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

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Abstract

In this study, we investigated changes in active layer thickness (ALT) and permafrost temperatures at different depths using data from permafrost monitoring network along the Qinghai-Xizang (Tibet) Railway since 2005. Among sites, average ALT is about 3.1 m with a range from about 1.1 m to 4.9 m. From 2006 through 2010, ALT has increased at a rate of about 6.3 cm a^{-1}. The mean rising rate of permafrost temperature at the depth of 6.0 m is about 0.02 °C a^{-1} estimated by linear regression using five years of data, and the mean rising rate of mean annual ground temperature (MAGT) at depth of zero amplitude is about 0.012 °C a^{-1}. Changes for colder permafrost (MAGT < -1.0 °C) is greater than that 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, with an average elevation of more than 4000 m a.s.l., is the highest and the most extensive plateau in the world (Liu and Chen, 2000), known as "roof of the world". Permafrost areas are estimated at about 1.3×10^6 km^2 (Nan, 2005), approximately 70.6 % of the land area over the Qinghai-Xizang (Tibet) Plateau (Zhou et al., 2000). Although permafrost area in Qinghai-Xizang (Tibet) Plateau (QXP) is only about 5.7 % of the 22.79×10^6 km^2 permafrost areas in the Northern Hemisphere (Zhang et al., 1999), it is estimated that China contains the biggest part of mountain permafrost area in the northern hemisphere (Zhang et al., 2003). So, it is very important to understand the thermal state of active layer and permafrost in QXP for permafrost change in Northern Hemisphere.

Zhao et al. (2010) synthetically analyze the thermal state of the active layer and permafrost in Central Asia, including QXP, as part of the International Permafrost Association's (IPA) International Polar Year (IPY) project. 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 in QXP. In our previous studies, we investigated changes of soil temperature within the active layer, permafrost temperature at 6.0 m depth from 1996 to 2006 (Wu and Zhang, 2008) and active layer thickness from 1995–2007 (Wu and Zhang, 2010) along the Qinghai-Xizang (Tibet) Highway. Due to the construction of the Qinghai-Xizang (Tibet) Railway, most of these sites were terminated. Most of all, these sites are relatively shallow, usually about 6 to 8 m in depth. A new permafrost monitoring network was established in 2005 along the Qinghai-Xizang (Tibet) Railway with 28 sites and borehole depth is greater than 15 m. Therefore, in this study, we analyze variation of active layer thickness, soil temperature near the permafrost table, permafrost temperatures at 6.0 m depth and mean annual ground temperature during the period of 2006–2010 using data from these new sites. This study can be referred as complementary to understand the thermal state of permafrost and active layer on Qinghai-Xizang (Tibet) Plateau during the International Polar Years.

2 Data and method

The data used in this study include soil temperatures along the Qinghai-Xizang Highway established in 1995/1998 and along the Qinghai-Xizang Railway established in 2005. Due to the main objective of monitoring engineering stability and permafrost change beneath embankment with asphalt pavement (Wu et al., 2010), borehole depths range from 6 to 8 m. Research results of these data and information of permafrost monitoring have been reported (Wu and Liu, 2004; Wu and Zhang, 2008; and Wu and Zhang, 2010). During the construction of Qinghai-Xizang (Tibet) Railway from 2005, 43 monitoring sites and three whether stations were established to detect changes in the thermal state of permafrost beneath embankment and embankment stability (Wu et al., 2008). Although the main objective of these 43 sites is to monitor thermal state of permafrost under the railway embankment, sites away from the embankment under the natural surface (about 30–80 m away from the centerline of the embankment) were also established and monitored to study the effect of climate

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change on permafrost (Wu et al., 2008). There are 28 sites of monitoring permafrost change under natural surface along the Qinghai-Tibet Railway (Fig. 1) (Wu et al., 2008). In this study, soil temperature data from these 28 sites under natural surface are used to analyze the change in active layer thickness and the thermal state of permafrost from 2005 to 2010. In this article, we mainly descript these 28 sites along the Qinghai-Xizang Railway.

