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Variability of temperature in the Tibetan Plateau based on homogenized surface stations and reanalysis data

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ABSTRACT: The Tibetan Plateau (TP) with an average elevation of over 4000 m a.s.l. is the world's highest and most extensive highland. The scarcity of climatic observations limits our understanding of surface air temperature change in the region. Thus, we compare temperatures and their trends from 71 homogenized surface stations (with elevations above 2000 m a.s.l.) with National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (NCEP/NCAR hereafter) and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40 hereafter) in the eastern and central TP during 1961–2004. For current climatology, ERA-40 is more similar to the surface stations than NCEP/NCAR. Compared with surface stations, both NCEP/NCAR and ERA-40 reanalyses have cold biases, which are mainly a result of differences in topographical height, and station aspect and slope. Warming trends at the surface stations are on average stronger than in both reanalyses, but ERA-40 captures the surface warming more clearly than NCEP/NCAR on an annual and seasonal basis. Since ERA-40 more closely represents the surface temperatures and their trends in the central and eastern TP, ERA-40 predictions are selected to examine change in the western TP where there are few surface stations. NCEP/NCAR, on the other hand, is more representative of free air temperature conditions. The 'observation minus reanalysis' (OMR) method can be used to estimate the impact of surface changes on climate by computing the difference between surface observations and NCEP/NCAR (which only contains the forcing influencing the assimilated atmospheric trends). The OMR trend is significantly increasing but the extent to which the changes in local environment are responsible needs further study. Copyright © 2012 Royal Meteorological Society

KEY WORDS warming trend; elevation dependency; Tibetan Plateau; reanalysis

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1. Introduction

The Tibetan Plateau (TP) with an average elevation of over 4000 m a.s.l. and an area of approximately 2.5×10^6 km^2 is the highest and most extensive highland in the world. The TP exerts profound influences not only on the local climate and environment but also on the global atmospheric circulation through its thermal and mechanical forcing (Yeh and Gao, 1979; Duan and Wu, 2005). The TP has the largest area of snow and ice in the mid-latitude regions and has therefore been called the 'Asian water tower' (Yeh and Gao, 1979), while it gets less attention than the Arctic or Antarctic. In the context of global warming, the air temperature in the TP is increasing (Liu and Chen, 2000), with an accelerating melt of glaciers (such as Tian *et al*., 2006; Kang *et al*., 2007) corroborating that this. In the past half-century, 82% of the plateau's glaciers have retreated and 10% of its permafrost has degraded (Qiu, 2008). These changes are expected to continue, changing the water supply for billions of people and probably altering the atmospheric circulation (Qiu, 2008). Being a crucial water resource for most of the Asian continent (Barnett *et al*., 2005; Zhang, 2007), the variability of water on the plateau is of critical importance. Zhu *et al*. (2011) found that dryness/wetness in the TP is associated with the dominance of a Scandinavian or Mediterranean/East Asia wave train, respectively.

Owing to both terrain complexity and extreme environmental conditions, most surface observational stations are situated in the lower parts of the eastern and central TP, often in valley locations. Temperature in the TP has been widely studied (Liu and Chen, 2000; Wang *et al*., 2008; Xu *et al*., 2008; Bothe *et al*., 2010). Warming in the TP is significant and can influence the atmospheric circulation at a large scale (Wang *et al*., 2008). Previous studies concerning temperature variability based on raw observations, such as Liu and Chen (2000) and You *et al*.

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(2008a, 2008b), are spatially biased with little coverage of the western TP and higher elevations (>4000 m). A reanalysis in theory overcomes this problem, but to be used to assess widespread climate change it requires validation against real observations where both exist. Hence temperatures retrieved from two reanalysis products are investigated and compared with surface observations in this study. Reanalyses include the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (NCEP/NCAR hereafter) (Kalnay *et al*., 1996) and the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40 hereafter) (Uppala *et al*., 2005). Frauenfeld *et al*. (2005) have compared ERA-40 with the raw observational data in the TP and Ma *et al*. (2008) have investigated homogenized surface observations with reanalyses over the whole China. Despite these studies, detailed comparisons between reanalyses data and homogenized observations are limited in the TP where topography is complex. Previous work (You *et al*., 2010a; 2010b) has analysed warming trends from both reanalyses and surface data, examining the relationships between trend magnitudes, elevation and atmospheric circulation changes. This study uses similar datasets but includes more detailed examination of local-scale and short-term differences between them. In particular, a comparison of instantaneous climatology, the modeling of bias between observations and reanalyses, and gaining an understanding of what controls the contrasts between station and reanalysis-based trends can extend understanding of climate variability in this important region.

After data sources and methods are outlined (Section 2), the current temperature climatology of the TP from surface observations and both reanalyses is compared in Section 3.1 and the differences in trends are described in Section 3.2. Based on this, ERA-40 is used to examine trend patterns in the western TP where surface data are virtually non-existent (Section 4.1), and NCEP/NCAR is selected to contrast surface and free-air warming patterns in the rest of the region (Section 4.2 and 4.3). The predictability of the differences between the datasets and the wider implications of our work are discussed in Section 5.

2. Datasets and methods

A brief description of the near surface air temperature dataset is presented. Those data provide the basis for the analysis of TP temperature variability and its relation to surface elevation.

2.1. Surface air temperature homogenized dataset

The surface air temperature homogenized dataset is the China Homogenized Historical Temperature Dataset (1951–2004 period) (version 1.0), which was released in 2006 by the National Meteorological Information Center, China Meteorological Administration (NMIC/CMA). The data have been homogenized to minimize the effect of station relocations. Discontinuities have been adjusted (Li *et al*., 2004a; 2004b). Detailed descriptions of data quality control and homogenization procedure are available in the above papers.

The TP in China ranges from approximately 26° to 40 °N and from 73° to 105 °E (Zhang *et al*., 2002), and there are 156 stations in the original dataset within this area. As coverage in the western TP is extremely patchy, the 71 stations above 2000 m a.s.l. are selected in the eastern and central TP with complete data for 1961–2004 for comparison with the reanalysis products (Figure 1). More details regarding station selection are described in our previous papers (You *et al*., 2008a, 2008b).

