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Can temperature extremes in China be calculated from reanalysis?

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ABSTRACT

Based on daily maximum, minimum and mean surface air temperature from National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis (NCEP/NCAR) and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses, the distributions of twenty temperature indices are examined in China during 1958–2011. ECMWF includes ERA-40 for the period 1958–2001 and ERA-Interim during 2002–2011. The consistency and discrepancy of extreme indices between reanalyses and observations (303 stations) are assessed. In most cases, temperature indices between NCEP/NCAR and ECMWF have good agreements. For both reanalysis, cold days/nights have decreased, while warm days/nights have increased since 1980. Temperatures of the coldest days/nights and warmest days/nights significantly increase over the entire China, and the diurnal temperature range demonstrates slight variations; the amounts of growing season length, and summer/tropical days have increased, consistent with the decrease in numbers of frost/ice days. Furthermore, the persistence of heat wave duration and warm spell days has increased and consecutive frost days have reduced. Meanwhile, consecutive frost days, cold wave duration and cold spell days from NCEP/NCAR have decreased and consecutive frost days have increased, while these indices from ECMWF turn to the opposite directions. Compared with observations, temperature extremes from two reanalyses have small relative bias and the root mean squared errors, while correlation coefficients are positively high. These suggest that both reanalyses can reproduce the variability of temperature extremes obtained from observations, and can be applied to investigate climate extremes to some extent, although the biases exist due to the assimilation differences.

1. Introduction

Due to the contradiction between the lack of observations and the increasing demand from the scientific community, it becomes urgent to acquire dataset with high resolution and long record in support of climate research and modeling, especially in the data scarce region such as the Tibetan Plateau (Kang et al., 2010). Reanalysis data refer to the results of state-of-the-art model output, data assimilation of numerical models, and the integration of non-regular observations, rawinsonde, aircraft, satellite and other data sources (Kalnay et al., 1996; Kistler et al., 2001). Reanalysis data extend for several decades, cover the entire globe from the Earth's surface to the above of the stratosphere, and play an extremely important role in the field of atmospheric science and climate research. Meanwhile, reanalysis data can be applied to understand the laws of atmospheric motion, investigate global and regional climate change and variability, identify the causes of climate variations and prepare for the input datasets for climate modeling. Reanalysis data are widely used in atmospheric science, diagnostic analysis, as well as the initial field for driving the regional and global climate models (Kalnay et al., 1996; Kistler et al., 2001; Uppala et al., 2005; Dee and Uppala, 2009).

However, it is noticed that that reanalysis data should not be equated with "observations" and "reality". The changing mix of observations and biases between observations and models can produce spurious variability and trend in the reanalysis. Zhao and Fu (2006) divided the reanalysis errors into the two classifications: (1) observing system changes such as lack of observations and errors in observations may lead to discrepancies and errors in reanalysis products, which can be regarded as the systematic errors; (2) numerical prediction models and assimilation programs such as shortcoming in the assimilating model/methodology can produce inaccurate/false data for reanalysis data. In summary, the uncertainties in the reanalysis data are difficult to understand and qualify, and more recent researches are to facilitate comparisons between reanalysis and observational datasets (Bengtsson et al., 2004; Simmons et al., 2004).

The widespread used reanalysis included the National Centers for Environmental Prediction/National Center for Atmospheric Research

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Reanalysis (NCEP/NCAR hereafter) (1948–present) (Kalnay et al., 1996) and European Centre for Medium-Range Weather Forecasts (ECMWF) 40 year reanalysis (ERA-40 hereafter) (1957–2002) (Uppala et al., 2005). ERA-Interim is the latest global atmospheric reanalysis produced by ECMWF covering the data since 1979 (Dee et al., 2011), and it is regarded as the new, more ambitious and next generation reanalysis to succeed ERA-40 (Dee and Uppala, 2009). On the global and regional scales, several studies have been retrieved different parameters and variables from reanalysis to compare the credibility with observations (Kalnay et al., 1996; Su et al., 1999; Zhang and Qian, 1999; Xu et al., 2001; Wei and Li, 2003; Simmons et al., 2004; Frauenfeld et al., 2005; Zhao and Fu, 2006; Xie et al., 2007; Zhao et al., 2007, 2008; You et al., 2009). However, the results are sensitive to the time period, regions, and selected observations.

In China, the observed surface air temperatures have been applied to evaluate the applicability of NCEP/NCAR reanalysis. The preliminary analysis shows that the monthly mean temperature from reanalysis is lower than the observed value. On a seasonal basis, surface air temperature in summer has a good credibility for reanalysis, while the winter has a poor credibility (Xu et al., 2001; Zhao and Fu, 2006; Ma et al., 2008; Zhao et al., 2008). Compared with NCEP/NCAR, ERA-40 reanalysis represents the temperature of the lower troposphere over East Asia very well, and can be used to study the inter-decadal climate change in that region (Huang, 2006). There are studies focusing on the applicability of reanalysis in the Tibetan Plateau. It is found that the surface air temperature from NCEP/NCAR does not identify significant warming and there are large geographical differences, while it shows more pronounced warming in the North China Plain region (Su et al., 1999; Xu et al., 2001; Ma et al., 2008). Over the Tibetan Plateau and its vicinity, Su et al. (1999) analyzed and tested the credibility of NCEP/NCAR reanalysis, and pointed out that the reanalysis is more reasonable because the mean distribution patterns from reanalysis are similar to observations. Wei and Li (2003) carried out the applicability of NCEP/NCAR reanalysis along the Qinghai-Tibet Railway, and found systematic temperature values obtained from reanalysis are less than the actual observed values. Frauenfeld et al. (2005) compared ERA-40 reanalysis with observations, and revealed that ERA-40 reanalysis is less susceptible to the influence of the local assimilation system after the spectral models with the real terrain are used. Xie et al. (2007) investigated two automatic weather stations' data in the southern Nyainqentanglha Mountains and Everest Northern Slope, and compared them with NCEP/NCAR reanalysis. They indicated that NCEP/NCAR reanalysis can reflect changes in the temperature at the synoptic scale, but temperature value from reanalysis is lower than the corresponding observed values. You et al. (2009) analyzed the applicability of NCEP/NCAR reanalysis in the glacier nearby Namco Lake district, and illustrated that reanalysis of the temperature is relatively good, and application of reanalysis in the critical region should take the impact of altitude into account. These results are identified for the surface air temperature in the entire Tibetan Plateau by the comparisons between observations and reanalyses including NCEP/NCAR and ERA-40 reanalysis (You et al., in press).

Overall, the applicability of reanalysis has been assessed and compared with the climate mean anomalies (such as the monthly and annual mean temperature). Fewer studies have been focused on the extreme climate and weather events such as extreme heat waves, extreme low temperatures, cold wave duration, which are more sensitive to climate change than their mean values (IPCC, 2007). Reanalysis data can be a potentially useful source of data for monitoring long-term changes in extremes in data sparse regions, but they have not been used in the field of temperature extremes (Zhang et al., 2011). The purpose of the present study is to evaluate the climate extremes calculated from reanalysis in China, the applicability of the inter-annual climate is evaluated with observations, which are needed to better understand the pattern, cause, frequency and intensity of climate extreme in China.

