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CLIMATIC WARMING IN THE TIBETAN PLATEAU DURING RECENT DECADES

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ABSTRACT

Adequate knowledge of climatic change over the Tibetan Plateau (TP) with an average elevation of more than 4000 m above sea level (a.s.l.) has been insufficient for a long time owing to the lack of sufficient observational data. In the present study, monthly surface air temperature data were collected from almost every meteorological station on the TP since their establishment. There are 97 stations located above 2000 m a.s.l. on the TP; the longest records at five stations began before the 1930s, but most records date from the mid-1950s. Analyses of the temperature series show that the main portion of the TP has experienced statistically significant warming since the mid-1950s, especially in winter, but the recent warming in the central and eastern TP did not reach the level of the 1940s warm period until the late 1990s. Compared with the Northern Hemisphere and the global average, the warming of the TP occurred early. The linear rates of temperature increase over the TP during the period 1955–1996 are about 0.16°C/decade for the annual mean and 0.32°C/decade for the winter mean, which exceed those for the Northern Hemisphere and the same latitudinal zone in the same period. Furthermore, there is also a tendency for the warming trend to increase with the elevation in the TP and its surrounding areas. This suggests that the TP is one of the most sensitive areas to respond to global climate change. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: Tibetan Plateau; climatic trend analysis; linear regression; surface air temperature

1. INTRODUCTION

Contemporary global warming has been the topic of numerous studies (e.g. Jones *et al*., 1986; Hansen and Lebedeff, 1988; Houghton *et al*., 1990, 1996; Vinnikov *et al*., 1990; Jones and Briffa, 1992). Observations indicate that the global average surface temperature has increased by about 0.3°–0.6°C since the late 19th century and by 0.2°–0.3°C over the last 40 years. In addition, indications are that recent years have been among the warmest since 1860, when instrumental records first became available. However, the warming has not been globally uniform. There are large regional differences in the surface air temperature change, e.g. greater surface warming of the land than of the sea in winter, especially in high northern latitudes (Houghton *et al*., 1996).

There is a growing demand for information about regional climate changes resulting from global warming because this information is important for understanding the causes and the regional impacts of climate change on human activities and ecosystems. Significant signals of regional climate change can provide the basis for the validation of climate models. The regional scale is of particular interest to nations and economic groups, and often there are homogeneous historical datasets within certain regions that can be used for climate change research. Recent concern about regional climate changes have focused attention on high-elevation areas. As far as the same latitudes of northern land are concerned, the surface

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temperature change seems to be related to elevation (Beniston *et al.*, 1997). Beniston and Rebetez (1996) found that surface climate change in the Swiss Alps associated with global warming showed an altitudinal dependency, i.e. the warming at high-elevation sites was more pronounced than at low-elevations. Simulations (Giorgi *et al.*, 1997) using a high-resolution limited-area model yielded values that were broadly consistent with the statistical analysis of the Swiss data. In the Tien Shan of central Asia, during the last half of this century, the warming trend in regions over 2000 m above sea level (a.s.l.) appeared to be greater than below 2000 m a.s.l. (Aizen *et al.*, 1997). Diaz and Bradley (1997) analysed surface temperature variations at many high-elevation sites of the Northern Hemisphere extratropics and indicated appreciable temperature changes in the high-elevation areas for the limited number of decades in which instrumental records were available. Based on results from an ensemble of climate change experiments with increasing greenhouse gases and aerosols using a coupled climate model, Fyfe and Flato (1999) recently found a marked elevation dependency of the simulated surface screen temperature increase over the Rocky Mountains.

The Tibetan Plateau (TP) is located in central Asia (Figure 1) with a mean elevation of more than 4000 m a.s.l. and an area of about 2300000 km^2. Surrounded by the Earth's highest mountains, such as the Himalayas, Pamir, Kunlun Shan and others, it is the highest and most extensive plateau in the world and has long been known as the roof of the world. Many studies show strong evidence that the TP exerts profound thermal and dynamical influences on the local weather and climate as well as on atmospheric circulation in the Northern Hemisphere (Manabe and Terpstra, 1974; Yeh and Gao, 1979; Manabe and Broccoli, 1990; Yanai *et al.*, 1992; Kutzbach *et al.*, 1993). However, owing to the lack of adequate observational data at the spatial and temporal resolution levels needed for climate research, it was only in the last few years that investigations into contemporary climate change over the TP have been carried out (cf. Tang *et al.*, 1998). Recent work carried out by Liu and Zhang (1998), on the basis of reconstructed climatic data, demonstrated that there was a warming trend over the TP during the last 90 years and suggested that the TP could be one of the most sensitive areas to global change. Ice cores on the TP also reflect a significant increase in temperature over the last few decades (Thompson *et al.*, 1993; Yao *et al.*, 1995), which is associated with a retreat of most mountain glaciers on the TP (see Tang *et al.*, 1998 for details).

Using almost all of the available instrumental records, the present study documents the change in surface air temperature over the TP. Particular emphasis is placed on recent climatic warming and its elevational dependency in and near the Plateau region.

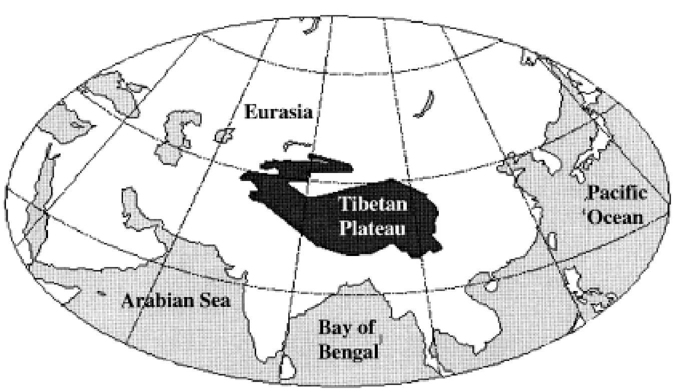

Figure 1. Map of the TP domain. The black area approximately indicates the TP where the elevation is above 2000 m a.s.l.