2.2. Reanalysis datasets

Monthly mean 2 m surface air temperatures for NCEP/NCAR were downloaded from the National Oceanic and Atmospheric Administration – Cooperative Institute for Research in Environmental Sciences (NOAA-CIRES) Climate Diagnostics Centre (http://www.cdc.noaa.gov/). The NCEP/NCAR reanalysis is a continually-updated gridded dataset representing the state of the Earth's atmosphere, incorporating observations (such as ship, rawinsonde, pibal, aircraft, satellite, and other data) with numerical weather prediction model output, quality controlling and assimilating these data with a data assimilation system. This dataset covers January 1948 to the present with a spatial resolution of 2.5° × 2.5° (Kalnay *et al*., 1996) and sub-daily temporal resolution. The NCEP/NCAR 2 m air temperature is a standard modelled field, which represents a linear interpolation between the surface skin temperature and free-air temperature at the lowest model sigma level (Kalnay *et al*., 1996).

Monthly mean 2 m surface air temperature ERA-40 reanalysis data were obtained from the European Centre for Medium-Range Weather Forecasts website (http://www.ecmwf.int/). ERA-40 temperatures are available from September 1957 to August 2002 with a spatial resolution of 2.5° × 2.5° (Uppala *et al*., 2005). The data include satellite-borne instruments, observations from aircraft, ocean-buoys, radiosonde and other surface platforms, but with a declining number of radiosonde ascents since the late 1980s. ERA-40 2 m air temperature is a post-processing product and is obtained by interpolation between the lowest model level and the surface (Uppala *et al*., 2005). ERA-40 is the most recent comprehensive reanalysis and the first to provide an alternative to the earlier NCEP/NCAR reanalysis for the years before 1979 (Bengtsson *et al*., 2004). Periods of 1961–2004 and 1961–2001 were selected from NCEP/NCAR and ERA-40 data, respectively.

2.3. Spatial comparision of datasets

To compare with surface stations, two slightly different approaches were investigated to identify the appropriate reanalysis value for comparison with the observed values. One is to compare the surface stations with reanalyses grid points with at least one surface station in the

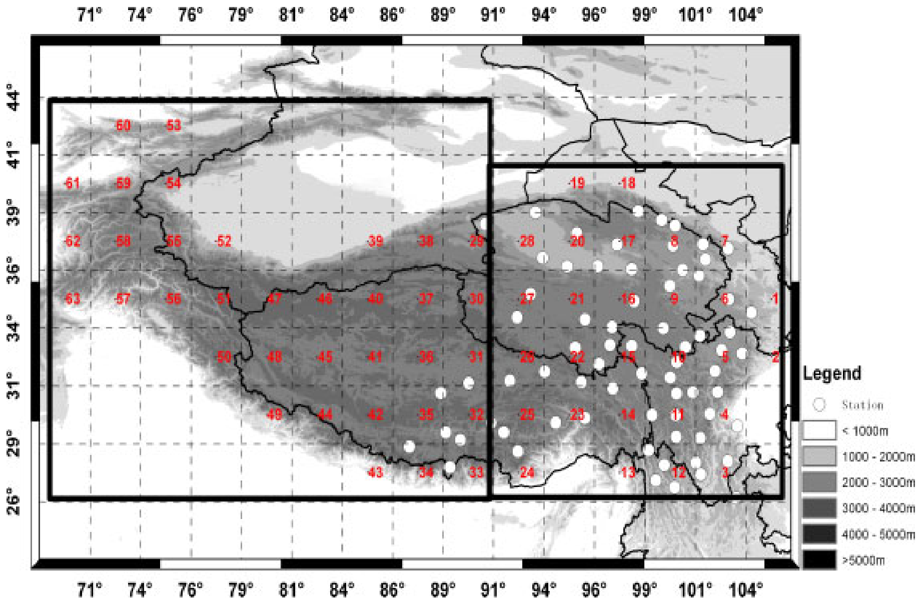

Figure 1. Topography of Tibetan Plateau (labelled 1–63). The white dots represent the 71 stations and the red numbers show the reanalysis grid points in the whole TP. The whole TP was subdivided into two parts by the rectangle: the eastern TP (labelled 1–28) and western TP (labelled 29–63).

immediate vicinity. This includes 29 grid points (labelled 1–35 in Figure 1 with the exception of 2, 13, 14, 18, 19 and 30). Surface stations are assigned to their nearest grid point (based on distance) and data from all the relevant stations are averaged for a given grid point. This average is not weighted by distance or corrected according to elevation, which means that the differences in elevation and/or location distribution between the stations and the grid point may be important (see Section 4). The other is to compare surface stations with reanalysis point obtained from the weighted average of the reanalysis values of the four grid boxes whose centers lie closest to the station. The average of the four grid boxes is obtained using the inverse distance weighted average (Mooney *et al.*, 2011). Both methods shows the grid points from reanalysis have higher correlation coefficients with the observations, and the bias between two methods are very lower, suggesting both methods have no significant influence on the results (not shown). Thus, the first and simple comparison method is adopted for subsequent study.

2.4. Surface elevation data and trend calculations

Surface elevations come from four datasets: (1) elevation of each surface station provided by the NMI/CMA, (2) NCEP/NCAR reanalysis model topography (available from website http://www.cdc.noaa.gov/), (3) ERA-40 reanalysis model topography (available from http://www.ecmwf.int/), and (4) GTOPO30 digital elevation data (available from http://eros.usgs.gov).