2. Data and methods

2.1. Reanalysis data

In this study, the daily maximum, minimum and mean temperatures from NCEP/NCAR, ERA-40 and ERA-Interim reanalysis are selected, which are in accordance with 190 grid points covering the entire China (Fig. 1). NCEP/NCAR reanalysis is provided by the National Oceanic and Atmospheric Administration (NOAA)/Earth System Research Laboratory (ESRL)/Physical Sciences Division (PSD), Boulder, Colorado, USA, from their website at http://www.cdc.noaa.gov/. The datasets cover January 1948 to the present with a spatial resolution of 2.5° × 2.5° (Kalnay et al., 1996), and are initialized with a wide variety of weather observations, including ships, planes, satellite observations. The daily maximum, minimum and mean temperatures of ERA-40 and ERA-Interim reanalysis data are obtained from the ECMWF website (http://www.ecmwf.int/). For ERA-40 reanalysis, it is available from September 1957 to August 2002 with a spatial resolution of 2.5° × 2.5° (Uppala et al., 2005). Compared with NCEP/NCAR, ERA-40 is produced by use of a wide range of observing systems, such as the satellite data and vertical temperature profile radiometer radiances starting in 1972 (Ma et al., 2009). Due to ERA-40 stop by 2002, ERA-Interim (1979–present) is used to extend ERA-40 to the present. It is shown that the difference of temperature between ERA-40 and ERA-Interim is slight during the overlapping period (1979–2001) (Fig. 1). Thus ERA-40 is used before 2001 ERA-Interim is applied after 2001 for this study. ERA-Interim use input observations prepared for ERA-40 until 2002 and has a spatial resolution of 1.5° × 1.5° (Dee et al., 2011). Both NCEP/NCAR and ERA-40 were assimilated using a 6-hourly 3D variational analysis (3DVAR), but ERA-Interim is based on a 12-hour four-dimensional variational analysis (4DVAR). Furthermore, the surface sea temperature and sea-ice concentrations described as boundary conditions differ in each reanalysis, and the forecast models and physical parameterizations are also different (Zhang et al., 2012). To qualify the comparison, all reanalyses are interpolated into 2.5° × 2.5° horizontal resolution using the linear interpolation methods.

2.2. Observations

To validate the reanalysis data, the daily maximum, minimum and mean temperatures for 303 stations are used in China (Fig. 1), provided by the National Meteorological Information Center, China Meteorological Administration (NMIC/CMA). The quality of observational data in China, meeting the World Meteorological Organization's (WMO) standards, and the climate extreme and its connection with atmospheric patterns have been discussed (You et al., 2011). For the calculation of observations, the internationally agreed indices are adopted, which are generated by the WMO Commission for Climatology (CCl), the World Climate Research Program (WCRP) project on Climate Variability and Predictability (CLIVAR) and Joint WMO-Intergovernmental Oceanographic Commission (IOC) Technical Commission for Oceanography and Marine Meteorology (JCOMM) Expert Team (ET) on Climate Change Detection and Indices (ETCCDI) (http://cccma.seos.uvic.ca/ETCCDI) (Peterson and Manton, 2008). Releasing climate indices and sharing the ETCCDI's indices are of great use to scientific community working on adaptation and climate model validation. In this study, the ETCCDI's indices from observations derived from You et al. (2011) will be applied to compare and validate the reanalyzed temperature extremes indices.

2.3. Extreme indices and calculation

Twenty temperature indices are selected in this study (Table 1). As it can be seen, some indices are commonly used to assess the intensity, frequency and duration of climate extreme events, and widely analyzed on the regional and global scales (e.g. Alexander et al., 2006; Peterson

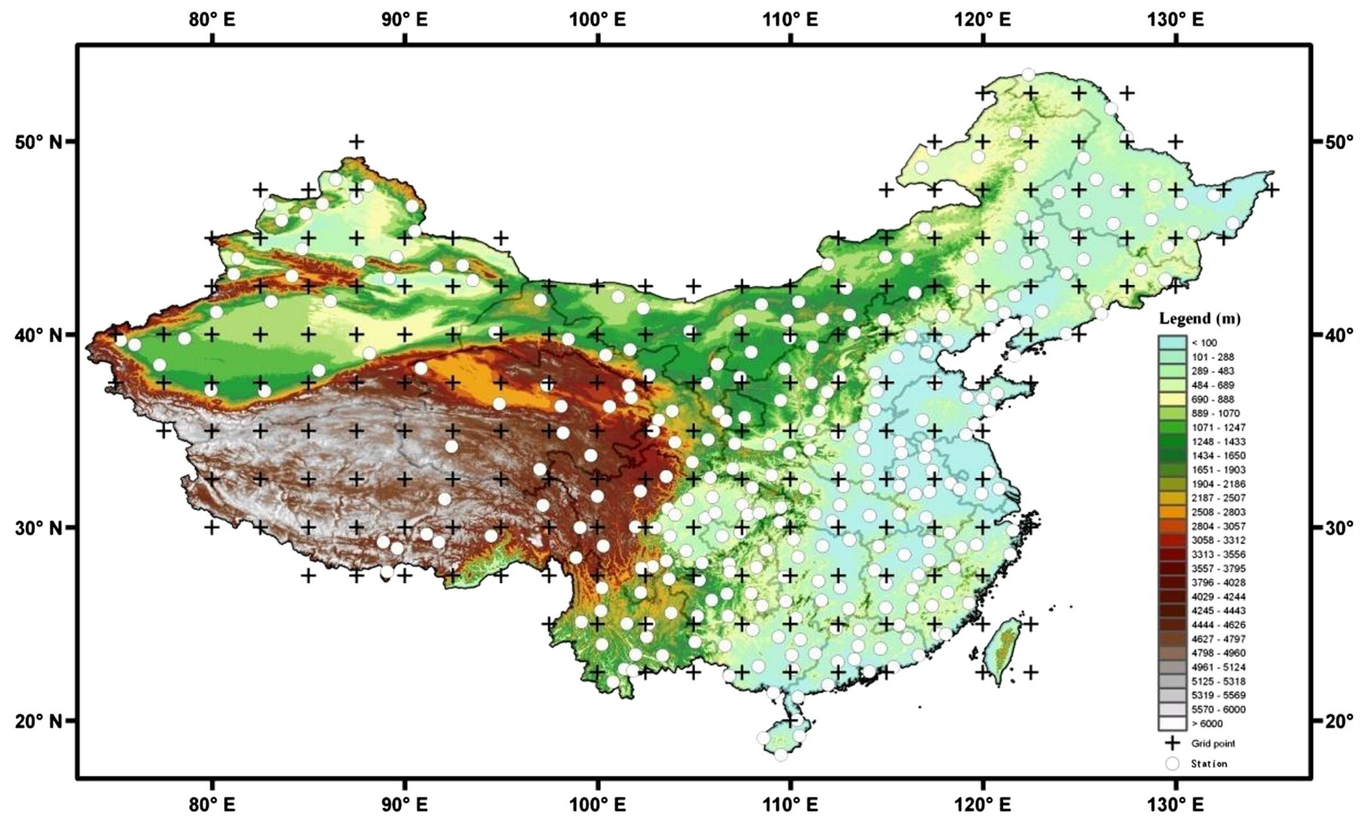

Fig. 1. Topography of China and the distribution of 190 grid points used in this study. The white dots are the 303 observational stations used as reference stations.

and Manton, 2008). Detailed descriptions are provided in Table 1, and more knowledge is available from http://cccma.seos.uvic.ca/ETCCDI.

The Mann–Kendall test for a trend and Sen's slope estimates are used to estimate trends in annual and seasonal temperature extreme series (Sen, 1968). The method has been widely used to compute trends in hydrological and meteorological series. In this paper, a trend is considered to be statistically significant if it is significant at the 5% level (Table 2). When repeating multiple statistical tests at different stations and if the indices are correlated between the different stations, it requires field significance testing. Different procedures have been developed to take into account cross-correlations in trend analysis, including the block-bootstrap (Douglas et al., 2000) or the False Dis-covery Rate (Ventura et al., 2004; Wilks, 2006) methods.

In the present study the block-bootstrap (Douglas et al., 2000) method has been applied to evaluate the field significance of the correlation between reanalyses and observations. Both reanalyses and observations are resampled to create 1000 different datasets, and the correlation between them is computed for each dataset.