2.1 Site description

These 28 monitoring sites along the 542 km of the QTR, from Xidatan to Anduo, span about 3.4 latitudinal degrees and about 2.6 longitudinal degrees on the eastern Qinghai-Xizang Plateau (Fig. 1). The elevation of these sites vary from 4500 m a.s.l. at Chumaer River high-plain sites to 4970 m a.s.l. at the Tanggula Mountain site, with an average elevation of about 4710 m a.s.l. These observed sites are distributed in various terrains, including high altitude mountains, high plains, and basins from north to south of the plateau. In the high altitude mountains along the QTR, that is, the Kunlun Mountains, Kekexili Mountains, Fenghuo Mountains, and Tanggula Mountains, the MAGTs are lower than −1.0 °C or −2.0 °C, the active layer thickness ranges from 1.2 m to 2.0 m, the permafrost thickness is larger than 60 m (Wu et al., 2010) and ice-rich permafrost exists from the permafrost table to 10 m deep below the ground surface. In the high plain along the QTR, that is, the high plain of the Chumaer River, the MAGTs range from −0.5 °C to −1.5 °C, the active layer thickness ranges from 2.0 m to 3.0 m, the permafrost thickness is lower than 50 m (Wu et al., 2010), and ice-rich permafrost is widespread from the permafrost table to 10 m deep below the ground surface. In the basins along the QTR, that is, the Beilu River, Yamer River, Wuli, Tuotuo River, Kaixinling, Zajiazangbu River and Anduo, the MAGTs are higher than −0.5 °C, exceptionally lower than −0.5 °C, most of the active layer thickness is larger than 3 m, but some is exceptionally lower than 2.5 m, permafrost thickness ranges from 10 m to 25 m, and thaw area is widespread. The geographical data and information of 28 sites along the Qinghai-Xizang Railway is listed in Table 1.

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2.2 Soil temperature measurements

Soil temperature was measured at depth 0 to 20 m for all sites. All measurements were made by a string of thermistors with an increment of 0.5 m with depth. These thermistors were made by the State Key Laboratory of Frozen Soil Engineering (SKLFSE) and temperature sensitivity of these thermistor sensors in the Laboratory is $\pm 0.05\,^{\circ}$C. The measurements in-situ was automatically collected by a data-log, CR3000, made by Campbell Co., USA at 10:10 a.m. Beijing Standard Time in each day. A string of thermistors is widespread used to monitor soil temperature (Cheng, 1980). There are about 20 yr for the application in the SKLFSE and all soil temperature monitoring in permafrost regions used a string of thermistors at present, including literatures dealing with permafrost temperature monitoring along Qinghai-Xizang Railway (Sheng et al., 2002; Zhao et al., 2004; Cheng Guodong, 2005; Cheng et al., 2007; Zhang et al., 2008; Wu and Zhang, 2008; Zhao et al., 2010).

2.3 Method

In this study, we analyze the temporal trend of ALT and permafrost temperature from 2006 to 2010. Because of soil temperature monitoring had been beginning since June 2005, ALT was estimated from 2005 to 2010. The changing rate of ALT was estimated using linear regression using six years of ALT data for each site with $P < 0.05$. Annual mean temperature data near permafrost table was estimated using daily temperature data at the monitoring depth approaching to the depth of multi-year average ALT from 2006 to 2010. Annual mean permafrost temperature at the 6.0 m depth and MAGT was estimated using daily temperature data from 2006 to 2010. As the same as ALT estimated, the changing rate of temperature was estimated using linear regression using five years of temperature data for each site with $P < 0.05$.