The Mann-Kendall test for a trend and Sen's slope estimates were used to detect and estimate trends in annual and seasonal (winter: DJF; spring: MAM; summer: JJA; autumn: SON) mean temperature series (Sen, 1968). A trend is considered to be statistically significant if it is significant at the 5% level ($P < 0.5$). The formula is as follows:

The Mann–Kendall statistic S is calculated as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \cdots sgn(x_j - x_k)$$

$$= \begin{Bmatrix} +1 & \text{if} & x_j - x_k > 0 \\ 0 & \text{if} & x_j - x_k = 0 \\ 1 & \text{if} & x_j - x_k < 0 \end{Bmatrix}$$

The variance for the statistic S is defined by:

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)}{18}$$

The test statistic Z is estimated as:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{VAR}(S)}} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{VAR}(S)}} & \text{if} \quad S < 0 \end{cases}$$

In which Z follows a standard normal distribution, If $|Z| > Z_{1-\alpha/2}$, where α denotes the significant level, then the trend is significant. Sen's method is used to estimate the Kendall slope, and it is defined as the median over all combinations of record pairs for the whole dataset. It is given as follows:

$$Q = \mathrm{Median}\left(\frac{x_j - x_k}{j - k}\right); i = 1, \ldots, N.$$

The Mann-Kendall test is a nonparametric method without considering distribution of the observational data, and has been widely used to perform trends in climate variables, such as temperature (Xu *et al*., 2008), precipitation (Liu *et al*., 2011a, 2011b) and extreme climate series (You *et al*., 2008a, 2008b). Meanwhile, the scientific communities of hydrology and water resources prefer the Mann-Kendall test. For example, the method was applied to analyse the river discharge during 1956–2000 (Cao *et al*., 2006), pan evaporation and vapour pressure in the TP (Liu *et al*., 2011a, 2011b).

3. Comparing TP near surface air temperature datasets: means and trends

Climatological means and half-century trends of the temperature datasets are analysed and compared with related studies before discussing the results.

3.1. Current climatology: surface stations and reanalysis data

Figure 2 shows the relationship between mean seasonal (MAM, JJA, SON, DJF) temperatures at each individual surface station and those from the nearest NCEP/NCAR and ERA-40 reanalysis grid point during 1961–2004. Subpanels give the seasonal breakdown. Each grid point is included only once. Descriptive statistics summarizing relationships between surface temperature and reanalysis temperatures are listed in Table I.

NCEP/NCAR shows a fairly good spatial correlation with the surface stations (a correlation of 0.58 on an annual basis) (You *et al*., 2010a). The strongest correlation occurs in winter ($R = 0.69$) (Table I). In most cases and seasons, the values of NCEP/NCAR are located to the right of the diagonal line of equality in Figure 2, meaning that NCEP/NCAR has a cold bias (Figure 1). ERA-40, on the other hand, shows a less systematic bias, revealing that the difference between stations and ERA-40 is smaller (Figure 1). Correlations are also usually slightly higher than with NCEP/NCAR. Like NCEP/NCAR, the weakest correlation occurs in summer with a value of 0.47 and the strongest in winter (0.77) (Table I). This is probably related to the enhanced latitudinal and elevational gradients in temperature across the domain in winter, making spatial patterns easier to model.

Compared with NCEP/NCAR, ERA-40 has higher correlation coefficients and lower standard deviations (Table I), indicating that it is more consistently closer to surface observations. This finding is consistent with other studies (Frauenfeld *et al*., 2005; Zhao and Fu, 2006; Ma *et al*., 2008; Zhao *et al*., 2008). This capability to produce a more realistic analysis of surface temperatures stems from improvements in observing systems, techniques of data assimilation, and the realism of the assimilating model (Simmons *et al*., 2004). ERA-40 has benefited from many of these more than NCEP/NCAR has. In

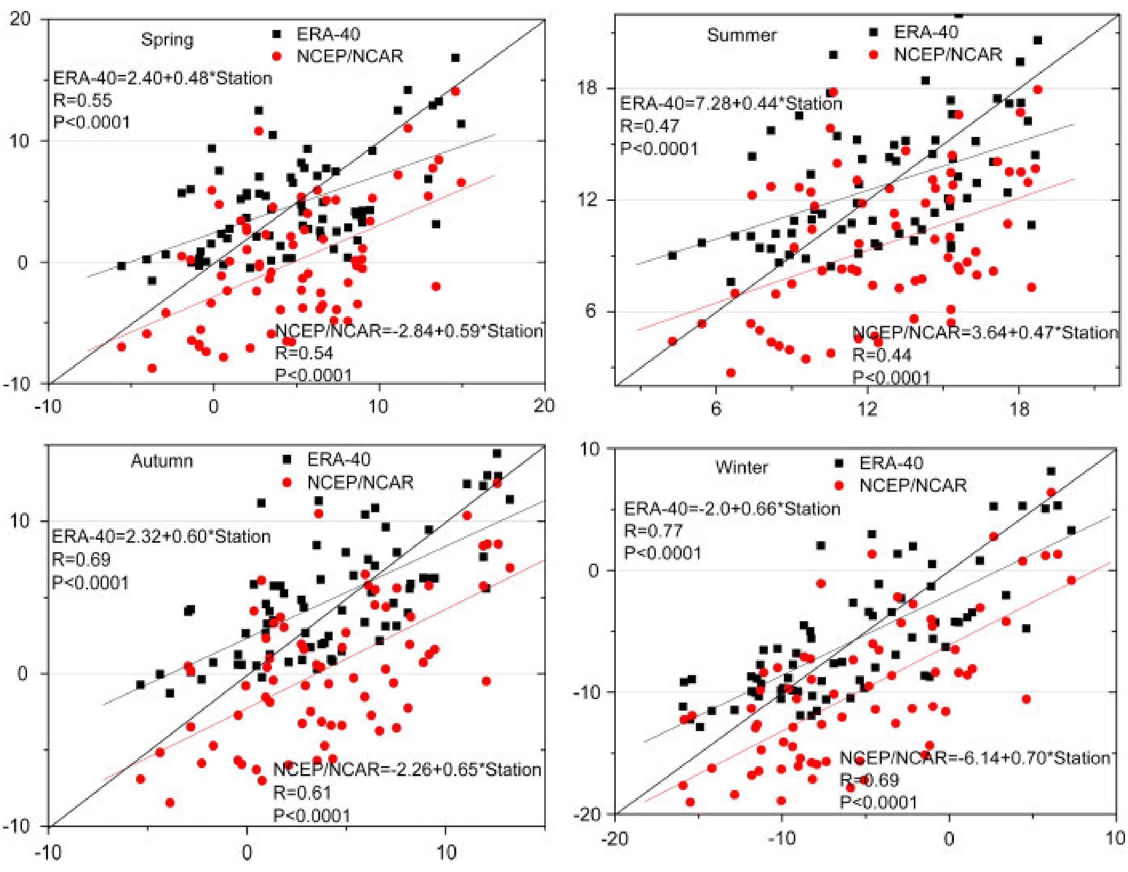

Figure 2. Comparison of temperature of surface stations during 1961–2004 with temperature from NCEP/NCAR and ERA-40 reanalysis data on a seasonal basis. The straight lines are linear fits, and R stands for correlation coefficients and P for statistical significance.

