The Cryosphere, 6, 607–612, 2012
www.the-cryosphere.net/6/607/2012/
doi:10.5194/tc-6-607-2012

The Cryosphere

Thermal state of the active layer and permafrost along the Qinghai-Xizang (Tibet) Railway from 2006 to 2010

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Received: 31 May 2011 – Published in The Cryosphere Discuss.: 22 September 2011
Revised: 26 March 2012 – Accepted: 26 March 2012 – Published: 31 May 2012

Abstract. In this study, we investigated changes in active layer thickness (ALT) and permafrost temperatures at different depths using data from the permafrost monitoring network along the Qinghai-Xizang (Tibet) Railway (QXR) since 2005. Among these sites, mean ALT is ∼3.1 m, with a range of ∼1.1 to 5.9 m. From 2006 through 2010, ALT has increased at a rate of $\sim$6.3 cm a^{-1}. The mean rate of permafrost temperature rise at the depth of 6.0 m is $\sim$0.02 °C a^{-1}, estimated by linear regression using 5 yr of data, and the mean rate of mean annual ground temperature (MAGT) rise at a depth of zero amplitude is $\sim$0.012 °C a^{-1}. Changes for colder permafrost (MAGT $<$ -1.0 °C) are greater than changes for relatively warmer permafrost (MAGT > -1.0 °C). This is consistent with results observed in the Arctic and subarctic.

1 Introduction

Qinghai-Xizang (Tibet) Plateau (QXP), with an average elevation of more than 4000 m above sea level (a.s.l.), is the highest and the most extensive plateau in the world (Liu and Chen, 2000) and is known as "roof of the world". Permafrost area on the Plateau is estimated at $\sim 1.3 \times 10^6$ km^2 (Nan, 2005), approximately 70.6 % of the land area of the QXP (Zhou et al., 2000). Although permafrost areas in the QXP make up only ∼5.7 % of the 22.79×10^6 km^2 of permafrost in the Northern Hemisphere (Zhang et al., 1999), it is estimated that China contains the largest mountain permafrost area in the Northern Hemisphere (Zhang et al., 2003). Zhao et al. (2010) synthetically analyzed the thermal state of the active layer and permafrost in Central Asia, including the QXP, as part of the International Permafrost Association's (IPA) International Polar Year (IPY) project Thermal State of Permafrost (TSP). This study is an additional contribution to the IPA's IPY project in studying changes in the thermal state of permafrost and active layer thickness (ALT) in the QXP. In previous studies, we investigated changes in soil temperature within the active layer, the permafrost temperature at 6.0 m depth from 1996 to 2006 (Wu and Zhang, 2008), and ALT from 1995 to 2007 (Wu and Zhang, 2010) along the Qinghai-Xizang (Tibet) Highway (QXH). Due to the construction of the Qinghai-Xizang Railway (QXR), most of these study sites were terminated. All of these sites were relatively shallow, usually ∼6–8 m in depth. A new permafrost monitoring network was established in 2005 along the QXR with 27 sites, and borehole depths are greater than 15 m. This study therefore analyzes variation of ALT, permafrost temperatures at 6.0 m depth, and mean annual ground temperature (MAGT), defined as permafrost temperature at a depth of zero annual amplitude, during the period of 2006–2010 using data from these new sites. This study is complementary to previous studies and contributes to the understanding of the thermal state of permafrost and the active layer on the QXP during the third International Polar Years.

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Table 1. Geographical data and information on the 27 sites along the QXR from 2006 to 2010.