2. DATA AND METHOD

Monthly mean surface air temperature data from most meteorological stations on the TP and its neighbouring areas are used in this study. The stations on the TP are mainly located in Qinghai, Xizang (Tibet) and Sichuan provinces of China, with a few from the former Soviet Union and India. All observational data within China were obtained from monthly meteorological data reports either compiled by the State Meteorological Administration of China or collected directly from the relevant provinces' meteorological bureaus. Data from outside China are extracted from the datasets of Jones *et al.* (1991), Jones and Briffa (1992) and Vose *et al.* (1992). It should be pointed out that most of the TP data used in this study have not been added to the global surface air temperature dataset of Jones *et al.* (1991) or to the Global Historical Climate Network (GHCN) of Vose *et al.* (1992).

Most meteorological stations on the TP were not established until the early 1950s, with the exception of a few observational records that were collected before the 1930s. Therefore, the time period considered is mainly from 1955 to 1996. Data were collected from a total of 197 stations, in which 100 stations are below 2000 m a.s.l. and 97 are above 2000 m a.s.l., including the highest mountain station (Anduo) located at 4801 m. Seventy-eight of the 97 high-elevation stations have continuous data during the period 1961–1990. Among these 78 stations, Xining and Lhasa, the most intensively used in the study, have been updated to 1998. From the station locations shown in Figure 2, it can be seen that the distribution of the stations is uneven and very sparse in the western TP, which may adversely effect the accuracy of the regional average. The station identification number prescribed by the World Meteorological Organization (WMO) and the station name, along with longitude, latitude, elevation and record period of the 97 stations over 2000 m a.s.l., are also listed in Table I. A few missing or clearly erroneous records of individual stations were replaced with estimated values predicted from multiple regression relationships established among a few neighbouring and highly correlated stations. Inspection of the data shows that these are generally of good quality.

To facilitate trend analyses and comparisons between the stations, the monthly temperature anomalies (MTA) are computed with reference to the 1961–1990 mean. Unless otherwise specified, the temperature anomalies referred to hereafter are relative to 1961–1990. The seasonal and annual mean anomaly values

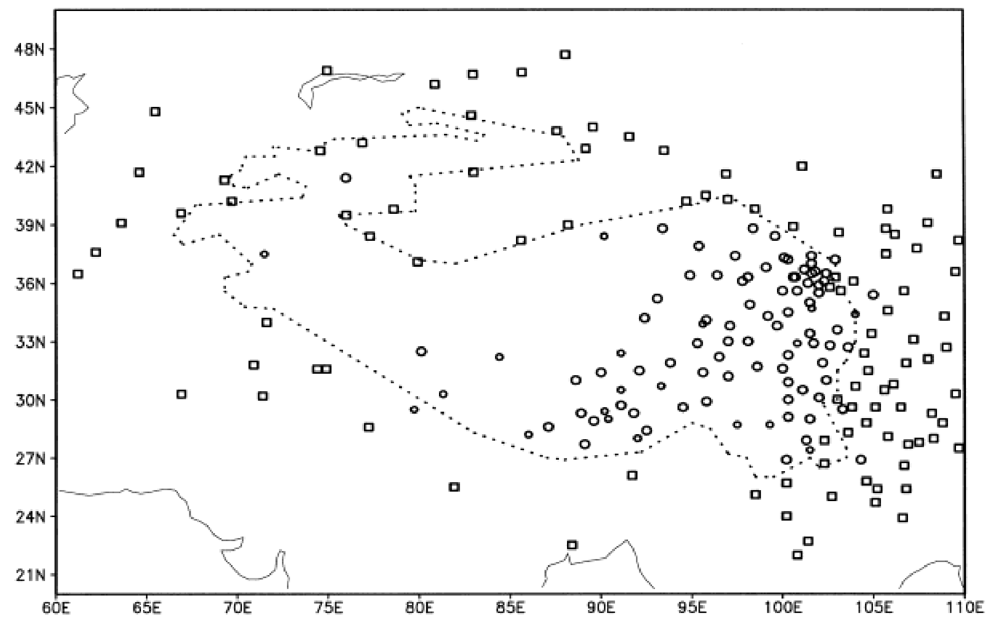

Figure 2. Location of the meteorological stations used. The circles and squares represent stations above and below 2000 m a.s.l., respectively. The smaller circles show stations without continuous data during 1961–1990. The dotted line is the contour of the TP

Table I. List of used stations above 2000 m a.s.l., including the station identification number (ID), station name, first year of record, latitude, longitude and elevation a.s.l.