Table I. Descriptive statistics of relationships between surface temperature of stations and that from reanalysis on an annual and seasonal basis. The study period periods for stations, NCEP/NCAR and ERA-40 are during 1961–2004, 1961–2004 and 1961–2001. The linear fits formula (Reanalysis $= a + b^*$ Stations) is used. R stands for correlation coefficients and P for statistical significance.

		a	b	Standard deviation	R	P value
NCEP/NCAR	Annual	−2.50	0.61	3.98	0.58	$<$0.0001
	Spring	−2.84	0.59	4.29	0.54	$<$0.0001
	Summer	3.65	0.47	3.50	0.44	$<$0.0001
	Autumn	−2.26	0.65	3.81	0.61	$<$0.0001
	Winter	−6.14	0.70	4.39	0.60	$<$0.0001
ERA-40	Annual	3.12	0.54	2.83	0.66	$<$0.0001
	Spring	2.40	0.48	3.42	0.55	$<$0.0001
	Summer	7.28	0.44	2.97	0.47	$<$0.0001
	Autumn	2.32	0.60	2.83	0.69	$<$0.0001
	Winter	−2.0	0.66	3.31	0.77	$<$0.0001

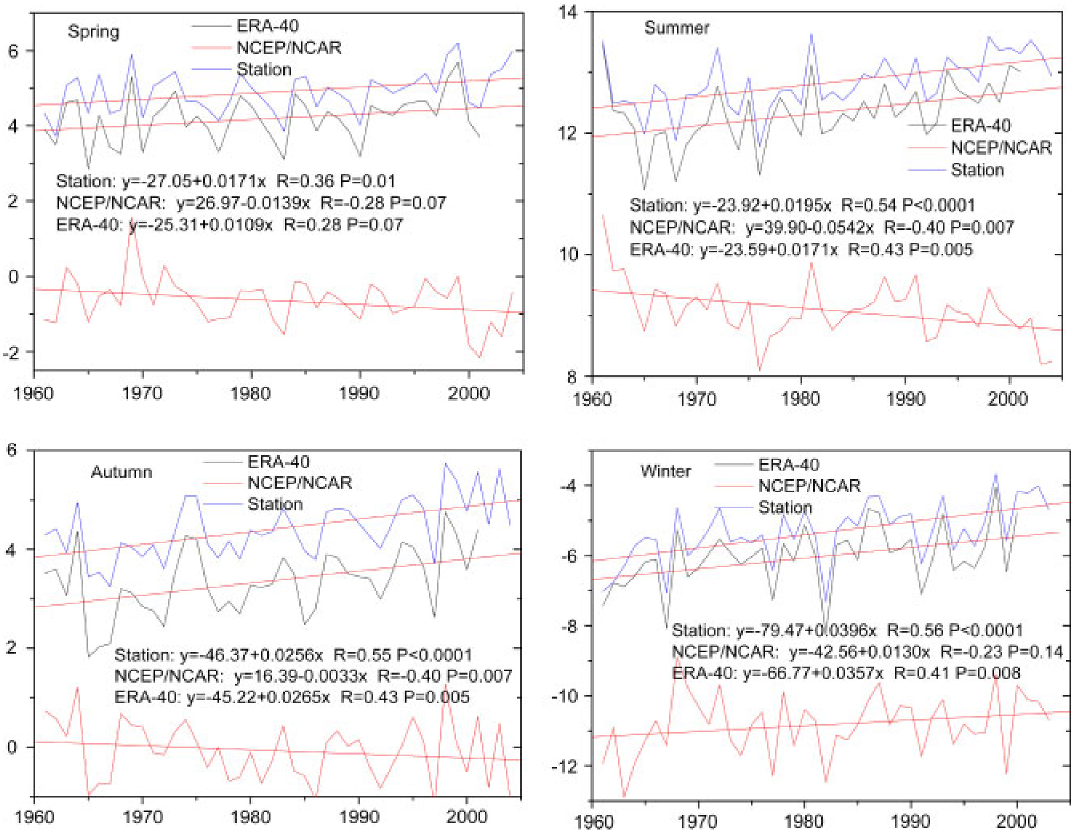

Figure 3. Average regional trends for surface stations, NCEP/NCAR and ERA-40 during 1961–2004 on a seasonal basis. Other is same as Figure 2.

particular, ERA-40 uses surface synoptic observations but NCEP/NCAR does not and is more dependent on free-air forcing (Simmons *et al*., 2004).

3.2. Temperature trends from surface stations and reanalysis data

Figure 3 shows regional temperature trends (based on calculating the unweighted mean temperature of all stations or grid points for each year solely for the geographical area of overlap between surface stations and reanalysis) for surface stations, NCEP/NCAR and ERA-40 during 1961–2001 on a seasonal basis. The surface stations show a mean regional temperature trend of 0.25 °C/decade (as in You *et al*., 2010a). Stations in the northwestern, southwestern and southeastern TP have the largest trends, in agreement with previous analysis of temperature extremes (You *et al*., 2008a). Although the regional trend is dominated by warmer winter (0.40 °C/decade) and autumn (0.26 °C/decade), consistent with the previous study by Liu and Chen (2000) and Ren *et al*. (2005) warming occurs in all seasons. Rising