Area	Site name	Location		Elevation (m)	Soil Type	Vegetation Cover (%)	Ecosystem	MAAT (°C) (Date of)	Active layer thickness (m)	MAGT at depth of 12 to 15 m (°C)	Disturbance extent
		Longitude, °	Latitude, °					measurement			
Kunlun Mts.	KM2	94.0515	35.6210	4757	clay	47	sandy grassland	–	1.83	−3.04	no
Budongquan	BD1	93.9633	35.6171	4636	sandy loam	8	sandy grassland	–	2.47	−0.60	no
Chumaer River High Plain	CM3	93.9633	35.5518	4547	sandy clay	24	sandy grassland	−4.6 (Zhao, 2004)	1.06	−1.20	with small puddle
	CM5	93.4465	35.3640	4507	clay with gravel	26			2.84	−1.20	with small puddle
	CM6	93.446	35.3636	4504	clay with gravel	17			3.06	−0.95	No
	CM7	93.2218	35.2774	4589	sandy clay	17			4.80	−0.41	No
Kekexili Mts.	WD3	93.1106	35.2044	4613	sandy clay	88	alpine meadow	−5.08 (2008)	1.93	−1.53	No
	WD4	93.0420	35.1384	4734		37			0.92	−2.56	No
Hongliang River Basin	HR3	93.0292	35.0691	4675	sand	23	sandy grassland	−4.37 (2008)	2.36	−1.11	No
Fenghuo Mts.	FH2	92.8986	34.6724	4894	sandy clay	67	alpine meadow	−5.4 (2005)	1.76	−2.02	Slight
	FH3	92.7823	34.6104	4715	sandy clay	60	sandy grassland		4.01	−0.65	No
Yamaer River Basin	YM1	92.7438	34.5757	4654	clay	23	sandy grassland	–	3.32	−0.39	no
	YM2	92.7307	34.5283	4616	sand	18			5.86	−0.25	slight
Wuli Basin	WL1	92.7260	34.4816	4587	sandy clay	25	alpine meadow	−3.8 (Zhao, 2004)	3.09	−0.63	no
Tuotuo River basin	TT1	92.23	33.88	4640	sandy loam	44	sandy grassland	−2.4 (2005)	2.60	−0.33	No
	TT2	92.20	33.76	4647	gravel	4				0.16	No
Kaixinling Basin	KL1	92.3399	34.0113	4672	sandy clay	23	alpine grassland	−3.4 (2008)	2.40	−0.69	no
	KL3	92.3398	33.9558	4622	sandy	22	sandy grass land		2.83	−0.72	no
	KL5	92.3417	33.9379	4622	sandy loam	19	sandy grassland		3.38	−0.60	with small puddle
Wengquan Basin	WQ1	91.9394	33.4687	4778	sandy clay	13	alpine grassland	–	4.65	−0.09	No
	WQ2	91.9459	33.3979	4817	sandy clay	9	sandy grassland		3.36	−0.32	No
Tanggula Mts.	TG2	91.8749	33.3037	4841	sandy clay	2	sandy grassland	−3.08 (2008)	4.99	0.71	No
	TG3	91.8040	33.0887	4926	sandy loam	41	alpine grassland		4.56	0.27	with small puddle
	TG4	91.7525	33.0715	4974	sandy loam	88	alpine wetland		2.77	−1.15	No
Zajiazangbu River Basin	TJ1	91.5341	32.5078	4868	sand	19	sandy grassland	–	3.50	−0.06	No
	TJ2	91.6205	32.3948	4887	sand	31	sandy grassland		3.42	−0.08	No
Anduo Basin	AD2	91.5815	32.3095	4814	sandy clay	88	alpine meadow	−1.68 (2005)	2.37	−0.08	No

MAGT is mean annual ground temperature. MAAT is mean annual air temperature.

2 Data and methods

The data used in this study include soil temperatures measured along the QXH in 1995/1998, and along the QXR in 2005. During the construction of the QXR from 2001–2006, 43 monitoring sites and three weather stations were established to detect changes in the thermal state of permafrost beneath the embankment, monitoring embankment stability (Wu et al., 2008). Although the main objective of these 43 sites is to monitor the thermal state of permafrost under the railway embankment, 27 sites away from the embankment under the natural surface (∼30–80 m away from the centerline of the embankment) were also established and monitored to study the effect of climate change on permafrost (Fig. 1; Wu et al., 2008). Data from these monitoring sites have been reported by Wu and Liu (2004) and Wu and Zhang (2008, 2010).

Because the environment and the surface conditions outside of the QXR embankment were protected during the construction period, we believe that these sites have not been impacted by the railway construction and operation during the past 10 yr. We conducted a comprehensive survey of surface conditions around these sites in September 2011 and found that the surface conditions beyond the embankment remain in their the original state compared with those several hundred meters away from the railway. We believe the surface disturbance by the railway is minimal and negligible. Long-term monitoring and further studies are certainly needed. Our study used soil temperature data from these 27 non-embankment sites to analyze the change in ALT and the thermal state of permafrost from 2005 to 2010.