ID	Station name	First year	Latitude, N	Longitude, E	Elevation (m)
36974	Natyn	1886	41°26′	76°	2049
38954	Horog	1937	37°30′	71°30′	2080
42147	Mukteswar	1897	23°7′	79°42′	2311
51886	Mangai	1964	38°21′	90°13′	3139
52602	Lenghu	1956	38°50′	93°23′	2734
52633	Tuole	1956	38°48′	98°25′	3368
52645	Yeniugou	1959	38°25′	99°35′	3320
52657	Babao	1956	37°11′	100°15′	2789
52713	Dachaidan	1956	37°51′	95°22′	3174
52737	Wulandelingha	1955	37°22′	97°22′	2982
52754	Gangcha	1957	37°20′	100°8′	3302
52765	Menyuan	1956	37°23′	101°37′	2851
52787	Wushaoling	1951	37°18′	102°52′	3045
52818	Geermu	1955	36°25′	94°54′	2809
52825	Nuomuhong	1956	36°26′	96°25′	2791
52835	Xiangride	1957	36°4′	97°48′	2907
52836	Dulan	1954	36°18′	98°6′	3192
52842	Wulan	1955	36°47′	99°5′	3089
52855	Huangyuan	1956	36°41′	101°14′	2635
52856	Gonghe	1953	36°16′	100°37′	2836
52862	Datong	1956	37°2′	101°33′	2569
52866	Xining	1936	36°37′	101°46′	2262
52868	Guide	1956	36°2′	101°26′	2238
52869	Huangzhong	1958	36°31′	101°34′	2665
52874	Ledu	1959	36°29′	102°23′	1982
52877	Hualong	1957	36°6′	102°16′	2836
52908	Wudaoliang	1956	35°13′	93°5′	4614
52943	Xinghai	1960	35°35′	99°59′	3324
52955	Guinan	1957	35°35′	100°45′	3202
52957	Tongde	1954	36°16′	100°39′	3290
52963	Jianzha	1959	35°56′	102°2′	2086
52968	Zeku	1957	35°2′	101°28′	3664
52974	Tongren	1959	35°31′	102°1′	2492
52996	Huajialing	1943	35°23′	105°	2451
55228	Geer	1960	32°30′	80°5′	4279
55248	Gaize	1973	32°9′	84°25′	4416
55279	Bange	1957	31°23′	90°1′	4701
55294	Anduo	1965	32°21′	91°6′	4801
55299	Naqu	1954	31°29′	92°4′	4508
55437	Pulan	1973	30°17′	81°15′	3901
55472	Shenzha	1960	30°57′	88°38′	4674
55493	Dangxiong	1962	30°29′	91°6′	4201
55578	Rikeze	1955	29°15′	88°53′	3837
55585	Nimu	1973	29°26′	90°10′	3811
55591	Lhasa	1935	29°40′	91°8′	3650
55598	Zedang	1956	29°15′	91°46′	3553
55655	Niemula	1966	28°11′	85°58′	3811
55664	Dingri	1957	28°38′	87°5′	4302
55680	Jiangzi	1956	28°55′	89°36′	4041
55681	Langcazi	1964	28°58′	90°24′	4433
55690	Cuona	1967	27°59′	91°57′	4281
55696	Longzi	1959	28°25′	92°28′	3861
55773	Yadong	1956	27°44′	89°5′	4301
56004	Tuotuohe	1956	34°13′	92°26′	4534
56016	Zhiduo	1967	33°51′	95°36′	4181
56018	Zaduo	1956	32°54′	95°18′	4069

Table I. (Continued)

ID	Station name	First year	Latitude, N	Longitude, E	Elevation (m)
56021	Qumalai	1956	34°8′	95°47′	4176
56029	Yushu	1951	33°1′	97°1′	3682
56033	Maduo	1953	34°55′	98°13′	4273
56034	Chengduo	1956	33°48′	97°8′	4418
56038	Shiqu	1960	32°59′	98°6′	4201
56041	Maqing	1959	34°16′	99°12′	4212
56043	Dawu	1959	34°28′	100°15′	3720
56046	Dari	1956	33°45′	99°39′	3969
56065	Waisi	1959	34°44′	101°36′	3501
56067	Jiuzhi	1958	33°26′	101°29′	3630
56079	Ruoergai	1957	33°35′	102°58′	3441
56093	Minxian	1937	34°24′	104°	2315
56106	Suoxian	1956	31°53′	93°47′	4024
56116	Dingqing	1954	31°25′	95°36′	3874
56125	Nangqian	1956	32°12′	96°29′	3645
56137	Changdu	1951	31°9′	97°1′	3307
56144	Dege	1956	31°44′	98°34′	3199
56146	Ganzi	1951	31°37′	100°	3394
56151	Banma	1965	32°56′	100°45′	3530
56152	Seda	1961	32°17′	100°20′	3896
56167	Daofu	1957	30°29′	101°7′	2959
56171	Aba	1955	32°54′	101°42′	3277
56172	Maerkang	1953	31°54′	102°14′	2666
56173	Hongyuan	1960	32°48′	102°33′	3493
56178	Xiaojing	1951	31°	102°21′	2369
56182	Songpan	1940	32°39′	103°34′	2852
56202	Jiali	1952	30°40′	93°17′	4489
56227	Bomi	1953	29°52′	95°46′	2737
56251	Xinlong	1959	30°56′	100°19′	2999
56257	Litang	1952	30°	100°16′	3951
56312	Linzhi	1953	29°34′	94°28′	3001
56357	Daocheng	1957	29°3′	100°18′	3729
56374	Kangding	1939	30°3′	101°58′	2616
56385	Emeishan	1941	29°31′	103°20′	3049
56434	Chayu	1955	28°39′	97°28′	2331
56441	Derong	1960	28°43′	99°17′	2424
56459	Muli	1959	27°56′	101°16′	2427
56462	Jiulong	1952	29°	101°30′	2994
56565	Yanyuan	1956	27°26′	101°31′	2545
56651	Lijing	1943	26°50′	100°28′	2393
56691	Weining	1937	26°52′	104°17′	2238

used in the following analyses were obtained from the monthly anomalies. Regional average values for various variables over the TP are derived from the simple arithmetic mean of all 97 stations higher than 2000 m a.s.l. on the Plateau for the time series from 1955 to 1996 and of 78 stations with continuous records for time series for the period 1961–1990. In addition, statistics of the temperature anomaly threshold excesses were also produced, as is discussed below.

In order to detect trends, the following linear regression is used:

$$y_x = a + bx + e_x,$$

where y_x denotes a surface temperature anomaly at time x (in years) and e_x is the deviation of the data from the straight line defined by a (the intercept) and the trend b (the slope), which represents the rate of increase or decrease of the temperature anomaly. The regression coefficients a and b are determined through a least-square fitting. The statistical significance of the trends is evaluated using the Student's t-test with the following significance parameter:

$$t = r[(n-2)/(1-r^2)]^{1/2},$$

where n and r are the total number of years in the study and the correlation coefficient between x and y_x, respectively.

In addition, temperature data from three atmospheric general circulation models (GCMs) are utilized for comparison with our results. The details are presented in Section 4.

3. RESULTS

3.1. The TP surface temperature change during the last 100 years

As mentioned above, most meteorological stations on the TP were established in the early 1950s, which limits the analysis of climatic change for a longer time scale in this region. To provide a background of recent climate change over the TP, the surface temperatures from five high-elevation stations having the longest records were collected: two from the former Soviet Union in the northwestern TP, one from India in the southwestern TP and two from China in the central and northeastern TP. However, two of the five stations have been excluded because the temperature variation from a former Soviet Union station is similar to that from the other one and the record from the India station contains much missing data during the last twenty years.