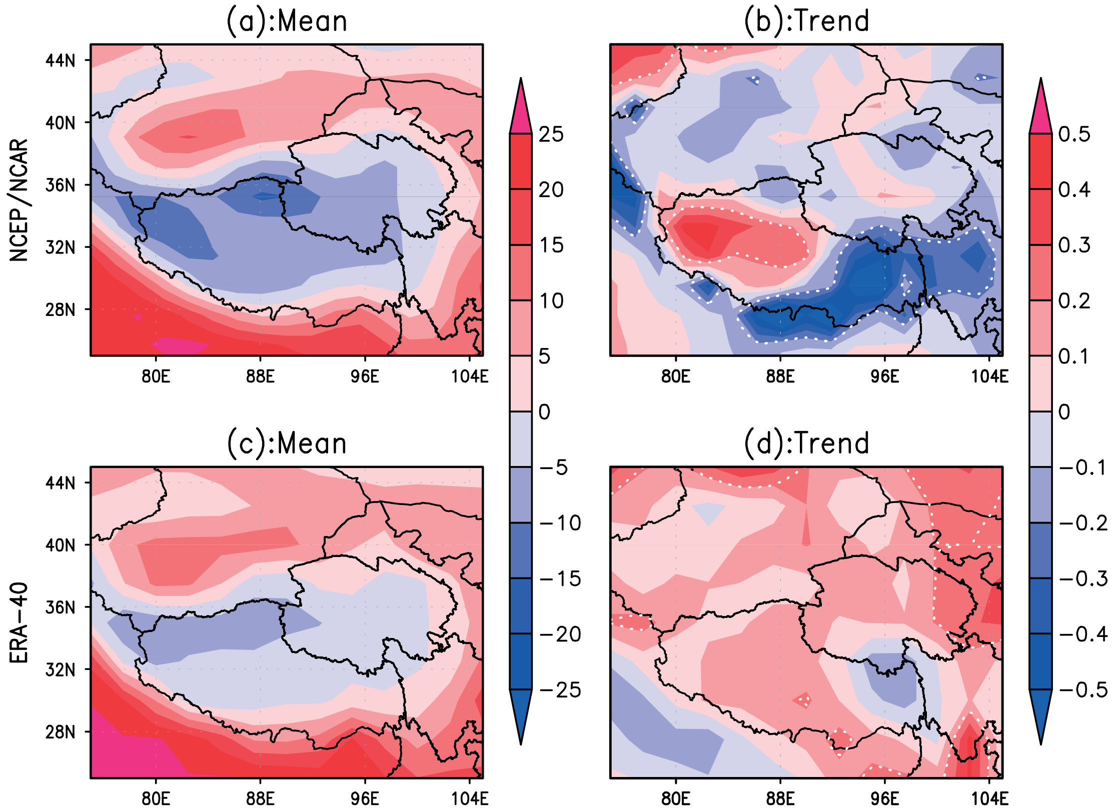

Figure 4. Spatial distribution of annual mean temperature (left plot, unit:° C/decade) and temperature trend magnitudes (right plot, unit:° C/decade) based on NCEP/NCAR and ERA-40 during 1961–2004 and 1961–2001, respectively.

temperatures are accompanied by abundant evidence of dramatic glacier shrinkage in the TP (Zhang, 2007).

For NCEP/NCAR, the regional annual temperature trend (unweighted mean of all grid points) shows a slight decrease (−0.02 °C/decade) and many grid points in the southeastern TP have decreasing trends (Figure 4). A large cooling trend also occurred in the southwestern region of the grid, mainly in northern India (Figure 4). On a seasonal basis, the regional temperature trend is positive only in winter (0.13 °C/decade) and cooling occurs in spring, summer and autumn. The cooling trend from NCEP/NCAR in the TP is quite different from other regions in the world (Simmons *et al*., 2004; Ma *et al*., 2008).

For ERA-40, the regional annual temperature trend is 0.22 °C/decade, and it is strongest in winter (0.36 °C/decade) and autumn (0.27 °C/decade). Most grid points in the southwestern TP have large increasing trends, but there is a cooling trend outside the plateau region in northern India, centering on 73 °E and 28°N (Figure 4). It is therefore possible that both NCEP/NCAR and ERA40 are inaccurately describing the climate change in that region. If the cooling is real, it may be related to the anthropogenic emission of air pollutants with an increase in population and industrialization in the region. Air pollutants from this region lead to a brownish haze, reducing the surface solar insolation and cooling the surface (Krishnanl and Ramanathan, 2002). This aspect definitely needs further study.

4. Discussions

4.1. Can reanalysis be applied to the TP?

Temperatures in the eastern TP are higher than that in the western TP because of the lower elevations (Frauenfeld *et al*., 2005). Owing to the relatively higher terrain and inaccessibility, long-term observational data in the western TP are lacking. Thus, other methods have been used to examine climate change in this region. Rangwala *et al*. (2010) used simulated output from two model experiments (SRES A1B and control) and showed that the western TP had relatively greater warming than the eastern TP during the late 20th and the 21st centuries, although the comparisons between warming rates varied significantly with the observation period (Rangwala *et al*., 2009).

There is scarce surface observational data in the western TP. Since ERA-40 is a good representation of surface trends in the eastern TP, assuming this is the case in the western TP we can extend our examination of ERA-40 temperature trends to 63 grid points to capture the larger area (Figure 1). Figure 5 shows the regional temperature trend for the whole TP (63 grid points), eastern TP (29) and western TP (34) based on ERA-40 during 1961–2001. Mean temperature trend magnitudes and average air temperatures during the same period are listed in Table II. The mean temperatures in the western TP are lower than in the east because of higher elevations.

Table II. Temperature trend magnitudes and average air temperature for the whole TP, eastern TP and western TP based on ERA-40 during 1961–2001 on an annual and seasonal basis. Bold values indicate trends with significance level higher than 95%. Units are degree per decade.