3. Results

Figs. 3 and 4 show the time series of twenty temperature extremes during 1958–2011 based on NCEP/NCAR and ECMWF reanalysis averaged 190 grid points in China. It is notable that the ECMWF includes ERA-40 for the period of 1958–2001 and ERA-Interim during 2002–2011. The trends of temperature extremes for the period of 1958–1979, 1980–2011 and 1958–2011 are summarized in Table 1. As shown in Table 1, the trends for the period of 1958–1979 and 1980–2011 are different, indicating the inter-decadal variations for temperature extremes are significant. In this study, only the spatial trends of temperature extreme for NCEP/NCAR and ECMWF during 1958–2011 are demonstrated and discussed in Figs. 5 and 6.

3.1. Percentile-based indices (TX10, TN10, TX90, and TN90)

Percentile-based indices include occurrences of cold days (TX10), cold nights (TN10), warm days (TX90) and warm nights (TN90), which selected the coldest and warmest deciles for both maximum and minimum temperature (Alexander et al., 2006). For TX10 and TN10, the spatial trends derived from NCEP/NCAR and ECMWF are negative in most northern China, but they have discrepancies in the Tibetan Plateau, where trends of NCEP/NCAR show negative but those of ECMWF display positive. For the time series anomalies, TX10 and TN10 calculated from NCEP/NCAR decrease for the period 1958–1979 and 1980–2011, and the regional trends of both indices during 1958–2011 are −0.71 days/decade and −0.42 ($P < 0.05$) days/decade, respectively, and the absolute trend magnitude of TX10 is higher than TN10 (Fig. 2). Meanwhile, TX10 from ECMWF slightly increases but TN10 decreases, and the regional trends for both indices during 1958–2011 are 0.15 days/decade and −0.30 days/decade, respectively, and only the latter has passed the significance level. Thus, TX10 and TN10 from NCEP/NCAR and ECMWF have inconsistencies, although the correlation coefficients between two reanalyses are positively high ($R = 0.43$ for TX10 and $R = 0.78$ for TN10). For the global and regional studies, both TX10 and TN10 from observations have negative trends and TN10 decreases rapidly than TX10 (Peterson et al., 2002; Aguilar et al., 2005; Alexander et al., 2006; Peterson et al., 2008; Aguilar et al., 2009). For example, the global means of TX10 and TN10 during 1951–2003 have decreased with rates of −0.62 days/decade and −1.26 days/decade, respectively (Alexander et al., 2006), and the regional trends of both indices in central and northern South America during 1961–2003 are −2.4 days/decade and −2.2 days/decade, respectively (Aguilar et al., 2005).

For TX90 and TN90, both indices calculated from NCEP/NCAR and ECMWF have positive trends in the entire China, and there have significant positive correlations between two reanalyses ($R = 0.91$ for TX90 and $R = 0.78$ for TN90). TX90 and TN90 from NCEP/NCAR depict

Table 1
Definitions of temperature extreme indices used in this study.

Index	Descriptive name	Definition	Units
TX10	Cold day frequency	Percentage of days when TX < 10th percentile of 1961–1990	%
TN10	Cold night frequency	Percentage of days when TN < 10th percentile of 1961–1990	%
TX90	Warm day frequency	Percentage of days when TX > 90th percentile of 1961–1990	%
TN90	Warm night frequency	Percentage of days when TN > 90th percentile of 1961–1990	%
DTR	Diurnal temperature range	Annual mean difference between TX and TN	°C
TXn	Coldest day	Annual lowest TX	°C
TNn	Coldest night	Annual lowest TN	°C
TXx	Warmest day	Annual highest TX	°C
TNx	Warmest night	Annual highest TN	°C
GSL	Growing season length	Annual count between the first span of at least 6 days with TG > 5 °C after winter and first span after the summer of 6 days with TG < 5 °C	days
FD	Frost days	Annual count when TN < 0 °C	days
ID	Ice days	Annual count when TX < 0 °C	days
SU	Summer days	Annual count when TX > 25 °C	days
TR	Tropical nights	Annual count when TN > 20 °C	days
CSU	Consecutive summer days	Annual largest number of consecutive days when TX > 25 °C	days
CFD	Consecutive frost days	Annual largest number of consecutive days when TN < 0 °C	days
CWDI	Cold wave duration index	Annual account number of days when, intervals of at least 6 consecutive days, TN < TNnorm-5 °C	days
CWFI	Cold spell days index	Annual account number of days when, intervals of at least 6 consecutive days, TG < 10th percentile of 1961–1990	days
HWDI	Heat wave duration index	Annual account number of days when, intervals of at least 6 consecutive days, TX > TXnorm + 5 °C	days
HWFI	Warm spell days index	Annual account number of days when, intervals of at least 6 consecutive days, TG > 90th percentile of 1961–1990	days

Note: TX is the daily maximum temperature; TN is the daily minimum temperature; TG is daily mean temperature; TNnorm is the mean of daily minimum temperatures for the period of 1961–1990; TXnorm is the mean of daily maximum temperatures for the period of 1961–1990.

consistent negative trends before 1980 and positive trends afterwards, which result to positive trends during 1958–2011 with rates of 1.39 days/decade and 2.24 days/decade ($P < 0.05$), respectively. The patterns for TX90 and TN90 from ECMWF are in good agreements with those from NCEP/NCAR during 1958–2011 (1.72 days/decade and 0.30 days/decade ($P<0.05$)). It is distinct that TX90 from two reanalyses has larger trend magnitudes than TN90. The asymmetrical changes for TX90 and TN90 are inconsistent with observations in China (Zhai et al., 1999; You et al., 2011), the eastern and central Tibetan Plateau (You et al., 2008), Southern Africa (Aguilar et al., 2009), North America (Peterson et al., 2008), but are consistent with the characteristic in central South America (Aguilar et al., 2005).

3.2. Absolute indices (TXn, TXx, TNx, TNn, and DTR)

Absolute indices represent maximum or minimum values within a selected period, and the annual basis is selected (Table 1), which includes temperatures of coldest days and nights (TXn and TNn) and warmest days and nights (TXx and TNx) in each year. The diurnal temperature range (DTR) is the difference between the daily maximum and minimum temperature, which is regarded as the absolute index in this study.

During 1958–2011, TXn and TNn from NCEP/NCAR and ECMWF show positive trends before 1980, and negative trends afterwards, while they demonstrate positive trends in the whole period. TXn and TNn for NCEP/NCAR have positive rates of 0.25 °C/decade and 0.18 °C/decade, respectively, and the significant increases for both indices occur in the northeastern China, consistent with the rapid increases of surface air temperature (You et al., 2011). Variability of TXn and TNn from ECMWF is very similar to NCEP/NCAR throughout the period 1958–2011, reflected by the high positive correlations with NCEP/NCAR ($R = 0.90$ and $R = 0.84$). The regional trends for TXn and TNn from ECMWF are 0.12 °C/decade and 0.21 °C/decade, respectively. For TXx and TNx, variabilities in NCEP/NCAR and ECMWF are very similar, and the correlations between two reanalyses are substantially higher

Table 2
Trends per decade for the regional indices of temperature extremes in China based on NCEP/NCAR and ECMWF reanalysis for the period of 1958–1979, 1980–2011 and 1958–2011. ECMWF includes ERA-40 during 1958–2001 as well as ERA-Interim during 2002–2011. The trends are calculated by the Mann–Kendall slope estimator. Values for trends significant at the 10% level are marked in bold. The values with asterisk indicate trends significant at the 5% level.