The longest record, which goes back to 1886, is from Natyn (41°26′N, 76°E, 2049 m a.s.l.) in the former Soviet Union. Figure 3 shows Natyn's annual mean temperature anomalies during the last 100 years. The Northern Hemisphere mean temperature anomalies for the same period (Jones *et al.*, 1986; Jones and Briffa, 1992) are also plotted in Figure 3 for comparison. Note here that 1950–1979 is used as a reference period. There is a marked warming trend in Natyn (1.31°C/century), which is similar to but stronger than that in the Northern Hemisphere (0.54°C/century), and a relatively high correlation of 0.29 (above the 0.01 significance level) between the temperature variations of Natyn and the Northern Hemisphere during the last 100 years. In addition, the temperature variation of Natyn has some notable characteristics, such

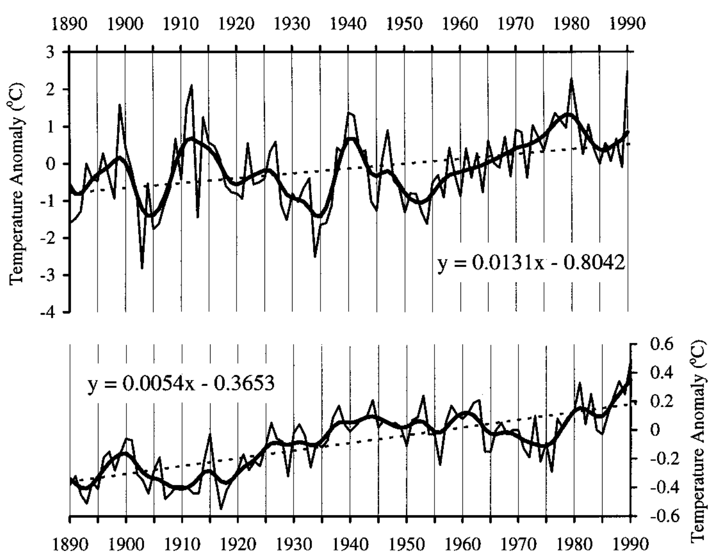

Figure 3. Annual mean temperature anomalies (relative to a 1950–1979 reference period) of the station Natyn (41°26′N, 76°E, 2049 m, top) and the Northern Hemisphere average (bottom) in the last 101 years. The thick solid curves represent the corresponding smoothed time series using a low-pass Gaussian filter and the thick dashed lines are fitted linear trends with a least-square procedure

as greater magnitude of change for all cool periods (in 1900s, 1930s, early 1950s and mid-1980s) and warm periods (in late 1890s, 1910s, 1940s and late 1970s to early 1980s). Of particular interest is the fact that the recent warming in Natyn started during the early 1950s while the Northern Hemisphere average did not commence warming until the mid-1970s.

The two other longest records, which came into being from the mid-1930s, are from China's Xining (at 36°37′N, 101°46′E, 2262 m a.s.l.) in the northeastern TP and Lhasa (at 29°40′N, 91°8′E, 3650 m a.s.l.) in the southern TP. From Figure 4, the annual mean surface temperatures (AMST) in both Xining and Lhasa have experienced substantial fluctuations during the last six decades. There is a warm period during most of the 1930s and 1940s, a general cooling from the late 1940s to the mid-1950s and a statistically significant warming trend of about 0.3°C/decade starting from the mid-1950s, roughly corresponding to the transition point of the curve of cumulative normalized temperature anomalies (CNTA). Generally speaking, these variations are in agreement with general features such as two major warming periods in the 20th century for Natyn, the Northern Hemisphere and global temperature changes (Jones *et al.*, 1986; Vinnikov *et al.*, 1990; Houghton *et al.*, 1996). However, two differences are worth noting. First, the recent warming began from about the mid-1950s to the early 1960s for Xining and Lhasa in the central and eastern TP as for the station Natyn in the western TP, but did not occur until the mid-1970s for the Northern Hemisphere and global average. This suggests that the recent warming over the TP may have started earlier than that displayed on the hemisphere or global scale. Second, unlike Natyn in the northwestern TP and the Northern Hemisphere, the recent warming over the central and eastern TP did not reach or exceed the peak shown in the 1940s until the late 1990s. Previous analyses (Wang and Ye, 1993; Ding, 1994) of all-China temperature variations have also shown that the peak temperature in the early 1980s was lower than that in the 1940s in China.

Although there are only a few longer temperature series currently available in the TP, they may be representative in reflecting general features of temporal change of the TP surface temperature. For example, the common feature that recent warming began from about the mid-1950s at the above three sites, which are all located at a distance from each other, implies that the recent warming could be a

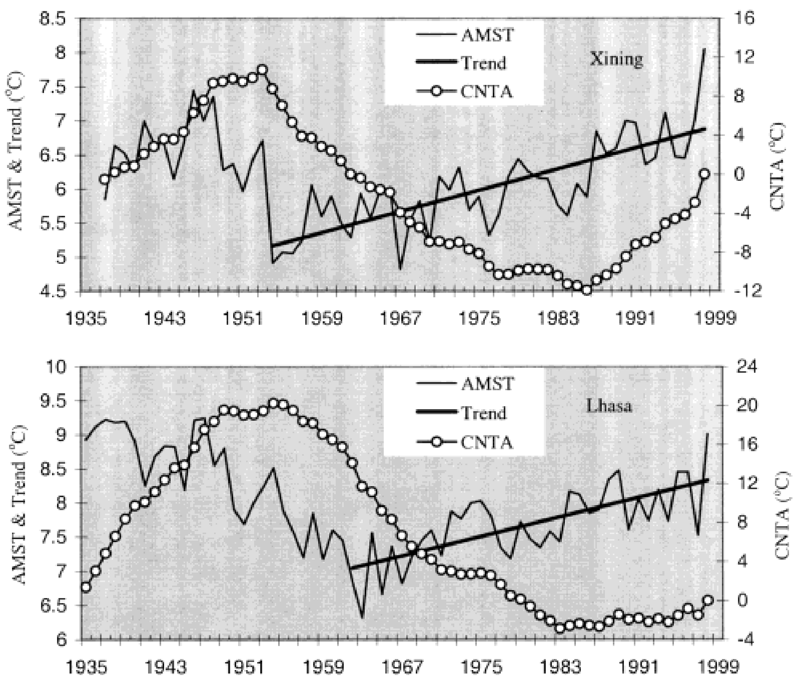

Figure 4. AMSTs and their CNTAs for 1935–1998 in Xining (36°37′N, 101°46′E, 2262 m a.s.l.) and Lhasa (29°40′N, 91°8′E, 3650 m a.s.l.). The heavy solid lines indicate the AMST trends for recent warming periods