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3 Variation of active layer thickness

ALT on Qinghai-Xizang (Tibet) Plateau has a sensitive response to climate change (Jin et al., 2000; Zhao et al., 2000; Cheng and Wu, 2007; Zhao et al., 2008) and its change was consistent with changes in air temperature (Zhao et al., 2004; Zhao et al., 2008; Wu and Zhang, 2010). Based on daily soil temperatures from the 28 sites, all sites average ALT from 2005 to 2009 along the Qinghai-Tibet Railway is 3.10 m; average ALT varied from less than 1.1 m at the CM3 site to greater than 4.9 m at TG2 site (Table 2). ALT from 2006 to 2010 along Qinghai-Tibet Railway has experienced a significant inter-annual variation. ALT increase from 2006 to 2010 along the Qinghai-Xizang Railway, but ALT at the sites of CM6, WQ1 and TG4 decrease from 2006 to 2010 (Table 2). Except for the decreasing of ALT at sites of CM6, WQ1 and TG4, the change of ALT increasing rate ranges from 1.2 cm a^{-1} at the site of CM5 to 26.1 cm a^{-1} at the site of WL3, with an average rate of 6.3 cm a^{-1} (Table 2). Continuously monitoring data of soil temperatures at the sites respectively established in 1995 and 1998 indicated that ALT experience a significant inter-annual variation from 1995 to 2010 (Fig. 2a), and the change of ALT increasing rate ranges from 2.2 cm a^{-1} to 16.12 cm a^{-1}, with an average rate of 7.8 cm a^{-1} (Fig. 2b), which is basically consistent with change rate of ALT in 28 sites along the Qinghai-Xizang (Tibet) Railway.

4 Variation of permafrost temperatures

For permafrost temperature at the 6.0 m depth, the variation trend of six sites is unobvious (Table 3) with $P > 0.05$. Variation of permafrost temperature at the 6.0 m depth shows an increasing trend, ranging from about 0.001 °C a^{-1} at site of TG3 to 0.08 °C a^{-1} at FH2 with an average of about 0.02 °C a^{-1} (Table 3). Over mountain areas, variation of permafrost temperature at 6 m depth shows a complicated process. Permafrost temperature at 6 m depth shows a decreasing trend, with a decreasing rate of –0.022 °C a^{-1} at KM2, while permafrost temperature at 6 m depth shows an

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increasing trend, with an increasing rate of 0.08 °C a^{-1} at FH2. The variation trend of permafrost temperature at 6 m depth at WD3 and WD4 is unobvious (Table 3). In high plain and basin, permafrost temperature at 6.0 m depth shows an increasing trend except for at site of CM6 and RR1, ranging from less than 0.001 °C a^{-1} at TG3 to greater than 0.049 °C a^{-1} at WL1, with an average of 0.016 °C a^{-1}.

Continuously monitoring data of soil temperatures at the sites respectively established in 1995 and 1998 indicated that permafrost temperature at 6.0 m depth experience a significant inter-annual variation from 1995 to 2010 (Fig. 3a), and rising rate of permafrost temperature ranges from 0.008 °C a^{-1} at the site of TG1 to 0.055 °C a^{-1} at the site of FH1, with an average rate of 0.029 °C a^{-1} (Fig. 3b), which is basically consistent with change rate of permafrost temperature at 6.0 m depth in 29 sites along the Qinghai-Xizang (Tibet) Railway.

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 the site of FH2, with an average of 0.012 °C a^{-1} (Table 4). However, increasing rate of MAGT in mountain areas is much higher than in high plain and basins. The rate of MAGT change in mountain regions ranged from 0.003 °C a^{-1} at the site of WD3 to 0.06 °C a^{-1} at the site of FH2, with an average 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 the site of AD1 to 0.029 °C a^{-1} at the site of YM2, with an average of 0.008 °C a^{-1} (Table 4).

5 Discussions and summary

This study examined variation of ALT, temperature near the permafrost table, permafrost temperature at 6.0 m depth and mean annual ground temperature along the Qinghai-Tibet Railway 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 Qinghai-Xizang (Tibet) Railway.

