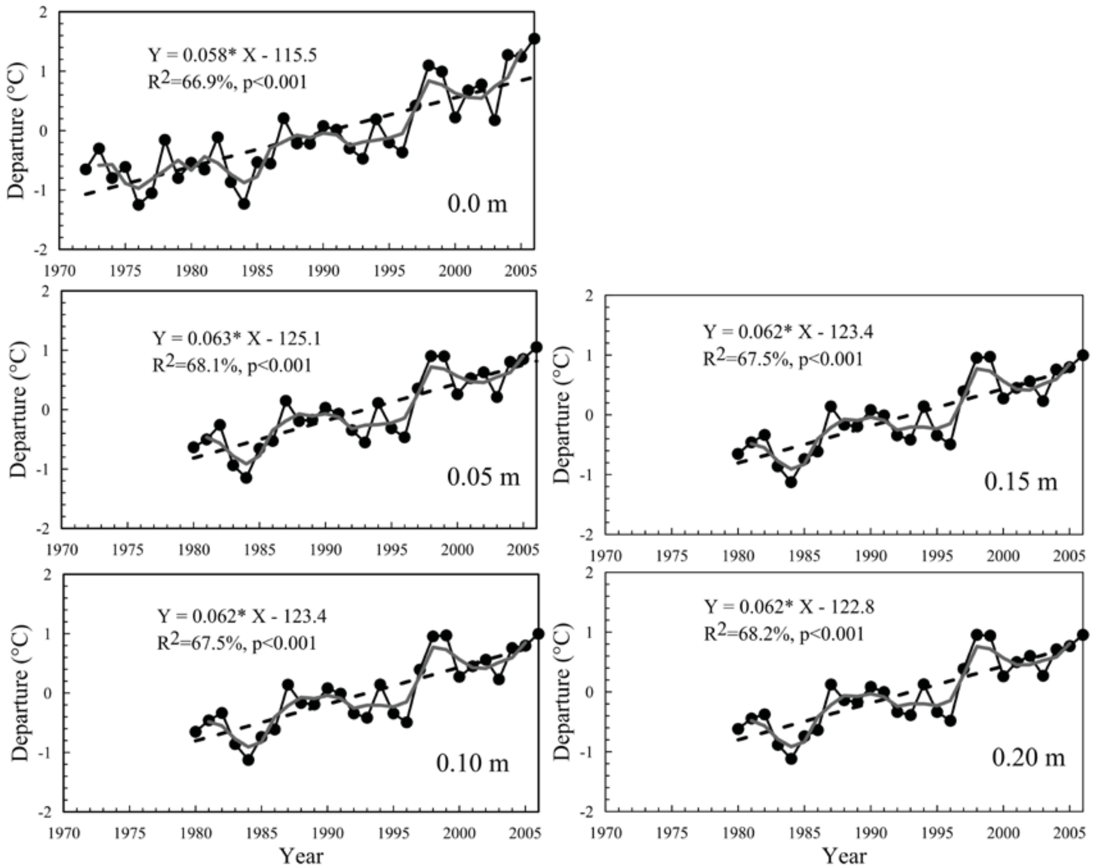

FIGURE 5. Time series of soil temperatures at 0.0–0.20 m depths between 1972 and 2006 in the Heihe River Basin. Gray bold line represents the 3-yr moving line. Black dotted line represents the linear least squares regression line.

tion of soil freeze, as well as MTSFG, are still relatively poorly understood.

Based on the characteristics of soil temperature in the freeze/thaw processes of the seasonal freezing layer, we put forward an idea for dividing the freeze/ thaw process of the seasonal freezing layer into four stages: winter freezing stage, spring thawing stage, summer warming stage, and autumn cooling stage.

Soil temperature, MTSFG, the onset and end dates of soil freeze, and the duration of soil freeze at 12 meteorological stations in the Heihe River Basin were averaged into composite long-term time series. Ground surface temperatures exhibit significant increasing trends of 0.65 °C decade^{-1} in spring, 0.73 °C decade^{-1} in summer, 0.48 °C decade^{-1} in autumn, and 0.44 °C decade^{-1} in winter during 1972–2006. MASTs at 0.0–0.20 m depths show an increasing trend of 0.58–0.63 °C decade^{-1} between 1972 and 2006. The onset date of soil freeze, the end date of soil freeze, and the duration of soil freeze between 1972 and 2006 exhibit a statistically significant trend of +2 days decade^{-1}, –4 days decade^{-1}, and –6 days decade^{-1}, respectively. The MTSFG for 1960–2007 reveals a statistically significant trend of –4.0 cm decade^{-1}, and a net change of –19.2 cm for the 48-year period. These are all related to the increase in spring, summer, autumn, and winter air temperatures and MAAT in the basin because of global warming.