phenomenon that occurred over the whole TP. However, short-term changes such as year-to-year variations in the western TP are not the same as in the central and eastern TP. There is, in fact, a very low correlation between the annual mean temperature of Natyn in the northwestern TP and that of Xining in the northeastern TP (0.19), as well as that of Lhasa in the south-central TP (− 0.11), in the 54 years from 1937 to 1990, despite a higher correlation between temperature variations at Xining and Lhasa (0.52) for the same period. Besides, Xining and Lhasa also have good correlations with the rest of the central and eastern stations on the TP. To illustrate this, correlation coefficients are computed between AMST anomalies at Xining (Lhasa) and those at the other 77 TP stations with continuous records during 1961–1990. The results indicate that Xining (Lhasa) has a mean correlation of 0.48 (0.46) with the other stations for annual temperature. Note in Figure 5 that the temperature variation at Xining (Lhasa) has a high correlation with that at other sites, especially in the northeastern (central) TP, considering that the correlation of 0.46 has exceeded the 99% confidence level for a series of 30 samples (28 df). In this case, the above temporal change characteristics of Xining and Lhasa might be regarded as a plausible representation of those in the whole central and eastern TP during the last 63 years except for Natyn in the western TP.

3.2. Spatial and temporal distribution characteristics of recent climatic warming in the TP

The above analyses point out that the recent warming over the TP began during the mid-1950s when most meteorological stations on the TP had just been established. Therefore, the following will focus on the latest warming since 1955 in order to characterize its spatial and temporal dimensions. Both annual and seasonal mean temperature anomaly trends were calculated for 78 TP stations with continuous records from 1961 to 1990. Almost all stations above 2000 m a.s.l. have upward temperature trends for annual average temperature (Figure 6(a)) and more remarkable warming trends for winter (Figure 6(b)). Of the 78 stations, annual temperature trends exceeding 0.2°C/decade and 0.1°C/decade are marked at 33 stations (in which 31 cases are significant at the 99% level) and 59 stations (in which 37 cases are significant at the 95% level), respectively. Winter temperature trends greater than 0.6°C/decade and 0.3°C/decade appear at 21 stations (in which 20 cases are significant at the 99% level) and 60 stations (in which 48 cases are significant at the 95% level), respectively. Thus, it is legitimate to state that the surface temperature exhibits markedly increasing trends in the central and eastern TP, but this is not so true in the western TP where there are only two stations with continuous data and considerable gaps. Nevertheless, referring to some discontinuous temperature records from a few sites in the western part of the TP, it is possible to estimate that there is a strong warming trend in the northwestern TP, but a weak warming trend in the southwestern TP. Figure 7 shows statistics of the monthly temperatures averaged for the 78 stations on the TP for the three most recent decades. In comparison with the 1960s, the 1980s monthly mean temperatures increase by nearly 1°C in the winter half year (October–March), but do not

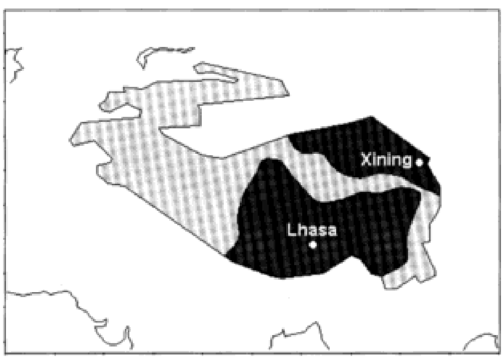

Figure 5. Schematic diagram of correlations of the annual mean temperature anomalies between two representative stations and the others on the TP during 1961–1990. The densely shaded region in which the Xining (Lhasa) is located corresponds to an area of the correlation greater than 0.6 between the temperature anomalies in Xining (Lhasa) and those from the other stations