Based on data from these 28 sites over 6 yr along the Qinghai-Tibet Railway, average ALT is about 3.1 m with a range of 1.06 m to 4.99 m. Except for the decreasing of ALT at sites of CM6, WQ1 and TG4, the mean increasing rate of ALT is about 6.3 cm a^{-1} with a range from 1.2 to 26.1 cm a^{-1}. The average temperature near permafrost table is about −0.62 °C with a range of 0.0 to −2.7 °C. The average permafrost temperature at 6.0 m depth is about −0.76 °C with a range from −0.08 to −2.84 °C. Except for lowering of permafrost temperature at the depth of 6.0 m at sites of KM1 and CM6, the mean rising rate of permafrost temperature at the depth of 6.0 m is about 0.02 °C a^{-1} with a range from 0.001 to 0.08 °C a^{-1}. The average MAGT is about −0.82 °C with a range of −0.06 to −3.04 °C. The mean rising rate of MAGT is about 0.012 °C a^{-1} with a range of 0.001 to 0.06 °C a^{-1}. The variation of cold permafrost thermal state with MAGT lower than −1.0 °C is larger than that of warm permafrost thermal state with MAGT higher than −1.0 °C.

Surprisingly, the change of ALT at the site of WL3 is up to 26.1 cm a^{-1}, its change was due to add a sand protection facilities, rock pane sandfence in natural surface. This rock pane sandfence raised surface temperature to lead the increase of thaw depth. The decreasing of ALT at the site of CM6, WQ1 and TG4 may depend on local effect, but we cannot explain which factors control the decreasing of ALT.

It is widely hypothesized that ALT and permafrost temperature will increase in response to climate warming. It may be complex for the response of ALT and permafrost temperature to climate change; however, the seasonality of air temperature change is possibly predominant for ALT and permafrost temperature variation over the Qinghai-Tibet Plateau (Wu and Zhang, 2010). ALT variation is disaccord with variation of temperature near permafrost table, and variation fluctuation of permafrost temperature at the different depth is disaccord. These differences may indicate that local factors may control on ALT and permafrost temperature variation in local scale.

Although climate warming result in rising of permafrost temperature and increasing of active layer thickness (Wang et al., 2000; Cheng and Wu, 2007; Wu and Zhang, 2008; Wu and Zhang, 2010), local factors control on the variation of permafrost temperature and active layer thickness in local scale, making spatial and temporal change disaccord under the effect of climate change. Spatial and temporal change of permafrost will result from a different feedback of permafrost change to climate change. Therefore, we should study the feature and mechanics of permafrost change under the effect of local factors and the relationships between permafrost and climate change.

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Table 1. The geographical data and information of 29 sites along the Qinghai-Xizang Railway.

Areas	Sites name	Location Longitude °	Latitude °	Altitude [m]	Soil Types	Vegetation Cover [%]	ALT [m]	MAGT [°C]
Kunlun Mts.	KM2	94.05	35.62	4757	clay	10 to 15	1.83	−3.04
Budongquan	BD1	93.96	35.55	4636	sandy clay	10 to 20	2.47	−0.60
Chumaer River High Plain	CM3	93.73	35.50	4547	sandy clay	20 to 30	1.06	−1.20
	CM5	93.45	35.36	4507			2.84	−1.20
	CM6	93.45	35.36	4504			3.06	−0.95
	CM7	93.22	35.28	4589			4.80	−0.41
Kekexili Mts.	WD3	93.11	35.2	4613	clay	60 to 80	1.93	−1.53
	WD4	93.04	35.14	4734			0.92	−2.56
Hongliang River Basin	HR3	93.03	35.07	4675	clay	20 to 30	2.36	−1.11
Fenghuo Mt.s	FH2	92.9	34.67	4894	clay	70 to 80	1.76	−2.02
	FH3	92.78	34.61	4715			4.01	−0.65
Yamaer River Basin	YM1	92.74	34.57	4654	sandy clay	20 to 30	3.32	−0.39
	YM2	92.73	34.53	4616			5.86	−0.25
Wuli Basin	WL1	92.73	34.39	4587	sandy clay	20 to 30	3.09	−0.63
	WL3	92.73	34.39	4587			5.45	−0.50
Kaixinling Basin	KL1	92.34	34.01	4672	clay	40 to 50	2.40	−0.69
	KL3	92.34	33.96	4622			2.83	−0.72
	KL5	92.34	33.93	4622			3.38	−0.60
Tuotuo River Basin	TT1	92.23	33.88	4640	sandy clay	30 to 40	2.60	−0.33
	TT2	92.20	33.76	4647				0.16
Wengquan Basin	WQ1	91.94	33.47	4778	clay	30 to 40	4.65	−0.09
	WQ2	91.95	33.40	4817			3.36	−0.32
Tanggula Mts.	TG2	91.88	33.31	4841	sandy clay	20 to 30	4.99	0.71
	TG3	91.80	33.09	4926			4.56	0.27
	TG4	91.75	33.07	4974			2.77	−1.15
Zajiazangbu River Basin	TJ1	91.53	32.51	4868	sandy clay	30 to 40	3.50	−0.06
	TJ2	91.62	32.39	4887			3.42	−40.08
Anduo Basin	AD2	91.58	32.31	4814	clay	60 to 70	2.37	−0.08