		Annual	Spring	Summer	Autumn	Winter
Trend magnitudes	Whole TP	3.44	4.06	13.28	3.52	−7.11
	Eastern TP	4.33	5.17	13.77	4.13	−5.77
	Western TP	2.73	3.17	12.90	3.03	−8.18
Average air temperature	Whole TP	**0.14**	0.04	0.04	**0.19**	**0.29**
	Eastern TP	**0.21**	0.12	**0.19**	**0.27**	**0.31**
	Western TP	0.09	0.01	−0.08	**0.14**	**0.30**

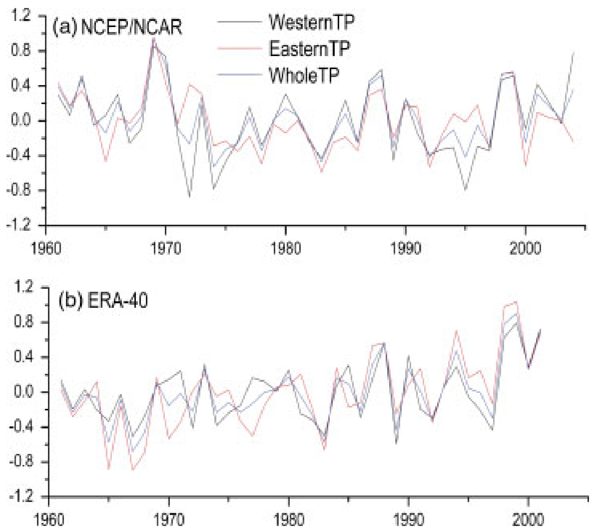

Figure 5. Average annual regional trends for the whole TP, eastern TP and western TP based on NCEP/NCAR (a) and ERA-40 (b) during 1961–2004 and 1961–2001, respectively.

Correlations between regional mean annual temperature for the whole TP, the eastern and western TP are 0.49 and 0.51, respectively. Figure 5 indicates that the variability of temperature based on ERA-40 is quite different in different regions. The regional air temperature for the whole TP is increasing, with a rate of 0.14 °C/decade, and trends are more prominent in winter and autumn (Table II). Although both the eastern and western TP show warming trends, especially in winter, the trends in the east appear to be larger (0.21 °C/decade) than in the west (0.09 °C/decade). This is inconsistent with model output results by Rangwala *et al*. (2010). It is notable that temperature trend assessment using reanalysis data is sometimes dangerous because of the changes in the amount and quality of assimilation data. For example, changes of data source can result in climatic jumps and produce spurious trends before and after the late 1970s because of different assimilation datasets (Frauenfeld *et al*., 2005).

There are two issues should be paid attention in the TP. One is the interpolating methods. The interpolating temperature from a coarse resolution into a finer resolution, can improve the results in the region with complex topography, but the interpolation method can also produce obvious bias between reanalysis and observation. The other is that the western TP has low density of stations, which need more multi-datasets such as remote sensing and field observation, to improve the scientific understanding. To summarize, the primary problem associated with climate analysis in the western TP is the lack of good horizontal resolution of historic climate records (Xu *et al*., 2008).

4.2. Can the 'observation minus analysis' method be used in the TP?

NCEP/NCAR clearly does not represent surface conditions well and is more representative of regional scale free atmosphere conditions. The 'observation minus reanalysis' (OMR) method calculated by the difference between observation and reanalysis, has been used with NCEP/NCAR to estimate the impact of surface properties (including urbanization and agricultural practices such as irrigation) on climate trends. Several studies therefore compute the trend in the difference between surface observations (which reflect all the sources of climate forcing, including surface effects) and NCEP/NCAR reanalysis (which only contains forcing influencing assimilated free-atmospheric trends) (Kalnay and Cai, 2003; Lim *et al*., 2005, 2008; Nunez *et al*., 2008). Pepin and Seidel (2005) take a similar approach to examine 'real' trends in surface/free-air temperature differences at mountain sites. Figure 6 shows the standardized anomaly of regional OMR for both NCEP/NCAR and ERA-40 on an annual and seasonal basis during 1961–2004. In general, seasonal trends of OMR for both reanalyses are similar to their annual trends. The OMR for ERA-40 shows a limited trend because ERA-40 uses surface air temperatures in the initialization of soil temperature and moisture, indicating that ERA-40 includes not only assimilated free atmospheric trends but also surface effects. In order to know whether NCEP/NCAR and ERA-40 are converging in describing the climatology and changes in the free atmosphere, the annual mean temperature differences between 1981–2001 and 1961–1980 at 850, 600, 400 and 200hPa are analysed (Figure 7), and the right and left plots are for NCEP/NCAR and ERA-40 reanalysis data respectively. It is clear that both the differences between NCEP/NCAR and ERA-40 are apparently larger at lower troposphere, and both reanalyses become more similar at upper tropospheric levels (400 and 200 hPa).

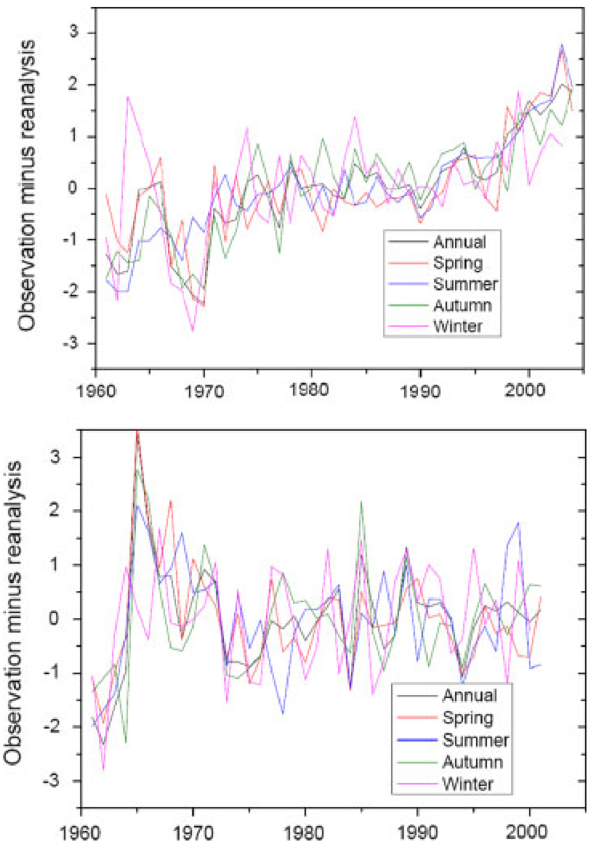

Figure 6. The anomaly of standard deviation for observation minus reanalysis (OMR) for NCEP/NCAR (top plot) and ERA-40 (bottom plot) during 1961–2004 and 1961–2001, respectively.