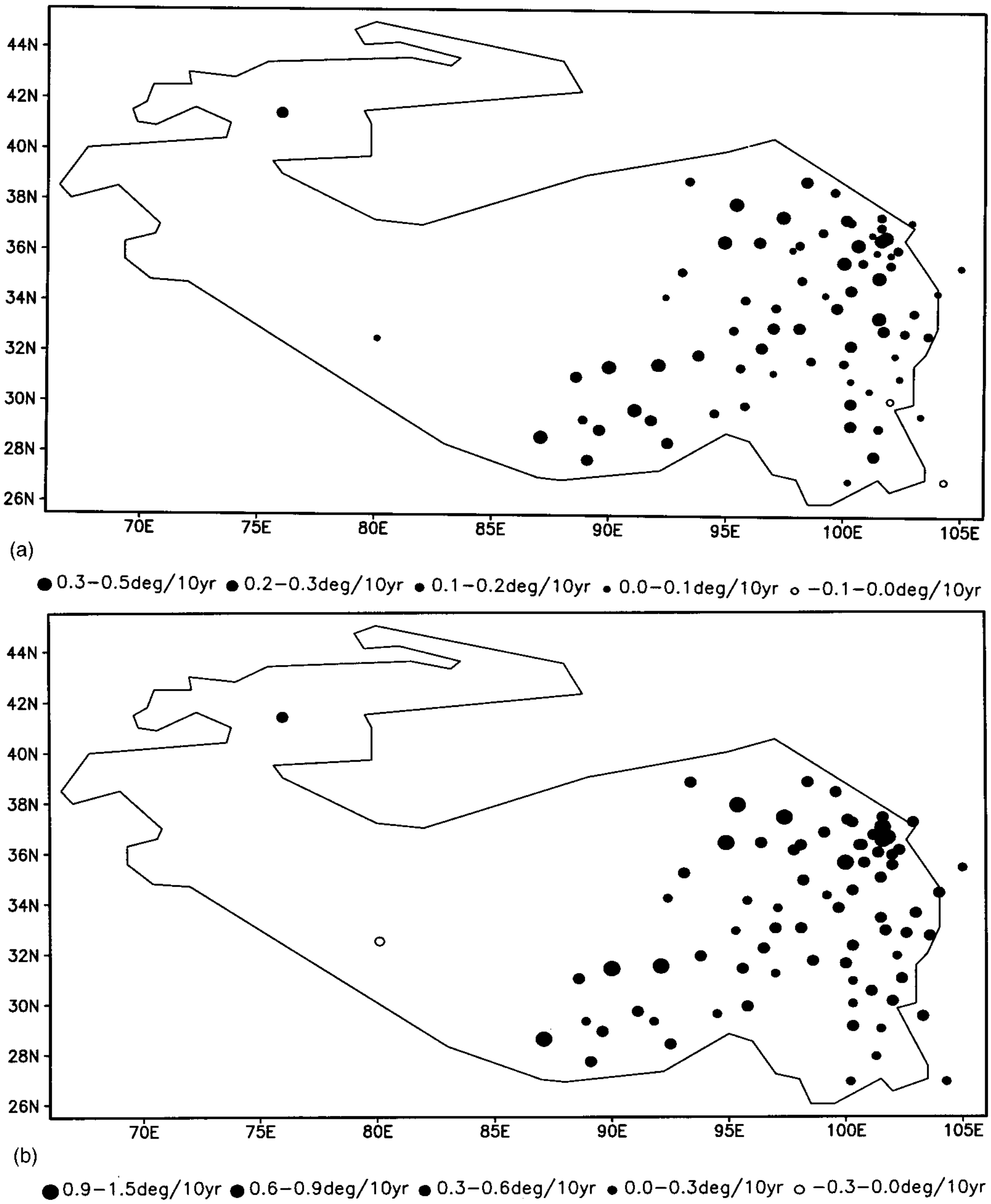

Figure 6. Surface temperature anomaly trends (1961–1990) in the TP for (a) annual and (b) winter averages

obviously change in the summer half year (April–September). Thus, the TP, as a whole, has undergone recent warming, especially in the winter half year.

In order to make the most of as many records as are available from the TP, all records from the 97 TP stations are employed to obtain a TP-wide temporal evolution for seasonal and annual average (simple arithmetic average of all stations) temperature anomalies from 1955 to 1996 (Figure 8). This figure shows intense warming trends for autumn (September–November), winter (December–February) and annual average temperature, all of which are significant at the 99% level, but shows weak trends for spring (March–May) and summer (June–August). Although the winter trend is the most pronounced, with a maximum value of 0.32°C/decade, the winter temperature anomaly has the largest variability. The above

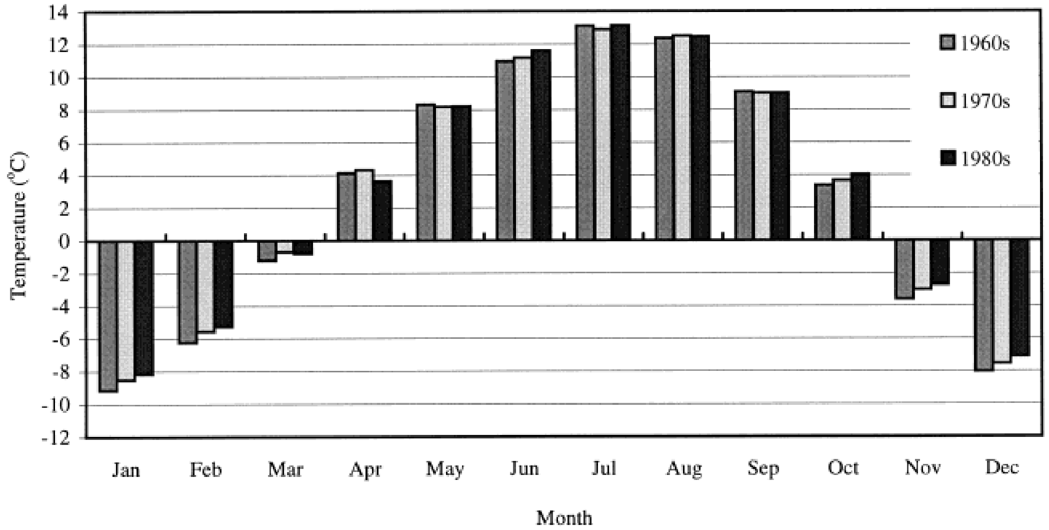

Figure 7. Histograms of monthly mean temperature averaged for 78 stations higher than 2000 m a.s.l. in the TP in the recent three decades

temperature changes for both periods (1961–1990 and 1955–1996) demonstrate the recent significant warming over the TP.

An index of the relative month station number (RMSN) of the MTA is used to check the change of the temperature variability. The RMSN is defined as the ratio of the number of stations with MTA exceeding a certain threshold value to the total number of stations with monthly observational records per decade. Table II lists RMSNs for six threshold (± 0, $\pm 1\sigma$ and $\pm 2\sigma$, where σ represents the S.D. of temperature anomalies at a site) excesses in the last four decades. The most striking result in Table II is that the RMSNs increase with time in the case of MTA > 0, $> 1\sigma$ or $> 2\sigma$, but decrease for MTA < 0, $< -1\sigma$ or $< -2\sigma$. To take the cases of MTA > 0, $> 1\sigma$ and $> 2\sigma$, for example, the RMSNs in 1956–1965 are 48.8, 14.2 and 2.2%, respectively, as against the values 62.8%, 26.0 and 6.6 for the period 1986–1995. No clear change in the temperature variability is found. For instance, the sums of RMSNs of temperature anomalies $> 1\sigma$ and $< -1\sigma$ do not show significant differences between the four decades.