Indices	Unit	1958–1979		1980–2011		1958–2011	
		NCEP/NCAR	ECMWF	NCEP/NCAR	ECMWF	NCEP/NCAR	ECMWF
TX10	days/decade	−0.09	0.93	**−0.48***	0.30	**−0.71***	0.15
TN10	days/decade	0.98	1.05	**−0.42**	−0.39	**−0.42***	**−0.30**
TX90	days/decade	−0.81	−1.28	**4.27***	**3.92***	**1.78***	**1.72***
TN90	days/decade	**−2.41***	**−1.22***	**3.71***	**4.71***	**1.39***	**2.24**
DTR	°C/decade	**0.22***	−0.04	**0.08***	**−0.05***	**0.08***	**−0.05***
TXn	°C/decade	0.15	−0.14	0.05	−0.09	**0.25***	0.12
TNn	°C/decade	−0.02	−0.12	0.04	0.06	**0.18***	**0.21***
TXx	°C/decade	0.09	−0.08	**0.38***	**0.34***	**0.23***	**0.14***
TNx	°C/decade	0.01	−0.12	**0.29***	**0.42***	**0.16***	**0.16***
GSL	days/decade	0.71	−0.14	**3.98***	**2.14**	0.72	**1.15**
FD	days/decade	**3.52***	0.80	**−2.50***	**−2.79***	**−0.54**	**−1.16***
ID	days/decade	−0.53	1.65	**−1.75***	**−1.44**	**−1.28***	**−0.68***
SU	days/decade	2.05	**−1.64**	**4.67***	**4.88***	**3.13***	**1.89***
TR	days/decade	**−1.38**	**−1.65**	**2.61***	**4.25***	**1.40***	**1.77***
CSU	days/decade	0.34	**−1.54**	**1.86***	**1.20***	**1.11***	−0.03
CDF	days/decade	0.86	0.80	−1.07	**−2.05***	−0.42	**−0.94***
CWDI	days/decade	0.41	0.75	0.24	**0.71***	−0.19	0.14
CWFI	days/decade	0.29	0.72	0.57	**2.51***	−0.18	**0.70***
HWDI	days/decade	−0.54	−1.12	**3.45***	**3.75***	**1.35***	**1.57***
HWFI	days/decade	**−4.37**	**−2.51**	**6.83***	**8.25***	**2.25***	**3.40***

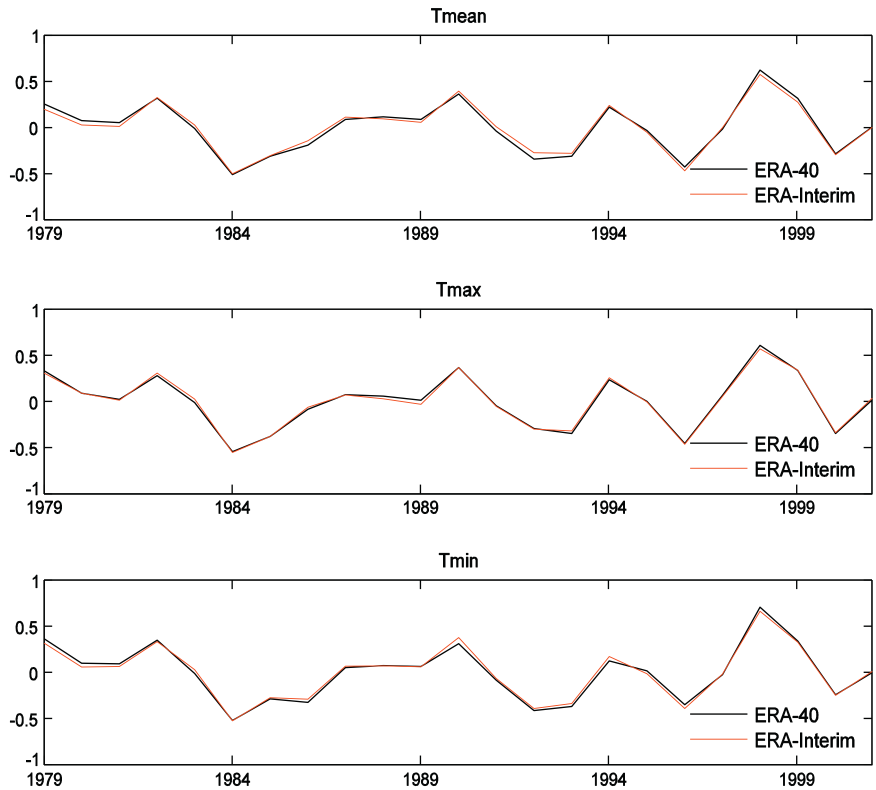

Fig. 2. Anomalies of daily maximum, minimum and mean temperatures in China during 1979–2001. The black curve shows the ERA-40 and red one represents ERA-Interim.

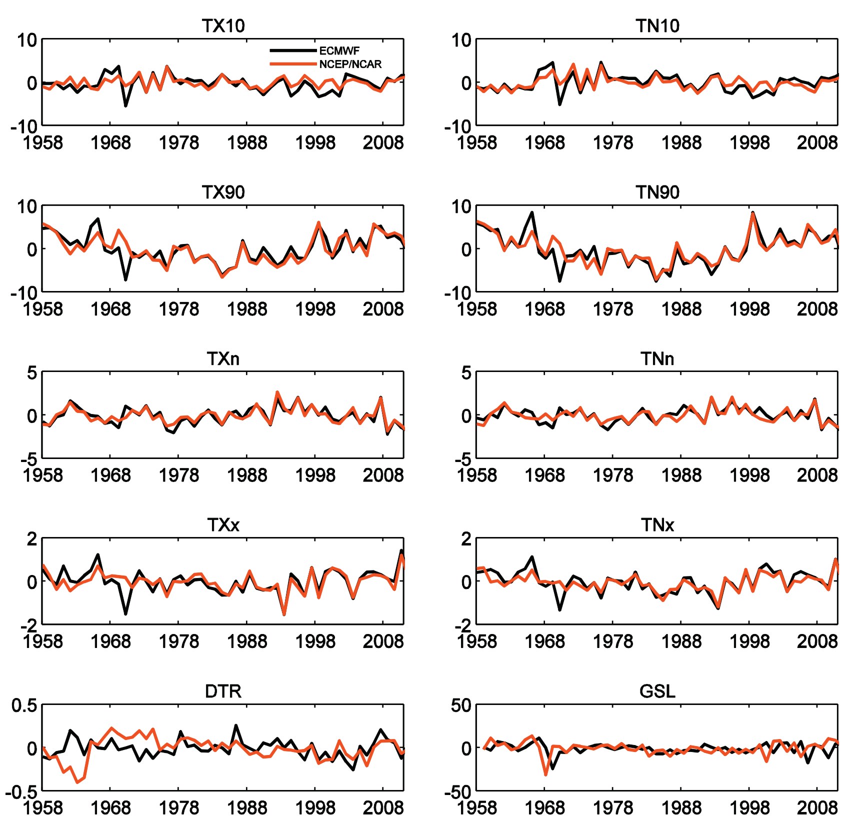

Fig. 3. Anomalies of TX10, TN10, TX90, TN90, TXn, TNn, TXx, TNx, DTR and GSL in China during 1958–2011. The black curve shows the NCEP/NCAR reanalysis and red one represents ECMWF. ECMWF includes ERA-40 during 1958–2001 as well as ERA-Interim during 2002–2011. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