Since 1990, the OMR for NCEP/NCAR has increased dramatically, coinciding with rapid urbanization and dramatic economic growth in southeastern China (Zhou *et al*., 2004). The regional diurnal temperature range (DTR) for the surface component also exhibits a statistically decreasing trend at a rate of −0.20 °C/decade during the same period (You *et al*., 2008a). The positive OMR trend is likely therefore partly to be the result of extensive local and regional land use changes (Kalnay and Cai, 2003; Nunez *et al*., 2008), which have been reported in eastern China (Zhou *et al*., 2004). A recent analysis (Zhang *et al*., 2010) shows that urbanization-induced increase of annual mean surface air temperature in the lower parts of the TP during 1961–2004 reaches 0.06 °C/decade, accounting for about 23% of the overall warming recorded by the commonly used national observation stations. Thus, the regional surface mean temperature trend in the TP (0.25 °C/decade) probably includes the combined effects of urbanization and large-scale surface forcing. According to the China Compendium of Statistics (Department of Comprehensive Statistics of the National Bureau of Statistics, 2006), the total population during the 1990s doubled from that of the 1960s, and the total sown area increased by 50% between 1961 and 2004 for the Tibet Autonomous region as a whole (Figure 8). A general atmospheric circulation model (ECHAM5) also indicates that human-induced land use changes in the TP have had a significant impact on local and regional climate (Cui *et al*., 2006). Increasing OMR in all seasons from our analysis also strengthens the case for additional surface forcing on climate change in the TP.

4.3. Can the temperature differences between stations and reanalysis be modeled in the TP?

In summary, both the instantaneous climatology and pattern of temperature trends appear to be more similar to the surface stations when using ERA-40 rather than NCEP/NCAR. Further analysis has examined how the differences in temperatures can be explained by model topography. The complex elevated topography of the TP means that the differences in elevation between surface stations and the ERA-40 and NCEP/NCAR reanalyses model elevations are not trivial (Zhao and Fu, 2006; Ma *et al*., 2008). The model elevation is often higher than the surface stations elevation because stations are located preferentially in flat or valley bottom locations. Classifying each of the 71 stations into one of three topographic types (summit, flat or valley) using a definition based on the relative heights of surrounding grid cells derived from GTOPO30 digital elevation data (You *et al*., 2008b) demonstrates this point (You *et al*., 2010a).

In previous paper (You *et al*., 2010a), we have analysed the relationships between annual air temperature differences (station minus reanalysis, dT) and elevation differences (mean surface station minus reanalysis model elevation, dH) for NCEP/NCAR and ERA-40 during 1961–2004. There is a negative correlation between dT and dH in both reanalyses, but the relationship is much stronger in ERA-40, annually and seasonally. Most of the temperature bias in ERA-40 is therefore due to the elevation difference, highlighting the possibility of 'topographic correction' and removal of 'elevation-induced bias' when evaluating reanalysis data (Zhao *et al*., 2008). In most cases, the model elevation in ERA-40 is lower than that in NCEP/NCAR (Figure 6 in You *et al*., 2010a), resulting in higher surface temperature in ERA-40. This is consistent with the conclusions in Ireland that the discrepancies between reanalysis and observations result from the difference in the treatment of land and sea surfaces in the reanalysis datasets (Mooney *et al*., 2011).

Although elevation accounts for a lot of the bias, aspect and slope could also be influential. Aspect and slope at each grid point are extracted from GTOPO30 digital elevation data. Temperature trend magnitudes were compared with aspect and slope for stations, NCEP/NCAR and ERA-40 data on an annual basis (not shown). In most cases, there is a slight negative relationship between temperature trend magnitudes and aspect as well as slope for stations, NCEP/NCAR and ERA-40. This suggests that change in topographic slope or station orientation should influence the trend magnitudes to a certain degree.

Topography also influences temperature trend magnitudes, which is consistent with other studies. Dobrowski *et al*. (2009) show that both regional synoptic-scale and landscape-scale physiographic factors control patterns of