Table 2. Multi-year mean, max, min and changing rate of ALT along Qinghai-Xizang Railway.

Areas	Sites name	ALT mean [m]	max [m]	min [m]	changing rate [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	3.8
	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 Mts.	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	*
	WL3	5.45	6.14	3.96	26.1
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

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Table 3. Multi-year mean, max, min, and changing rate of permafrost temperature at the 6.0 m depth permafrost temperature at 6 m depth.

Areas	Sites name	permafrost temperature at 6 m depht mean [°C]	max [°C]	min [°C]	changing rate [°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
	WL3	−0.37	−0.26	−0.48	0.049
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

*$P > 0.05$

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Table 4. Multi-year mean, max, min and changing rate of MAGT.

Areas	Sites name	MAGT mean [°C]	max [°C]	min [°C]	changing rateo [$°C\,a^{-1}$]
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
	WL3	−0.50	−0.49	−0.5	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

*$P > 0.05$

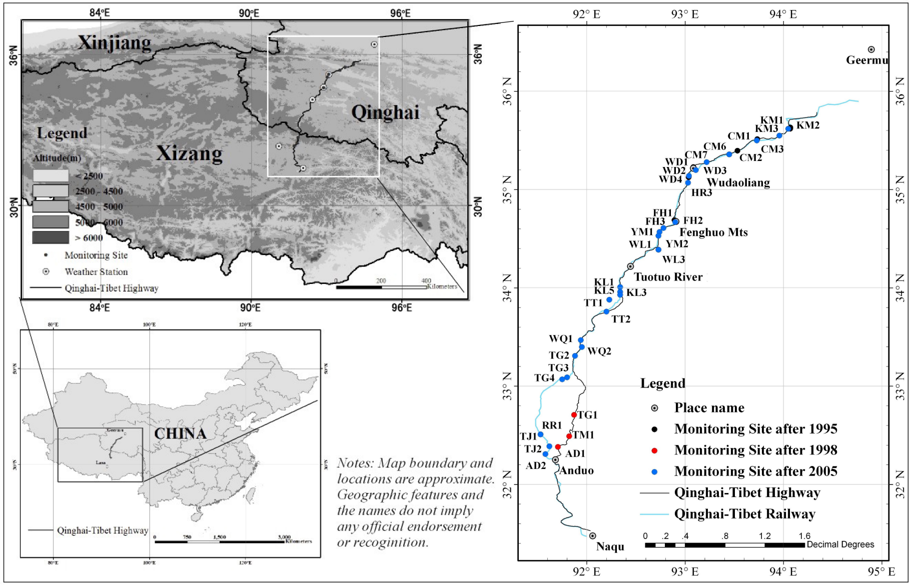

Fig. 1. Monitoring network Along the Qinghai-Xizang (Tibet) Railway and Highway.