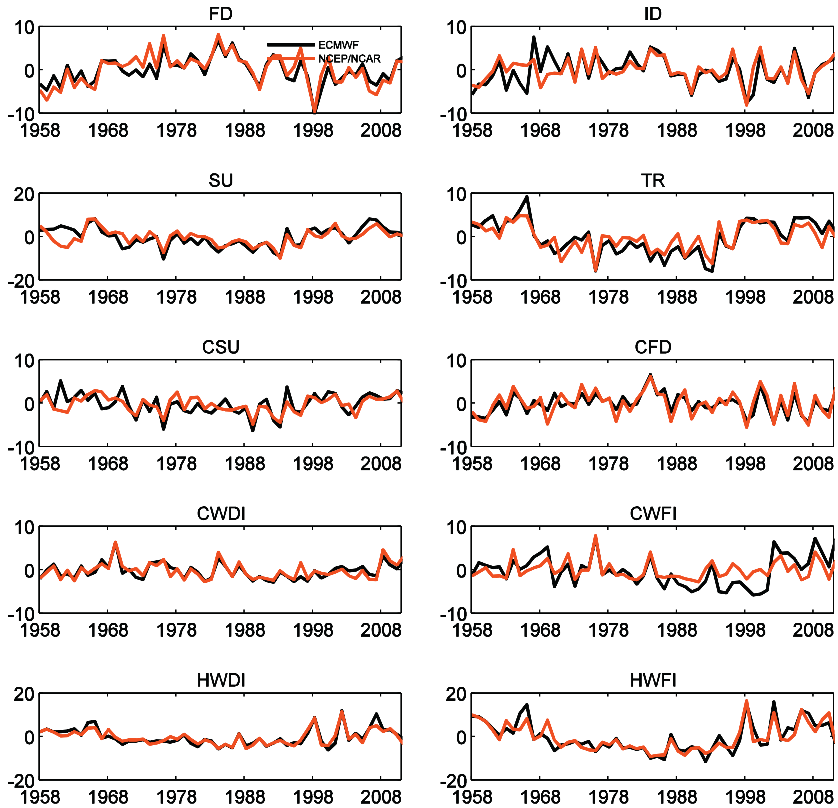

Fig. 4. Anomalies of temperature extremes indices (FD, ID, SU, TR, CSU, CFD, CWDI, CWFI, HWDI and HWFI) in China during 1958–2011. The black curve shows the NCEP/NCAR reanalysis and red one represents ECMWF. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(R = 0.82 for TXx and R = 0.86 for TNx). During 1958–2011, TXx and TNx from NCEP/NCAR show increases in most regions in China, with the regional rates of 0.23 °C/decade and 0.16 °C/decade, respectively, which are distinctly higher than ECMWF (0.14 °C/decade and 0.16 °C/decade). Beside differences of the trend magnitudes between NCEP/NCAR and ECMWF, differential changes of indices from maximum and minimum temperatures for two reanalysis are also found. Indices of maximum temperature from NCEP/NCAR (such as TXn and TXx) are more sensitive to warming than those of the minimum temperature (such as TNn and TNx), in contradiction with ECMWF. For the observational studies in Africa, indices of minimum temperature have larger trend magnitudes than those of maximum temperature (New et al., 2006; Aguilar et al., 2009), which are opposite to that in central South America (Aguilar et al., 2005).

Previous studies show that changes in DTR can be an evidence of climate change (Easterling et al., 1997; Alexander et al., 2006). Although DTR from NCEP/NCAR and ECMWF has a negative correlation (R = −0.37), slight variations are seen in both reanalyses during the period 1958–2011, and these are particularly the case for the spatial patterns of trend in the entire China. Both two reanalyses cannot capture the variability of DTR observed from stations in China (You et al., 2011), which shows that the trend in DTR during 1961–2003 is −0.18 °C/decade with a significant at the 0.05 level. On the global scale, decreased DTR from observations is identified due to the minimum temperatures that have increased at a faster rate than the maximum temperatures (Easterling et al., 1997; Alexander et al., 2006), which were probably affected by local effects such as urban growth, irrigation, desertification, and land use change.

3.3. Threshold indices (FD, ID, SU, and TR)

Threshold indices are defined as the number of days on which the temperature values fall above or below a fixed threshold, including occurrence of frost days (FD), ice days (ID), summer days (SU) and tropical nights (TR) (Alexander et al., 2006). The numbers of FD and ID from NCEP/NCAR and ECMWF have increased before 1980, and decreased afterwards. The positive correlations of FD and ID between two reanalyses are higher than 0.8, indicating both reanalyses have highly correlated. During 1958–2011, FD and ID from two reanalyses represent negative trends in most regions in China. FD and ID from NCEP/NCAR have negative trends, with rates of −0.54 days/decade and −1.28 days/decade, respectively, while the trends of two indices from ECMWF are −1.16 days/decade and −0.68 days/decade, respectively. The change of FD from two reanalyses is similar to that in the Middle East, which shows the regional trend of FD is −0.6 days/decade during 1950–2003 (Zhang et al., 2005). In the Tibetan Plateau, FD is also negative with a rate of −4.32 days/decade during 1961–2005 (You et al., 2008).

The numbers of SU and TR from NCEP/NCAR and ECMWF are in good agreements during 1958–2011, with a correlation coefficient of about 0.7. Both SU and TR decrease before the 1990s and significantly increase afterwards, and the positive trends can be seen in most regions in China. The rates of both indices for NCEP/NCAR during 1958–2011 are 3.13 days/decade and 1.4 days/decade, and 1.89 days/decade and 1.77 days/decade for ECMWF. The reanalyzed rates for SU and TR are less than the regional trends in southern Africa during 1961–2000 (New et al., 2006), which shows the trends are 5.05 days/decade and 2.93 days/decade, respectively. In the Middle East during 1950–2003, the trends for SU and TR also significantly decrease with rates of 1 days/decade and 3.7 days/decade (Zhang et al., 2005).

3.4. Duration indices (GSL, CSU, CDF, CWDI, CWFI, HWDI, and HWFI)

Duration indices define the periods of excessive warmth, cold, wetness or dryness or in the case of growing season length, periods of mildness (Alexander et al., 2006). In this study, duration indices include

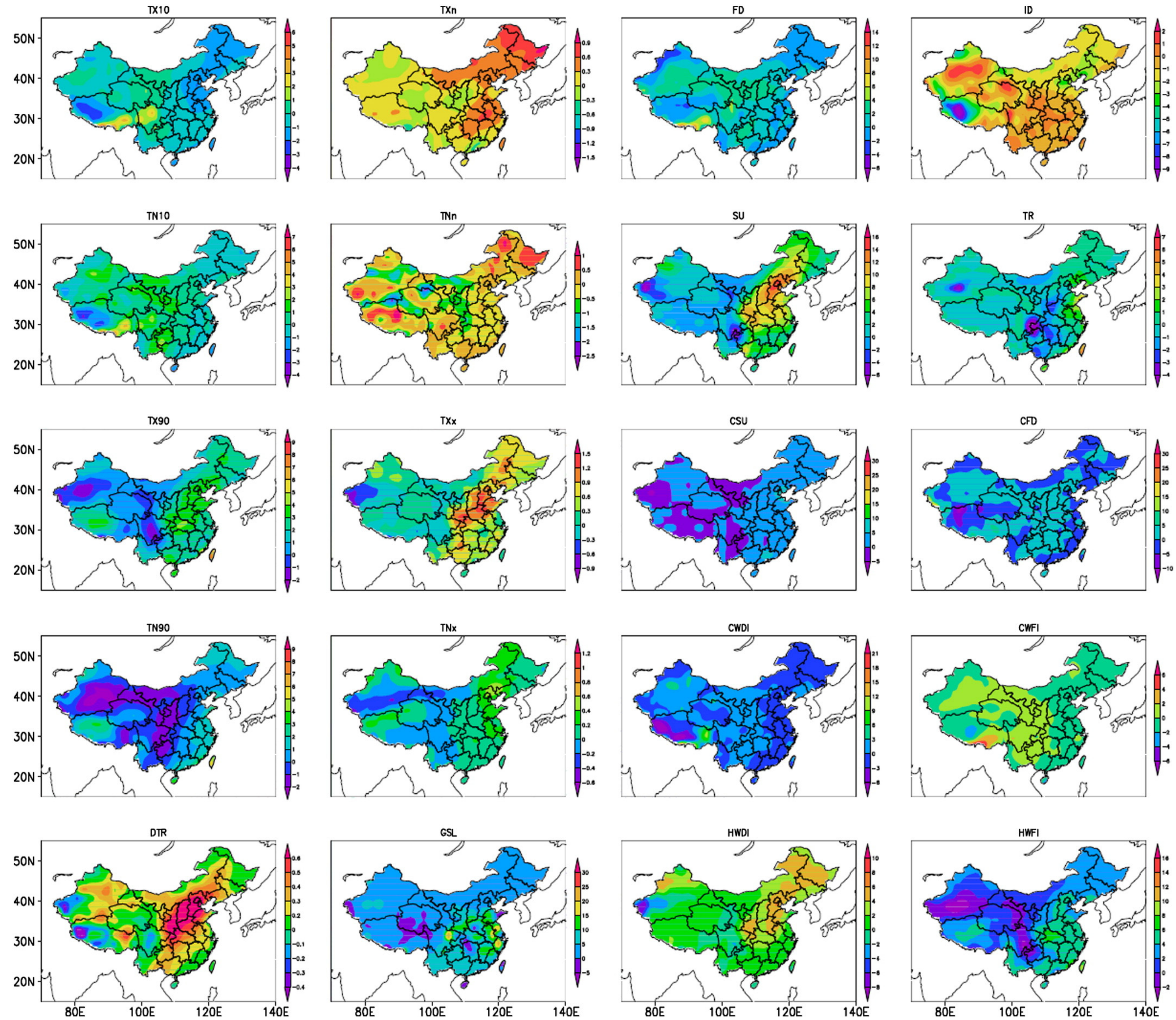

Fig. 5. Spatial trend patterns of temperature extreme indices from NCEP/NCAR reanalysis in China during 1958–2011. The unit of each index is the same as in Table 1.