2.1 Site description

The 27 monitoring sites along the 542 km of the QXR, from Xidatan to Anduo, span ∼3.4° latitude and ∼ 2.6° longitude (Fig. 1). The elevation of these sites varies from 4500 m a.s.l. at Chumaer River high-plain sites to 4970 m a.s.l. at the Tanggula Mountain site, with a mean elevation of ∼4710 m a.s.l. These sites are distributed in various terrain, including high-altitude mountains, high plains, and basins from north to south of the Plateau. In the high-elevation mountains along the QTR (the Kunlun Mountains, Kekexili Mountains, Fenghuo Mountains, and Tanggula Mountains), the MAGTs are lower than −1.0 °C or −2.0 °C, the ALT ranges from 1.2 m to 2.0 m, the permafrost thickness is greater than 60 m (Wu et al., 2010), and ice-rich permafrost exists from the permafrost table down to 10 m below the ground surface. In the high plain along the QTR (the high plain of the Chumaer River), the MAGTs range from −0.5 °C to −1.5 °C, the ALT ranges from 2.0 m to 3.0 m, the permafrost thickness is less than 50 m (Wu et al., 2010), and ice-rich permafrost

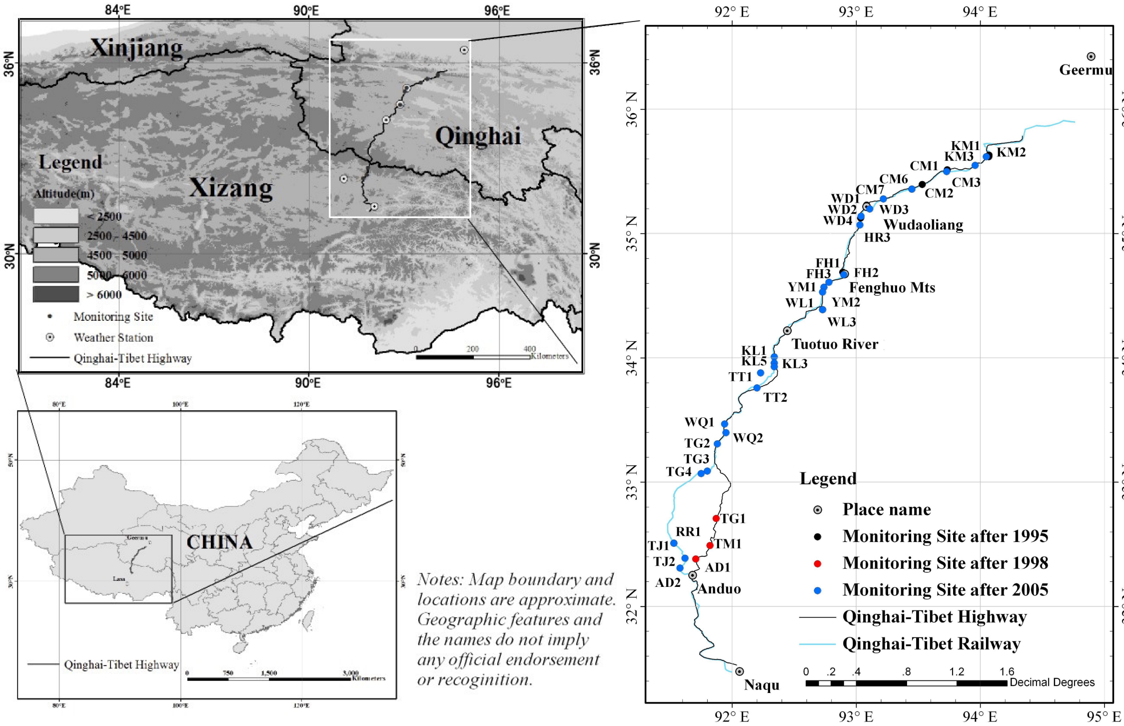

Fig. 1. Monitoring network along the Qinghai-Xizang (Tibet) Railway and Highway.

is widespread from the permafrost table to 10 m below the ground surface. In the basins along the QTR (the Beilu River, Yamer River, Wuli, Tuotuo River, Kaixinling, Zajiazangbu River, and Anduo), the MAGTs are higher than −0.5 °C (but some are much lower than −0.5 °C), most of the ALT is greater than 3 m (but some is exceptionally lower than 2.5 m), permafrost thickness ranges from 10 m to 25 m, and thawed areas are widespread. Geographical data and information about the 27 QXR sites are listed in Table 1. There are few weather data from the QXR; therefore, the air-temperature data in Table 1 were measured in different years. Ecosystem, vegetation and engineering disturbance for all sites were surveyed in situ in September 2011.