3.3. The elevational dependency of the climatic warming trends in the TP and its surrounding areas

To complement the work of Beniston and Rebetez (1996) and Diaz and Bradley (1997), the elevational dependency of the recent climatic warming over the TP was examined. The 178 stations on the TP and its surrounding areas, as shown in Figure 2, are located at every elevation from 0 to 5000 m a.s.l. and have different temperature trends. Figure 9 displays AMST anomaly trends categorized according to 24 elevation ranks of the 178 stations for 1961–1990. It can be seen that there exists a clear tendency of the surface temperature trends to increase generally as the site elevation rises. For example, there are eight, four and six stations at 600–800 m, 2400–2600 m and 4200–4400 m a.s.l. or at approximately 700 m, 2500 m and 4300 m a.s.l., on average, corresponding to mean trends of about 0.05, 0.15 and 0.25°C/decade, respectively. The surface temperature for cold seasons shows the same trends (not shown). This elevational dependency in the TP is similar to that found in the Swiss Alps (Beniston and Rebetez, 1996), except that monthly mean rather than minimum temperature data were used in the present paper. The altitudinal warming signal is of great interest for understanding mountain environmental variations during global climate change.

4. DISCUSSION AND CONCLUSIONS

In this paper, emphasis was placed on the surface temperature changes during the last decades in a particular high-elevation region, the TP. The time series from a few limited records with a longer span demonstrate

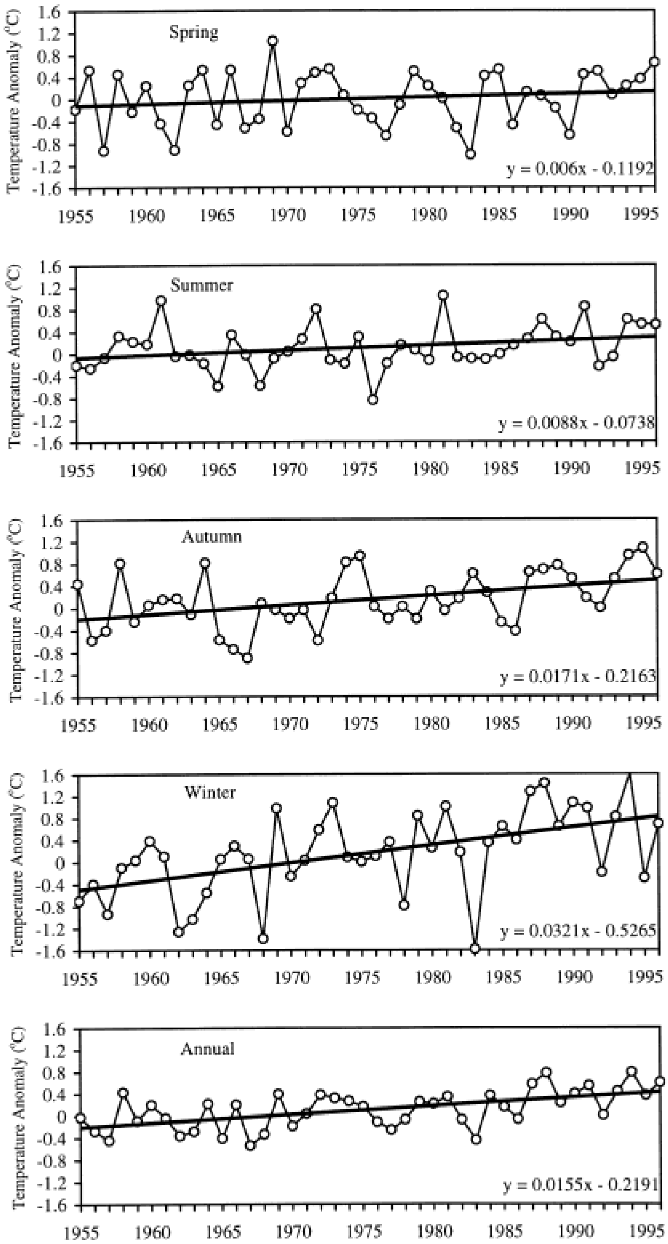

Figure 8. Seasonal and annual averaged time series of mean surface temperature anomalies in the TP from 1955 to 1996 for spring, summer, autumn, winter and annual from the top to the bottom. The thick lines indicate the least-square linear treads

Table II. RMSN of MTA for six threshold values in the last four decades (%)

MTA	>0	<0	$>1\sigma$	$<-1\sigma$	$>2\sigma$	$<-2\sigma$
1956–1965	48.8	51.0	14.2	17.6	2.2	4.3
1966–1975	53.1	46.7	15.8	12.3	2.8	2.3
1976–1985	52.3	47.6	16.2	13.8	3.5	2.8
1986–1995	62.8	37.0	26.0	9.8	6.6	1.8

σ denotes the S.D. See the text for the definition of RMSN.

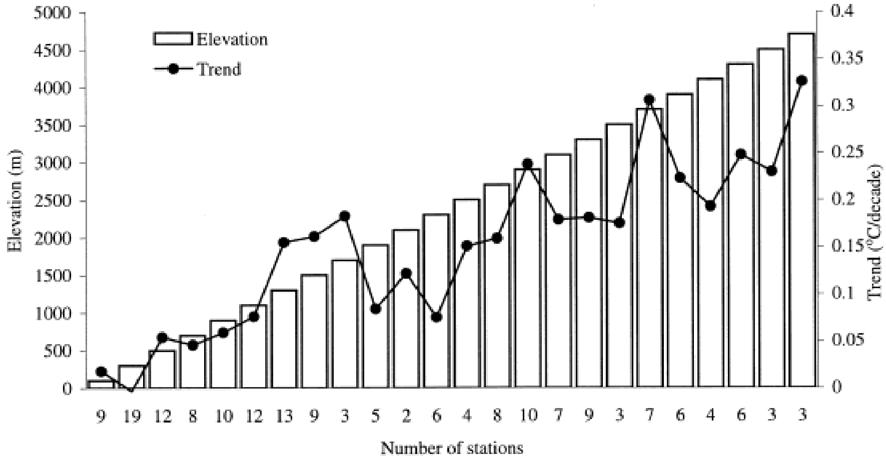

Figure 9. AMST anomaly trends for 1961–1990 categorized according to the 24 elevation ranks of the 178 stations in the TP and its surrounding areas