However, there are currently only 12 meteorological stations in the Heihe River Basin, and they are at elevations of mostly under 2000 m a.s.l. Additional soil temperature monitoring stations should be established in the future, especially between 2000 m a.s.l. and 3000 m a.s.l.

The 0 °C isotherm is regarded as the freeze/thaw depth, which is calculated through linear interpolation method throughout the 0.0–3.20 m temperature profile. Frauenfeld et al. (2004) found that the relationship between the linearly interpolated MTSFG and the observed values revealed a perfectly significant correlation during 1930–1990 at 190 stations located throughout Russia. However, it is important to note that, although the freeze depth could be estimated using the depth of the 0 °C isotherm, it is not necessarily always the same as the "true" freeze depth. For high water/ice content soils, it could lead to errors in using the propagation depth of the 0 °C isotherm as the freeze depth due to latent heat effect (Frauenfeld et al., 2004).

Any missing MAST at 0.0–0.20 m depths was interpolated based on data at the nearest meteorological station, through the linear regression method with a significance level of $p \leq 0.05$, at least. Yet, as the reason that only daily ground surface temperature was observed at the Wutonggou, Yeniugou, and Jihede Stations, MASTs at 0.05–0.20 m depths in 1980–2006 at these 3 stations were impossible to be interpolated. This means that the averaged MAST time seies at 0.0 m depth in 1972–2006 is structured based on 12 meteorological stations in the basin, while that at 0.05, 0.10, 0.15, and 0.20 m depths in 1980–2006 is only based on 9 stations. Furthermore, the onset date of soil freeze at 8 stations (Jinta, Yeniugou, Wutonggou, and Jihede excluded), as

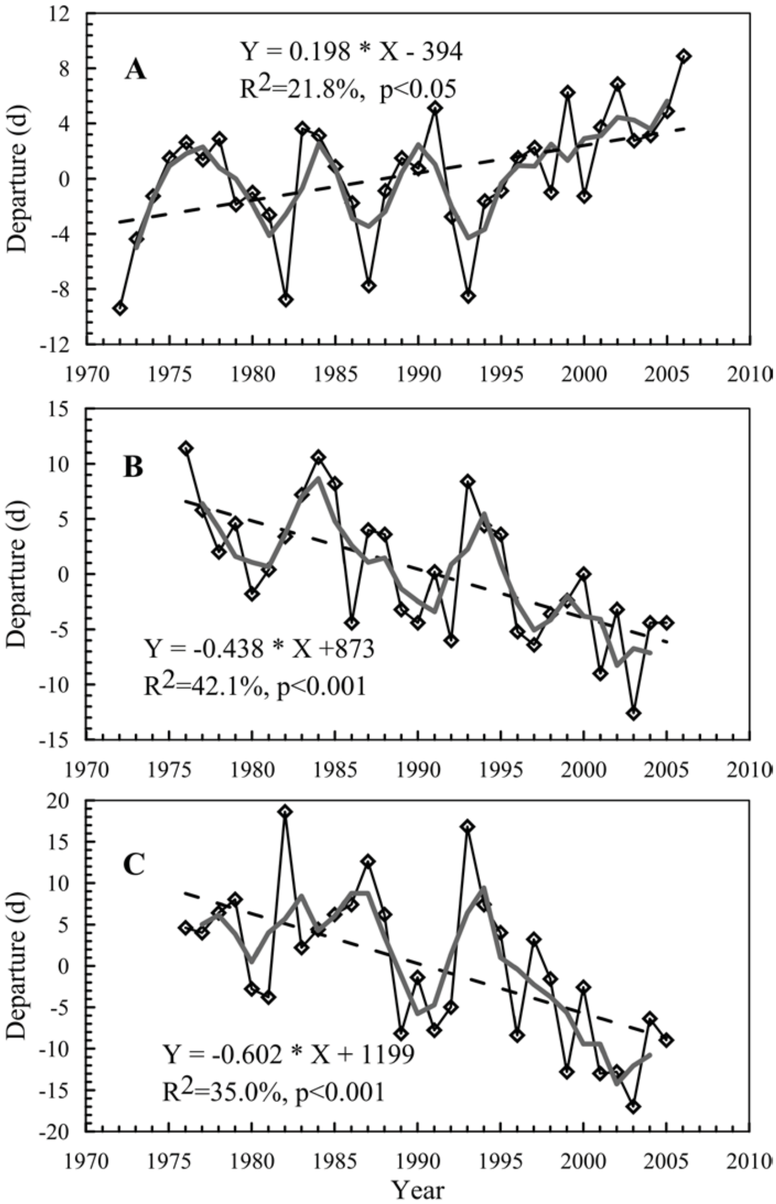

FIGURE 6. Time series of (A) onset date of soil freeze, (B) end date of soil freeze, and (C) duration of soil freeze between 1972 and 2006 in the Heihe River Basin. Gray bold line represents the 3-yr moving line. Black dotted line represents the linear least squares regression line.