2.2 Soil temperature measurements

The use of thermistor strings to measure soil temperature has been widely accepted since 1982 (Cheng, 1980), and such strings have been used in the QXP region since the 1990s by the Chinese State Key Laboratory of Frozen soil Engineering (SKLFSE). They are currently used to monitor permafrost temperature along the QXR (Sheng et al., 2002; Zhao et al., 2004; Cheng, 2005, 2007; Zhang et al., 2008; Wu and Zhang, 2008; Zhao et al., 2010).

In this study, soil temperature was measured from 0 to 20 m deep at all sites with string of thermistors at depths of 5, 20, 40, 80, 120, 160, and 200 cm from the surface to 2 m deep; 0.5 m intervals from 2 m to 10 m deep; and 1 m intervals from 10 m to 20 m deep, including 33 thermistors. The thermistors were made by the SKLFSE, and their laboratory temperature accuracy is ±0.05 °C. In-situ measurements were automatically collected by a data logger (CR3000, made by Campbell Co., USA), at 10:00 a.m. Beijing Standard Time each day.

2.3 Methods

We analyzed the temporal trend of ALT and permafrost temperature from 2006 to 2010. ALT is estimated as the maximum thaw depth in the late autumn, through linear interpolation of soil temperature profiles between two neighboring points above and below the 0 °C isotherm at all sites (Wu et al., 2010). Because soil temperature monitoring at the QXR began in June 2005, ALT can be estimated from 2005 to 2010. The rate of change in ALT was estimated using linear regression, using 6 yr of ALT data for each site with $P < 0.05$. Annual mean permafrost temperature at the 6.0 m depth, and MAGT, were estimated using daily temperature data from 2006 to 2010. The rate of change in temperature was estimated using linear regression, using 5 yr of temperature data for each site, with $P < 0.05$.

3 Variation of active layer thickness

ALT on the QXP has a sensitive response to climate change (Jin et al., 2000; Zhao et al., 2000; Cheng and Wu, 2007;

Table 2. Multi-year mean, maximum, minimum, and changing rate of active layer thickness along the QXR from 2006–2010.

Area	Site name	Active layer thickness mean (m)	max (m)	min (m)	Rate of change (cm a^{-1})
Kunlun Mts.	KM2	1.83	1.94	1.72	*
Budongquan	BD1	2.47	2.66	2.40	4.30
Chumaer River High Plain	CM3	1.06	1.21	0.95	3.80
	CM5	2.84	2.89	2.75	1.20
	CM6	3.06	3.16	2.95	−3.5
	CM7	4.80	4.84	4.73	*
Kekexili Mts.	WD3	1.93	2.46	1.74	3.4
	WD4	0.92	1.05	0.86	5.0
Hongliang River Basin	HR3	2.36	2.45	2.19	1.5
Fenghuo Mt.s	FH2	1.76	1.97	1.64	5.4
	FH3	4.01	4.14	3.94	4.1
Yamaer River Basin	YM1	3.32	3.70	3.02	8.7
	YM2	5.86	6.00	5.75	4.5
Wuli Basin	WL1	3.09	3.18	2.98	*
Kaixinling Basin	KL1	2.40	2.49	2.33	2.8
	KL3	2.83	2.92	2.74	2.0
	KL5	3.38	3.60	3.08	5.8
Tuotuo River Basin	TT1	2.60	2.76	2.44	4.3
Wengquan Basin	WQ1	4.65	4.84	4.44	−6.8
	WQ2	3.36	3.50	3.13	3.7
Tanggula Mts.	TG2	4.99	5.50	4.44	19.9
	TG3	4.56	5.00	4.01	15.4
	TG4	2.77	2.88	2.49	−5.2
Zajiazangbu River Basin	TJ1	3.50	4.68	3.43	4.90
	TJ2	3.42	3.48	3.31	1.74
Anduo Basin	AD2	2.37	2.47	2.29	3.70

* $P > 0.05$

Table 3. Multi-year mean, maximum, minimum, and changing rate of permafrost temperature at 6 m depth from 2006–2010.