growing season length (GSL), consecutive summer days (CSU) and consecutive frost days (CFD), cold wave duration index (CWDI) and cold spell days index (CWFI), heat wave duration index (HWDI) and warm spell days index (HWFI).

Although GSL from NCEP/NCAR and ECMWF has a slight negative correlation (R = −0.02), it rapidly increases since the 1980s, especially for NCEP/NCAR, which leads to the positive trends for both reanalyses during 1958–2011 (0.72 days/decade and 1.15 days/decade). The observed GSL in the Tibetan Plateau increases with a rate of 4.25 days/decade during 1961–2005 (You et al., 2008). The trends of reanalyzed GSL is also lower than the observations in China (You et al., 2011).

The number of CSU from NCEP/NCAR is positively correlated with that from ECMWF (R = 0.6), and CSU from both reanalyses decreases before the mid-1980s and increases afterwards, leading to the rates of 1.11 days/decade and −0.03 days/decade during 1958–2011. Same as other temperature extreme indices, the number of CDF from NCEP/NCAR is positively correlated with that from ECMWF (R = 0.84), and CDF from both reanalyses increases/decreases before/after the mid-1980s, and the rates are −0.42 days/decade and −0.94 days/decade during 1958–2011.

Although CWDI from NCEP/NCAR is positively correlated with that from ECMWF (R = 0.86), the trend from NCEP/NCAR is negative (−0.42 days/decade), but that for ECMWF is positive (0.14 days/decade). The entire China has the same trend patterns. For CWFI from NCEP/NCAR, it decreases before the 1980s and increases afterwards, resulting to the trend of −0.18 days/decade. CWFI from ECMWF is positively correlated with that from NCEP/NCAR, especially before the 1980s, while the trend for the whole period is 0.70 days/decade.

For HWDI and HWFI, both indices from NCEP/NCAR slightly decrease before the 1980s, and increases during the 1990s. The regional trends for both reanalyses are 1.35 days/decade and 2.25 days/decade, respectively, which the positive trends are apparent in the northern China. HWDI and HWFI from ECMWF positively correlate with those from NCEP/NCAR (R = 0. 86 for HWDI and R = 0. 92 for HWFI), the positive trends for two indices during 1958–2011 are 1.57 days/decade and 3.4 days/decade.

4. Discussion and conclusions

In this study, the spatial and temporal distributions of trends in temperature extremes from NCEP/NCAR and ECMWF reanalyses have

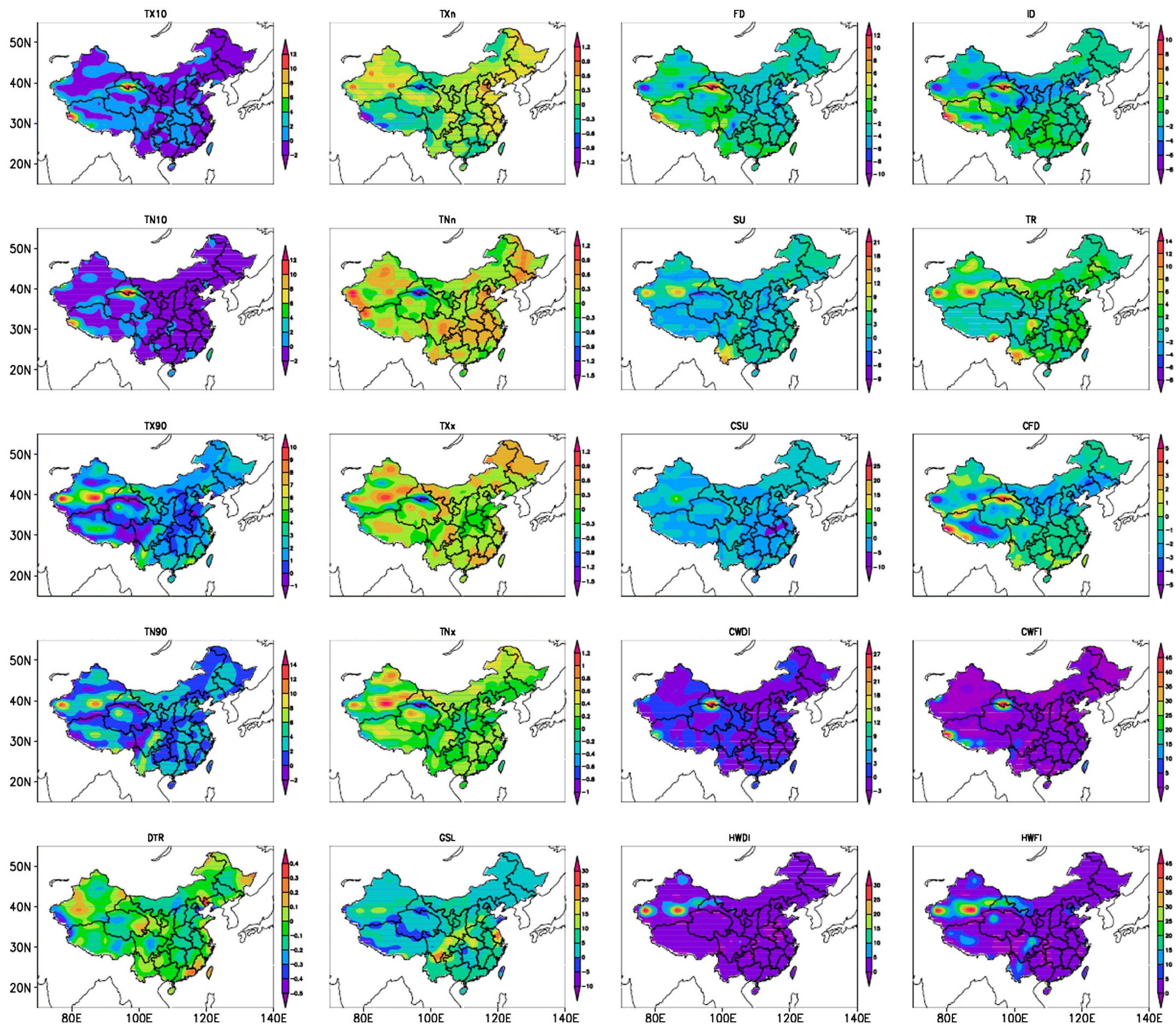

Fig. 6. Spatial trend patterns of temperature extreme indices from ECMWF reanalysis in China during 1958–2011. The unit of each index is the same as in Table 1.

been examined during 1958–2011. Twenty temperature indices developed by the joint CC1/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices have been selected. For the percentile-based indices, significant increases in warm nights/days and significant decreases in cold nights/days are obtained from two reanalyses during 1958–2011, especially for the period 1980–2011. The absolute indices show patterns consistent with a general warming trend, which are consistent with previous studies in the world (e.g. Alexander et al., 2006; You et al., 2011). Based on the two reanalyses, trends in minimum temperature extremes are same as those in maximum temperature extremes (Fig. 7), which lead to the slight variation in DTR, inconsistent with the observational studies such as You et al. (2011) and Easterling et al. (1997). For the threshold indices, the warming climate has caused the numbers of frost/ice days to decrease while the numbers of summer/tropical days have increased. The duration indices have also changed during the past decades, while the discrepancies exist between two reanalyses.