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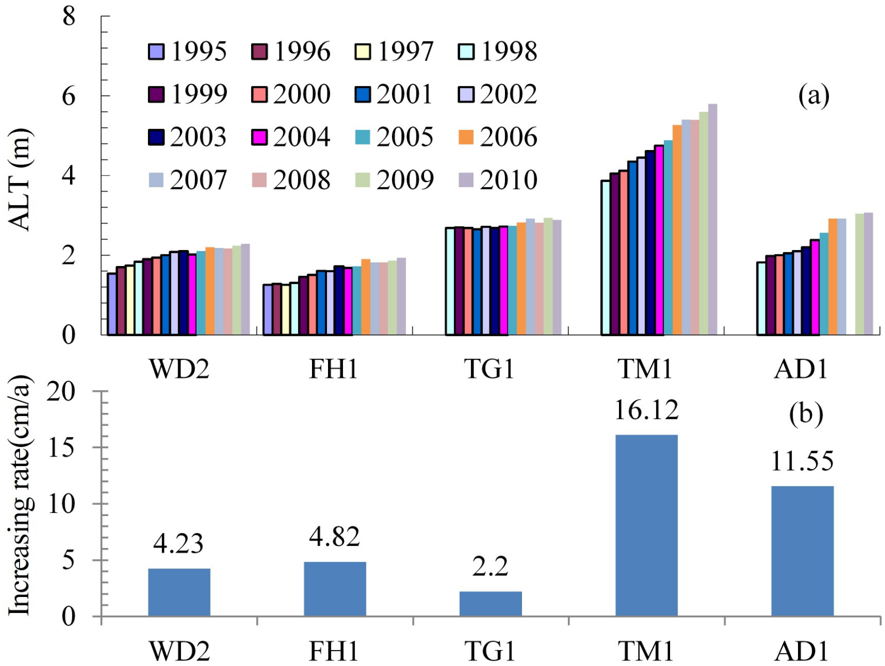

Fig. 2. ALT along the Qinghai-Xizang (Tibet) Highway, **(a)** active layer thickness; and **(b)** increasing rate of ALT. The increasing rate was estimated using linear regression for each site using 10 yr of ALT data with $P < 0.05$.

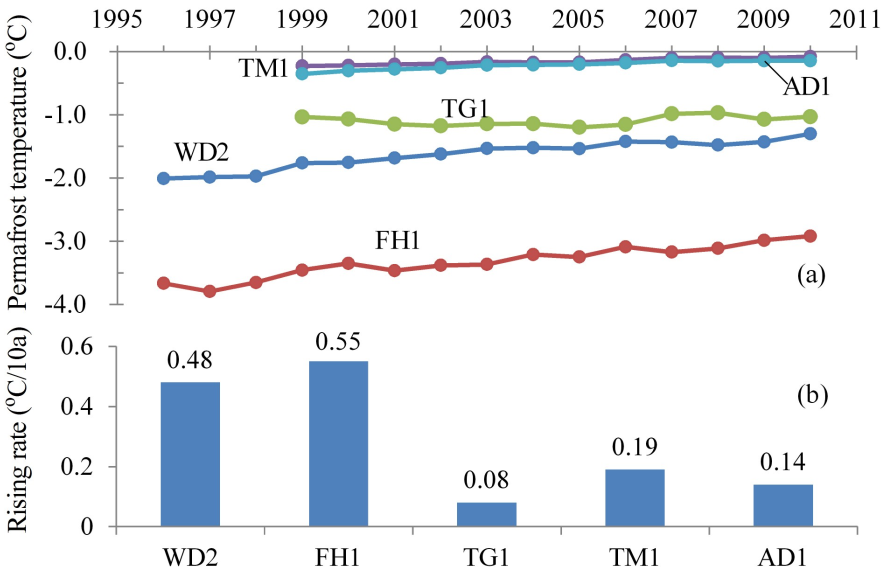

Fig. 3. Variation of permafrost temperature at 6.0 m depth along the Qinghai-Xizang (Tibet) Highway, **(a)** variation of permafrost temperature at 6 m depth, and **(b)** rate of permafrost temperature change at 6.0 m depth. The rate of permafrost temperature change was estimated using linear regression using the record of data for each site with $P < 0.05$.

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