Area	Site name	Permafrost temperature at 6 m depth mean (°C)	max (°C)	min (°C)	Rate of change (°C a^{-1})
Kunlun Mts.	KM2	−2.84	−2.80	−2.94	−0.022
Budongquan	BD1	−0.56	−0.53	−0.59	0.015
Chumaer River High Plain	CM3	−1.53	−1.49	−1.56	0.017
	CM5	−0.94	−0.91	−0.98	0.016
	CM6	−0.70	−0.68	−0.72	−0.007
	CM7	−0.18	−0.16	−0.20	0.008
Kekexili Mts.	WD3	−1.51			*
	WD4	−2.59			*
Hongliang River Basin	HR3	−0.87	−0.82	−0.95	0.029
Fenghuo Mt.s	FH2	−1.86	−1.66	−2.01	0.080
	FH3	−0.42	−0.40	−0.43	0.008
Yamaer River Basin	YM1	−0.28	−0.22	−0.34	0.032
	YM2				*
Wuli Basin	WL1	−0.66	−0.64	−0.69	0.018
Kaixinling Basin	KL1	−0.66	−0.63	−0.68	0.012
	KL3	−0.55	−0.53	−0.59	0.012
	KL5	−0.38	−0.33	−0.45	0.029
Tuotuo River Basin	TT1	−0.42			*
	TT2				*
Wengquan Basin	WQ1	−0.11	−0.09	−0.14	0.009
	WQ2	−0.39			*
Tanggula Mts.	TG2	−0.08	−0.06	−0.09	0.010
	TG3	−0.12	−0.12	−0.13	0.001
	TG4	−1.32			*
Zajiazangbu River Basin	TJ1	−0.36	−0.33	−0.38	0.017
	TJ2	−0.26	−0.22	−0.30	0.020
Anduo Basin	AD2	−0.29	−0.27	−0.30	0.006

* $P > 0.05$

Zhao et al., 2008), and it changes consistently with changes in air temperature (Zhao et al., 2004, 2008; Wu and Zhang, 2010). Based on daily soil temperatures from the 27 sites, mean ALT varied from less than 1.1 m at the CM3 site to greater than 5.9 m at the YM2 site (Table 2). ALT from 2006 to 2010 along the QXR has experienced a significant inter-annual variation. ALT increased from 2006 to 2010 along the QXR, but ALT at sites CM6, WQ1, and TG4 decreased from 2006 to 2010 (Table 2). Except for this decrease, the ALT increase ranges from 1.2 cm a^{-1} at site CM5 to 19.9 cm a^{-1} at site TG2, with a mean rate of 6.3 cm a^{-1}, except at sites CM6, WQ1, and TG4 (Table 2). Continuous soil temperature monitoring data from the sites established in 1995/1998 indicated that ALT experienced a significant inter-annual variation from 1995 to 2010 (Fig. 2a), and the ALT increase ranges from 2.2 cm a^{-1} to 16.12 cm a^{-1}, with a mean rate of 7.8 cm a^{-1} (Fig. 2b), which is basically consistent with rate of change of ALT in the 27 sites along the QXR.

4 Variation of permafrost temperatures

Permafrost temperature at 6 m depth at six sites showed no variation (Table 3), with $P > 0.05$. At the remaining sites, permafrost temperature at 6 m depth showed an increasing trend, ranging from ∼0.001 °C a^{-1} at site TG3 to 0.08 °C a^{-1} at site FH2, with a mean of ∼0.02 °C a^{-1} and $P < 0.05$ (Table 3). Over mountain areas, permafrost temperature variation at 6 m depth is a complicated process that exhibits a decreasing trend, with a decreasing rate of −0.022 °C a^{-1} at site KM2, but an increasing trend at site FH2, with an increasing rate of 0.08 °C a^{-1} . At sites WD3 and WD4, there is no trend in permafrost temperatures at 6 m depth (Table 3). In high-plain and basin environments, permafrost temperature at 6 m depth shows an increasing trend, except at site CM6, ranging from less than 0.001 °C a^{-1} at site TG3 to greater than 0.049 °C a^{-1} at site WL1, with a mean of 0.016 °C a^{-1}; less than the mean increase of all sites.