that the temperature variation over the TP during the last 100 years shows substantial fluctuations and appears to be similar to that in the Northern Hemisphere, but with a larger magnitude of change and at an earlier time. A statistically significant warming trend over the TP since the mid-1950s has been detected, especially in cold seasons, although there does not seem to be an obvious change in the temperature variability. The increases in the linear rates of the all-plateau temperature during 1955–1996 are about 0.16°C/decade for the annual mean and 0.32°C/decade for the winter mean, which exceed those for the Northern Hemisphere and the same latitudinal zone for the same period. Recent climatic warming in different parts of the TP is not completely the same in form. There is a strong upward trend in the central, eastern and northwestern TP, although recent warming in the central and eastern TP did not reach the level of warmth in the 1940s until the late 1990s, while in the southwestern TP there is only a weak warming trend. Besides, there is also a tendency for the warming trends to increase with elevation in the TP and its surrounding areas.

It seems that the recent warming over the TP began early and appeared intense with respect to global warming compared with its neighbouring areas or the same latitudinal zone. In this sense, the TP can be regarded as one of the most sensitive areas to global change (Liu and Zhang, 1998). Consequently, temperature changes over high-elevation regions such as the TP could be used as a detection tool or as a monitor for global warming (Giorgi *et al*., 1997). As a matter of fact, the high sensitivity of the TP climate change to global change has been confirmed to a certain extent by some palaeoclimate investigations. By analysing GCM-simulated January and July general circulation and climate changes in the TP and the surrounding area for seven periods in the last 18000 years (Kutzbach and Guetter, 1986), Liu and Wei (1995) found that the TP climate had a strong response to the variation of insolation induced by the Earth's changed orbital parameters. For example, it was cooler for the mid-Holocene in January than at present but warmer in July, with centres of the temperature differences just over the TP. These characteristics are in agreement with climatic changes reconstructed from geological evidence surrounding the TP (e.g. Houghton *et al*., 1990, p. 205; Liu and Wei, 1995).

Although the TP surface temperature trend was analysed, its cause has not been referred to in this paper. From current climate model simulations with enhanced greenhouse gases (Manabe *et al*., 1991; Cubasch *et al*., 1992; Murphy and Mitchell, 1995; Houghton *et al*., 1996), the increase in the TP surface temperature is a major characteristic of all models. This implies that the TP warming could be attributed to human activities related to the increase in atmosphere greenhouse gases. In this study, simulations of the doubling CO_2 concentration experiments for the TP area from the Geophysical Fluid Dynamics Laboratory (GFDL) (Wetherald and Manabe, 1988; Mitchell *et al*., 1990), the Canadian Climate Center (CCC) (Boer *et al*., 1992) and the UK Meteorological Office (UKMO) (Murphy, 1995; Murphy and Mitchell, 1995) models were analysed. These models have relatively coarse spatial resolutions, with about

Table III. Surface air temperature differences (°C) between the doubling CO_2 concentration experiment and the $1 \times CO_2$ experiment from GFDL, CCC and UKMO climate models averaged for various elevation ranges in the Tibetan plateau (22°–46°N, 70°–110°E)

Elevation (m)	GFDL	CCC	UKMO
0–6000	3.58 (121)	5.29 (91)	3.52 (120)
0–500	3.22 (19)	3.34 (14)	3.15 (22)
500–1000	3.60 (12)	5.31 (10)	3.57 (15)
1000–1500	4.04 (23)	6.42 (22)	3.52 (22)
1500–2000	4.00 (14)	6.13 (14)	4.07 (14)
2000–2500	3.56 (13)	4.41 (7)	3.42 (13)
2500–3000	3.19 (9)	4.81 (8)	3.70 (2)
3000–3500	3.39 (5)	5.39 (5)	3.58 (9)
3500–4000	3.50 (7)	4.58 (1)	3.34 (4)
4000–4500	3.44 (8)	5.08 (4)	3.48 (7)
4500–5000	3.36 (6)	5.55 (6)	3.69 (10)
5000–5500	3.32 (3)	— (0)	3.49 (2)
5500–6000	2.81 (2)	— (0)	— (0)

Numbers in parentheses indicate the model grid numbers included in every elevation range.

2.25° latitude × 3.75° longitude for the GFDL, 3.75° latitude × 3.75° longitude for the CCC and 2.5° latitude × 3.75° longitude for the UKMO. The doubling CO_2 experiments with the GFDL and the CCC models are an equilibrium response but the experiment with the UKMO model is a transient response. See related references for details. From examining the model outputs for the TP, the authors could not find the elevational dependency of climatic warming as represented in the observational records (see Table III). This inconsistency may reflect imperfection or defects in the current climate models. As is stated in Houghton *et al*. (1990), the reliability of GCM prediction is still low on a regional scale owing partly to the coarse spatial resolution of models and partly to the inadequate treatment of physical processes, especially land surface processes in complex topographic areas like the TP. In addition, on a regional scale, there are pronounced climate variations associated with natural climatic variability. As for the cause of a more pronounced warming over the TP than its surrounding areas, the authors believe that this is the result of snow-albedo feedback on the TP, as was also simulated over the Alpine region (Giorgi *et al*., 1997). Moreover, several model experiments (Oglesby, 1990; Phillipps and Held, 1994; Dong and Valdes, 1995) demonstrated that the TP is one of the most sensitive areas of snow feedback on Earth. Therefore, it is a reasonable deduction that snow-albedo feedback may be mainly responsible for the excessive warming over high-elevation areas. However, to clarify the cause of the TP regional climate change, detailed models and diagnostic studies are needed.

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