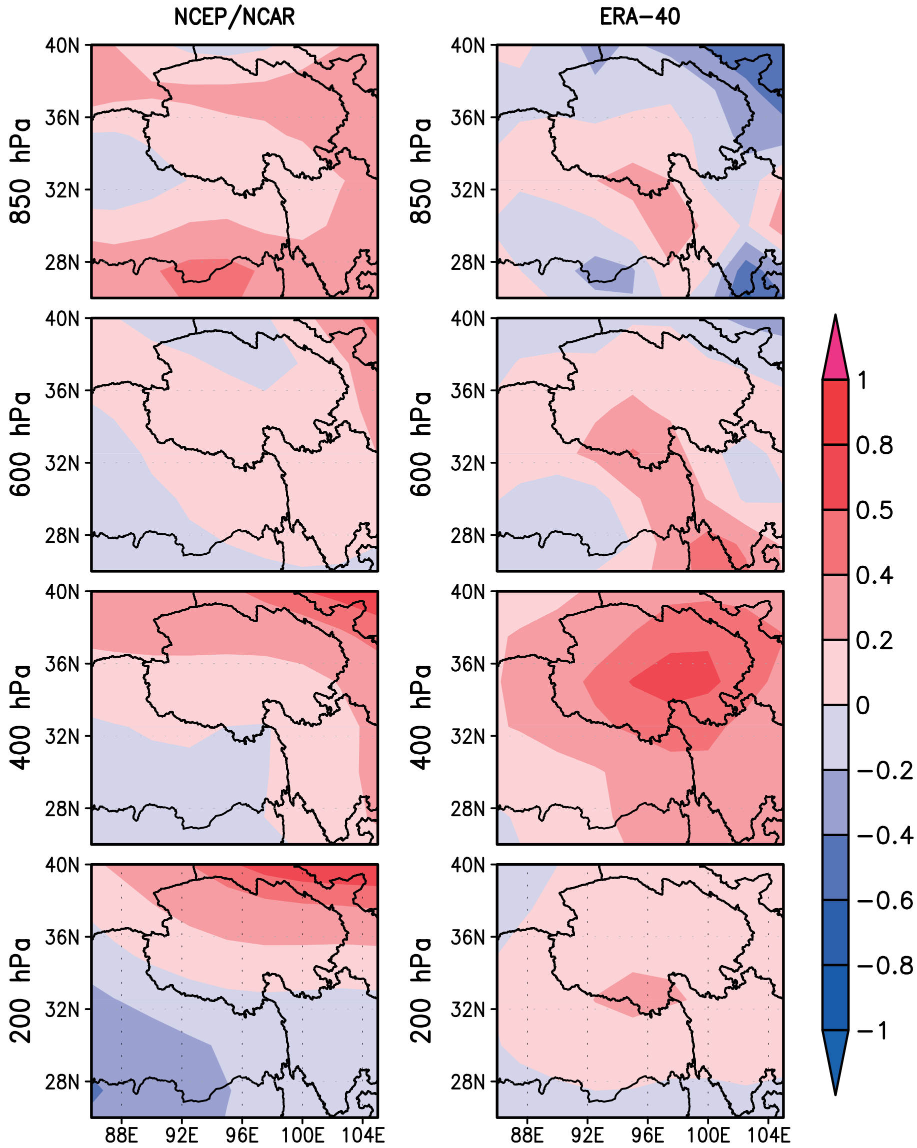

Figure 7. Annual mean temperature differences between 1981–2001 and 1961–1980 at 850, 600, 400 and 200hPa, and the right and left plots are for NCEP/NCAR and ERA-40 reanalysis data respectively.

temperature in mountain environments, and Thomas and Herzfeld (2004) try to generate new climatic data for East Asia based on localized relief information and geostatistical methods. Furthermore, on a daily basis the difference between the surface and free-air datasets is also correlated with meteorological factors such as snow cover, cloud cover and wind vectors, illustrating the importance of local surface radiative exchange at mountain locations (Pepin and Seidel, 2005). More attention to such issues should be given when examining trends in the TP from different sources, since topographical differences between grid point and station locations are clearly related to mean bias and differences in trend magnitudes and patterns (You *et al*., 2010a).

5. Conclusions

We have compared observed surface temperatures and their trends based on 71 homogenized surface stations with elevations above 2000 m a.s.l. in the eastern and central TP with equivalent temperatures at the nearest NCEP/NCAR and ERA-40 reanalysis grid points. The regional annual mean trend of 0.25 °C/decade is substantiated by many environment consequences, such as glacier shrinkage and land degradation. The warming in the surface stations is on average stronger than in both reanalyses. Although ERA-40 shows pronounced warming on an annual and seasonal basis, the regional annual mean trend is slightly less steep than surface stations, and most temperature trend magnitudes at grid points are lower than at individual surface stations. NCEP/NCAR fails to capture any warming trends with the exception of winter and the regional annual mean temperature trend is negative. As was the case for current climatology, ERA-40 is much more similar to the surface stations and captures the surface warming trends better than NCEP/NCAR on an annual and seasonal basis. NCEP/NCAR and ERA-40 are similar in representing

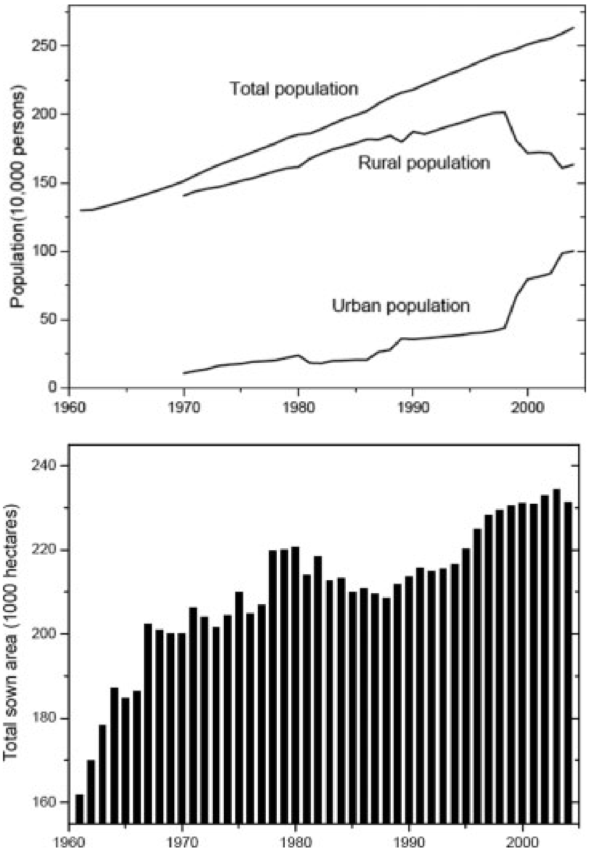

Figure 8. The total population grouped by residence (top plot) and total sown area (bottom plot) of Tibet Autonomous region during 1961–2004.

the free atmospheric conditions over the TP; however, NCEP/NCAR is not as good at representing surface temperatures or their trends in the TP.

Using ERA-40, we assess temperature trend magnitudes and mean temperature for the whole, eastern and western sections of the TP. Both the eastern and western TP show warming trends, especially in winter, but the trend in the eastern TP is larger (0.21 °C/decade) than in the west (0.09 °C/decade). Since NCEP/NCAR largely represents the free atmosphere, the OMR method has been used to estimate the impact of changes in land use (including urbanization and agricultural practices such as irrigation) by computing the trend in the difference between surface and NCEP/NCAR temperatures. The regional OMR trend is significantly increasing, which corresponds with a rapidly increasing urban population and an increase in total sown area. Our results further strengthen the case for using surface station in the TP to represent surface climate should be acknowledged the land use changes.

Correlations between air temperature differences (dT) and elevation differences (dH) shows that there are significant negative correlations for NCEP/NCAR and ERA-40. In most cases, the elevation differences (model elevation minus surface stations elevation) are positive because surface stations are situated in flat areas and valley bottoms which are lower than the reanalysis model topography. In ERA-40, the elevation difference is the main reason for the cold biases but the pattern is less systematic for NCEP/NCAR. The relationships between temperature trend magnitudes and aspect as well as slope for stations, NCEP/NCAR and ERA-40 data show that changes in topographic slope or station orientation should influence the trend magnitudes in the TP to a certain degree. Because much of the variation between ERA-40 and the surface stations is explained by topography, we suggest topographic correction is made to remove most of the elevation induced bias when making future comparisons.

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