Permafrost soil temperature at the monitoring sites established in 1995 and 1998 indicates that permafrost temperature at 6 m depth experienced a significant inter-annual variation from 1995 to 2010 (Fig. 3a), and permafrost temperature rose from 0.008 °C a^{-1} at site TG1 to 0.055 °C a^{-1} at site FH1, with a mean rate of 0.029 °C a^{-1} (Fig. 3b), which is consistent with rate of permafrost temperature change at 6.0 m depth in the 27 sites along the QXR.

MAGT shows an increasing trend, ranging from less than 0.001 °C a^{-1} at the site of AD2 to greater than 0.06 °C a^{-1} at site FH2, with a mean of 0.012 °C a^{-1} (Table 4). However, rate of increase of MAGT in mountain areas is much higher than in high-plain and basin areas, ranging from 0.003 °C a^{-1} at site WD3 to 0.06 °C a^{-1} at site FH2, with a mean of 0.026 °C a^{-1} (Table 4). Over high plains and basins, the rate of MAGT change ranged from 0.001 °C a^{-1} at site AD1 to

Table 4. Multi-year mean, maximum, minimum, and changing rate of mean annual ground temperature from 2006–2010.

Area	Site name	MAGT at depth of 12 to 15 m mean (°C)	max (°C)	min (°C)	Rate of change (°C a^{-1})
Kunlun Mts.	KM2	−3.04	−2.99	−3.1	0.027
Budongquan	BD1	−0.60	−0.61	−0.58	0.007
Chumaer River High Plain	CM3	−1.20	−1.19	−1.21	0.004
	CM5	−1.20	−1.16	−1.23	0.016
	CM6	−0.95	−0.94	−0.97	−0.003
	CM7	−0.41	−0.38	−0.44	0.014
Kekexili Mts.	WD3	−1.53	−1.50	−1.57	0.017
	WD4	−2.56	−2.50	−2.61	0.025
Hongliang River Basin	HR3	−1.11	−1.06	−1.19	0.03
Fenghuo Mt.s	FH2	−2.02	−1.9	−2.16	0.06
	FH3	−0.65	−0.64	−0.67	0.003
Yamaer River Basin	YM1	−0.39	−0.37	−0.41	0.012
	YM2	−0.25	−0.20	−0.34	0.029
Wuli Basin	WL1	−0.63	−0.63	−0.64	0.003
Kaixinling Basin	KL1	−0.69	−0.67	−0.71	0.009
	KL3	−0.72	−0.7	−0.74	0.009
	KL5	−0.60	−0.58	−0.63	0.012
Tuotuo River Basin	TT1	−0.33	−0.32	−0.33	0.003
	TT2	0.16	0.17	0.16	0.004
Wengquan Basin	WQ1	−0.09	−0.08	−0.1	0.003
	WQ2	−0.32	−0.29	−0.36	0.029
Tanggula Mts.	TG2	0.71			*
	TG3	0.27	0.27	0.26	0.003
	TG4	−1.15	−1.13	−1.16	0.004
Zajiazangbu River Basin	TJ1	−0.06			*
	TJ2	−0.08	−0.09	−0.06	0.007
Anduo Basin	AD2	−0.08	−0.08	−0.09	0.001

* $P > 0.05$

0.029 °C a^{-1} at site YM2, with a mean of 0.008 °C a^{-1} (Table 4).

5 Discussions and conclusions

This study examined variation of ALT, permafrost temperature at 6 m depth, and MAGT along the QXR, using daily soil and permafrost temperature measurements from 2006 to 2010. Our results show that ALT and permafrost temperatures have extensive temporal and spatial differences along the QXR.

Based on data from 27 sites over 5 yr along the QXR, mean ALT is ∼3.1 m, with a range of 1.1 to 5.9 m. Except for the thinning of the active layer at sites CM6, WQ1, and TG4, the mean rate of ALT increase is ∼6.3 cm a^{-1}, with a range from 1.2 to 19.9 cm a^{-1}. The mean permafrost temperature at 6 m depth is ∼−0.76 °C, with a range from −0.08 to −2.84 °C. Except for the lower permafrost temperature at sites KM1 and CM6, the mean rate of permafrost temperature rise is ∼ 0.02 °C a^{-1}, with a range from 0.001 to 0.08 °C a^{-1}. The mean MAGT is ∼−0.82 °C, with a range of −0.06 to −3.04 °C. The mean rate of MAGT rise is ∼0.012 °C a^{-1}, with a range of 0.001 to 0.06 °C a^{-1}. The variation in the thermal state of cold permafrost with a MAGT lower than −1.0 °C is larger than that of warm permafrost with a MAGT higher than −1.0 °C. The decrease of ALT at sites CM6,