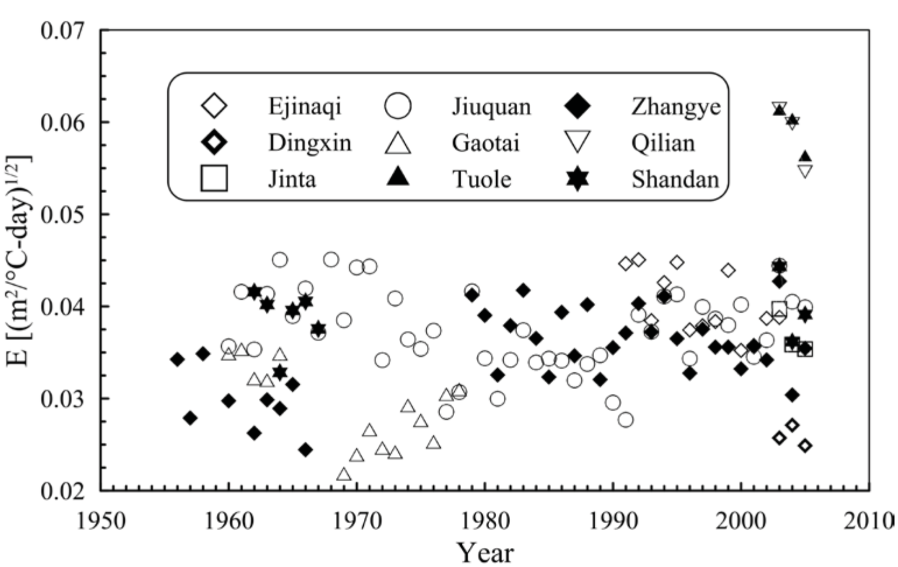

FIGURE 7. Edaphic factor (*E*) (a catch-all scaling parameter) at 9 meteorological stations in the Heihe River Basin from the1950s to 2005.

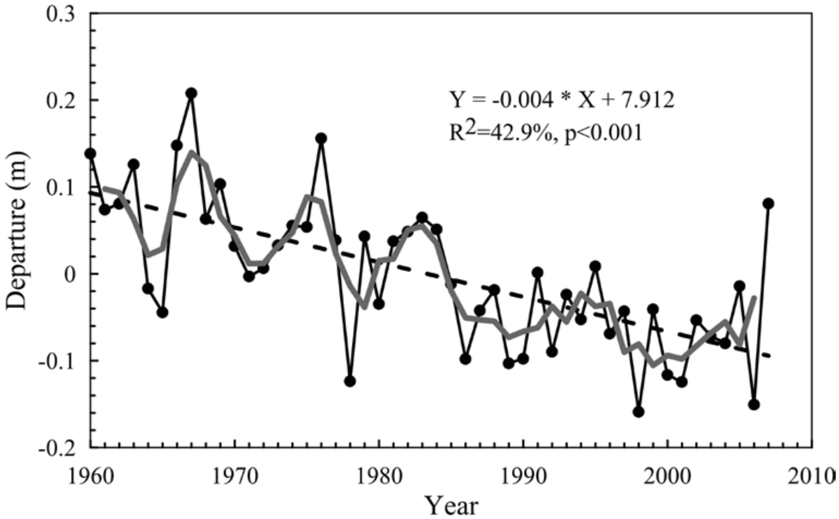

FIGURE 8. Averaged time series of maximum thickness of the seasonally frozen ground (MTSFG) from 1960 to 2007 in the Heihe River Basin. In panel, gray solid line in bold and black dotted line represent the 3-yr moving line and the linear least squares regression line, respectively.

well as the end date and duration of soil freeze at 6 stations (Jinta, Qilian, Tuole, Yeniugou, Wutonggou, and Jihede excluded), are used to structure their averaged time series in 1972–2006 and in 1976–2006, respectively. Time series of the E factor at the 5 stations, including Ejinaqi, Jiuquan, Gaotai, Zhangye, and Shandan, is much longer. Yet only three points (i.e., in 2003, 2004, and 2005) of the E factor at the others 4 stations (Dingxin, Jinta, Tuole, and Qilian) could be used to calculate the averaged values, which might cause some errors. However, the composited time series of the MASTs at 0.05–0.20 m depths, onset/end date of soil freeze, duration of soil freeze, and MTSFG could also provide an integrated view of changes of the soil thermal regimes in the Heihe River Basin because of the data scarcity.

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