It seems that the temperature extremes have connections with the global warming. In recent decades, China has experienced significant climate changes and the atmospheric circulation is characterized by an inter-decadal transition in the late 1970s (Wang et al., 2012). Overall, the annual and seasonal mean, maximum and minimum temperatures in China have increased since the 1950s (Table 3). The annual mean surface air temperature has increased with a rate of 0.22 °C/decade during 1956–2002, and the daily maximum and minimum air temperatures have increased at rates of 0.13 and 0.32 °C/decade from 1955 to 2000, respectively (Wang and Gong, 2000). It is clear that the daily minimum temperatures significantly increased at a higher rate than the daily maximum and mean temperatures, and warming is more pronounced in the northeast China and less in the southwest China (Wang and Gong, 2000; Liu et al., 2004). Seasonally, the changes in daily minimum, maximum and mean temperatures are more significant in winter, which mostly contribute to the increase on the annual basis (Zhai et al., 1999). Meanwhile, the observed temperature extremes in China are significant. Zhai et al. (1999) revealed that upward trends in whole China have been detected for the frequencies of warm days/nights, with the largest increases since the mid-1980s. At the same time, the downward trends are also significant for the frequencies of cold days/nights. The frost day has a significant downward trend, indicating that the frost-free season in China

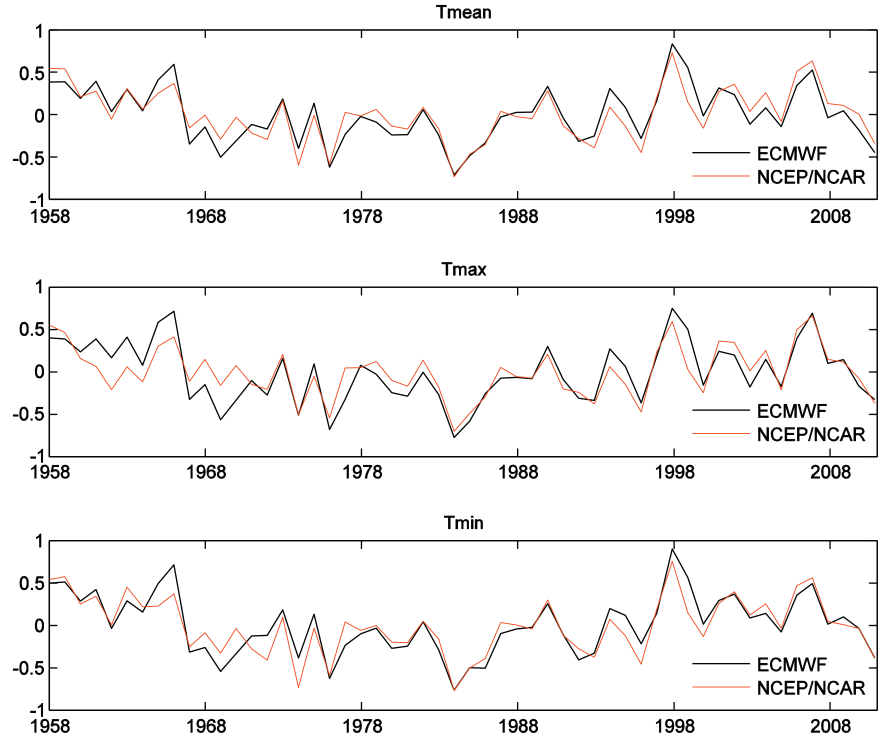

Fig. 7. Anomalies of annual maximum, minimum and mean temperature from ECMWF and NCEP/NCAR in China during 1958–2011.

has been prolonged. Furthermore, the warming climate is always accompanied by changes in the mean and extreme climate, which have great impacts on the society and economy (Wang et al., 2012).

Whether the temperature extremes derived from reanalyses represent the real extreme change, it is unclear in previous studies. To assess the reanalysis, ten temperature indices derived from NCEP/NCAR and ECMWF reanalyses are compared with those from the observational stations during 1961–2003 (Table 4). The indices at each grid point are interpolated with the inverse distance weighting method for the 303 stations (Fig. 1), and the temperature extremes from stations are obtained from You et al. (2011). In comparison with the observational data, temperature extremes from NCEP/NCAR reanalysis have a small relative bias ($<2\%$), and are positively correlated with the observations ($R > 0.4$) with the exception of DTR. In most temperature indices, the values of the root mean squared error are very low. For the temperature extremes from ECMWF reanalysis, the patterns are similar to those from NCEP/NCAR. In most temperature indices, the relative bias and the root mean squared error are relatively small while the correlation coefficients between observations and ECMWF reanalysis are positively high. Figs. 8 and 9 show the histogram of bootstrapped

Table 3
Trends of temperature during various studied periods based on the observational data in China.

Regions	Period	Variable	Trend	Reference
Eastern and central Tibetan Plateau	1961–2003	Monthly TX	0.18	Liu et al. (2006)
Eastern and central Tibetan Plateau	1961–2003	Monthly TN	0.41	Liu et al. (2006)
China	1951–1995	TX in spring	0.027	Zhai et al. (1999)
China	1951–1995	TX in summer	−0.006	Zhai et al. (1999)
China	1951–1995	TX in autumn	0	Zhai et al. (1999)
China	1951–1995	TX in winter	0.144	Zhai et al. (1999)
China	1951–1995	Annual mean TX	0.03	Zhai et al. (1999)
China	1951–1995	TN in spring	0.179	Zhai et al. (1999)
China	1951–1995	TN in summer	0.001	Zhai et al. (1999)
China	1951–1995	TN in autumn	0.153	Zhai et al. (1999)
China	1951–1995	TN in winter	0.417	Zhai et al. (1999)
China	1951–1995	Annual mean TN	0.175	Zhai et al. (1999)
Northeastern China	1951–1994	TG in winter	0.35	Wang and Gaffen (2001)
Northwestern China	1951–1994	TG in winter	0.31	Wang and Gaffen (2001)
China	1951–1994	TG in winter	0.23	Wang and Gaffen (2001)
China	1955–2000	TX in winter	0.265	Liu et al. (2004)
China	1955–2000	TX in spring	0.094	Liu et al. (2004)
China	1955–2000	TX in summer	0.054	Liu et al. (2004)
China	1955–2000	TX in autumn	0.095	Liu et al. (2004)
China	1955–2000	TN in winter	0.557	Liu et al. (2004)
China	1955–2000	TN in spring	0.296	Liu et al. (2004)
China	1955–2000	TN in summer	0.19	Liu et al. (2004)
China	1955–2000	TN in autumn	0.275	Liu et al. (2004)

Note: TX is the daily maximum temperature; TN is the daily minimum temperature; TG is daily mean temperature; The unit of trend is °C/decade.

Table 4
Comparison of temperature extreme based on observations and reanalysis in China during 1961–2003. The observational temperature indices derived from You et al. (2011). The unit of trend in each index is same as Table 1.