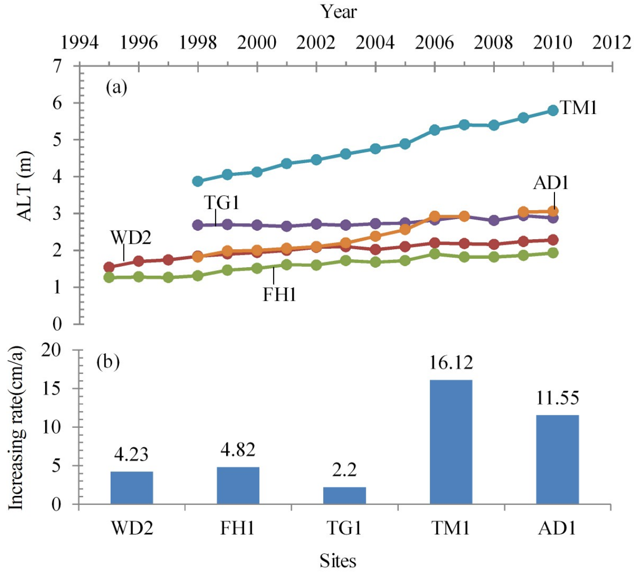

Fig. 2. Active layer thickness (ALT) along the Qinghai-Xizang (Tibet) Highway. **(a)** ALT. **(b)** Increasing rate of ALT. The increasing rate was estimated using linear regression for each site using 10 yr of ALT data with $P < 0.05$.

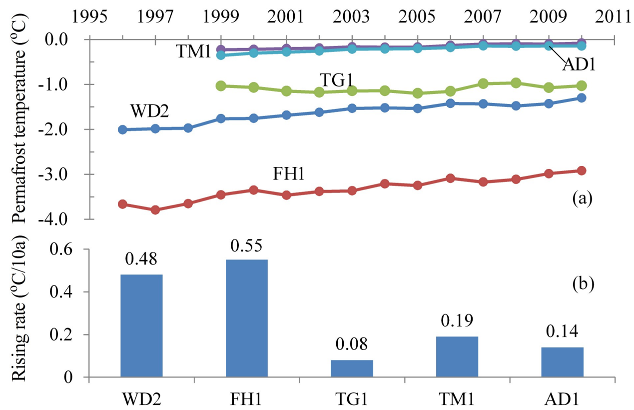

Fig. 3. Variation of permafrost temperature at 6 m depth along the Qinghai-Xizang (Tibet) Highway. **(a)** Variation of permafrost temperature at 6 m depth. **(b)** Rate of permafrost temperature change at 6 m depth. The rate of permafrost temperature change was estimated using linear regression, with $P < 0.05$.

WQ1, and TG4 may depend upon local effects, but we cannot explain which factors control the decreasing ALT.

It is widely hypothesized that ALT and permafrost temperature will increase in response to climate warming. Such a response may be complex; however, the seasonality changes in air temperature change may be predominant in the ALT and permafrost temperature variations over the QXP (Wu and Zhang, 2010). ALT variation is in disaccord with fluctuations in permafrost temperature at the different depths. These differences may indicate that local factors may control ALT and permafrost temperature variation at the local scale.

Although climate warming results in rising permafrost temperature and increasing ALT (Wang et al., 2000; Cheng and Wu, 2007; Wu and Zhang, 2008; Wu and Zhang, 2010), local factors control the variation of permafrost temperature and ALT, creating spatial and temporal change discordances under the effects of climate change. Spatial and temporal changes in permafrost will result from varying feedbacks of permafrost change to climate change. Therefore, further studies are required into the features and mechanics of permafrost under the effects of local factors, and the relationships between permafrost and climate change.

Acknowledgements. This work was supported by the Global Change Research Program of China (grant 2010CB951402), and the Program for Innovative Research Group of the Natural Science Foundation of China (grant 41121061), and the project (grant Y02C671001).

Edited by: S. Gruber

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