Index	Relative bias(%)	Correlation coefficients	Root mean squared error
NCEP/NCAR			
DTR	−0.52	−0.47	0.85
TN10	−0.04	0.77	0.31
TN90	0.23	0.97	0.43
TX10	−0.08	0.70	0.25
TX90	0.26	0.89	0.47
TNn	0.26	0.75	0.57
TNx	−0.11	0.89	0.40
TXn	1.55	0.86	1.23
TXx	−0.23	0.75	1.23
FD	0.33	0.66	5.22
ECMWF			
DTR	−0.34	0.70	0.55
TN10	−0.06	0.69	0.34
TN90	0.29	0.91	0.54
TX10	−0.05	0.67	0.25
TX90	0.26	0.89	0.47
TNn	0.16	0.84	0.36
TNx	−0.10	0.80	0.36
TXn	0.98	0.88	0.77
TXx	−0.17	0.84	0.91
FD	0.27	0.84	4.18

correlation coefficients between reanalyses and observations for the temperature indices. The histogram shows the variation of the correlation coefficient across all the bootstrap samples, indicating that the relationship between reanalyses and observations is not accidental. These comparisons with the observations suggest that the temperature indices from reanalysis can capture the variability of the observations, although there have differences of absolute values with observations and the discrepancies between two reanalysis are apparent in some indices such as duration indices. This is also suggested the discrepancies in temperature extremes between reanalysis and observations exist, although the annual maximum, minimum and mean temperature between NCEP/NCAR and ECMWF are consistent (Fig. 7).

The differences between the actual and model topography and scale issues between point measurements and grid cell average values should be one of the reasons accounting for the origin of these discrepancies between two reanalyses (Betts et al., 2003). On a global scale, linear trends computed during 1958–2011 are generally lower in ERA-40 and NCEP/NCAR compared with the climate research unit (CRU) data, but there are agreements to within about 10% for ERA-40 in the rate of warming of the terrestrial Northern Hemisphere since the late 1970s (Simmons et al., 2004). Due to improvements in technique of data assimilation schemes and physical parameterizations, surface temperature from ERA-40 has a better agreement with CRU than NCEP/NCAR (Simmons et al., 2004). The cold bias in reanalysis has been found in China, where the annual mean surface temperature from ERA-40 and NCEP/NCAR are lower than the observations by −0.93 °C and −2.78 °C, respectively, primarily contributed by the negative differences in the western China (Ma et al., 2008). In general, surface air temperature from ERA-40 better represents observed air temperatures in China than NCEP/NCAR does (Ma et al., 2008). For a varied study period, underestimation of ERA-40 temperature is generally less than 1 °C in the eastern China and greater than 12 °C in the western China (Su et al., 1999; Zhao and Fu, 2006; Zhao et al., 2008). In the Tibetan Plateau, topographical differences between grid points and observations, and other reanalysis model differences such as surface land schemes, cause differences in trend identification and patterns for both NCEP/NCAR and ERA-40 reanalysis (You et al., 2010). After calibrating of altitude effects in reanalysis, Zhao et al. (2008) found that the accuracy of surface temperature from reanalysis depends much on the attitudes of the original data and the increase of local elevation and topographical complexity can improve bias of temperature for reanalysis. Thus, the discrepancies in temperature extremes between two reanalysis and observations come from the discrepancies in the assimilation systems in two reanalyses, which

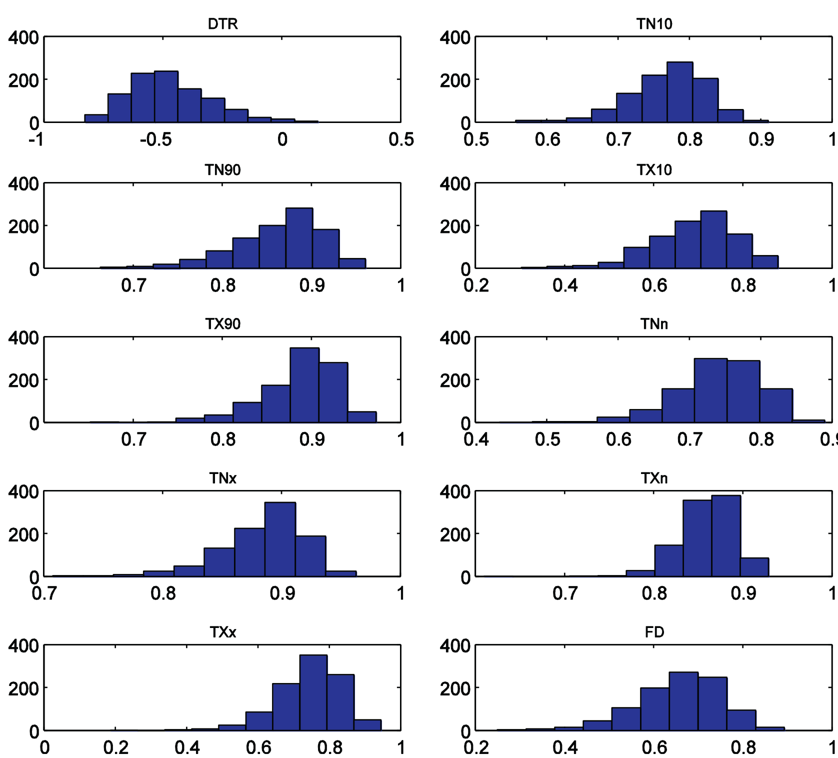

Fig. 8. Histogram of bootstrapping a correlation coefficient between NCEP/NCAR and observations for the temperature indices. Both NCEP/NCAR and observations are resampled to create 1000 different datasets, and the correlation between them is computed for each dataset.

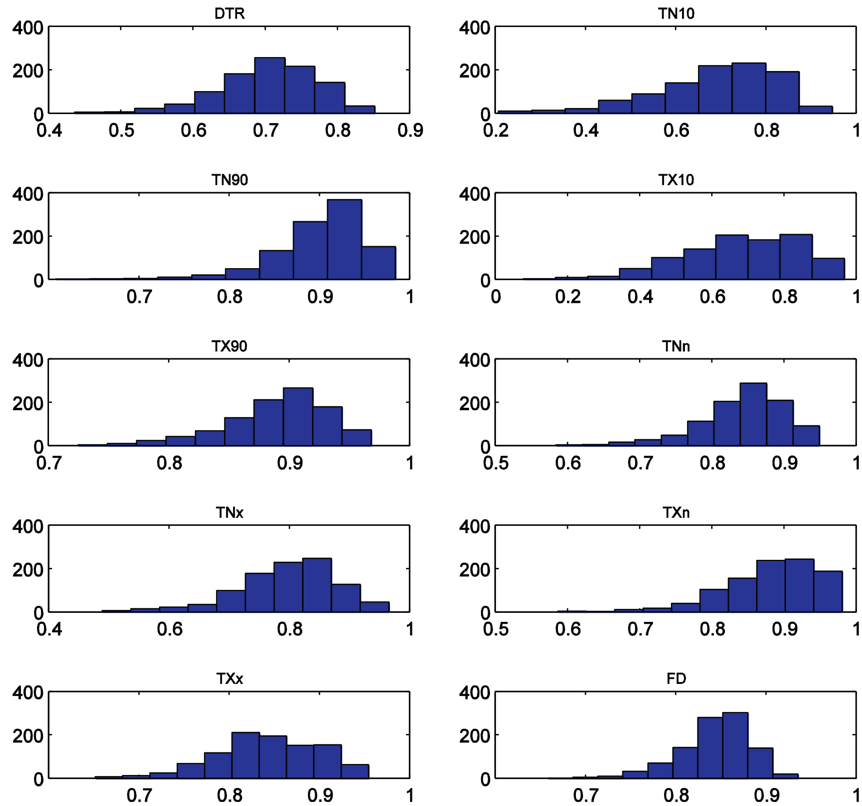

Fig. 9. Same as Fig. 8, but for ECMWF.

should be acknowledged as the reanalyses are considered to calculate the climate extremes.

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References

Aguilar, E., et al., 2005. Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003. J. Geophys. Res.-Atmos. 110, D23107.
Aguilar, E., et al., 2009. Changes in temperature and precipitation extremes in western central Africa, Guinea Conakry, and Zimbabwe, 1955–2006. J. Geophys. Res.-Atmos. 114, D02115.
Alexander, L.V., et al., 2006. Global observed changes in daily climate extremes of temperature and precipitation. J. Geophys. Res.-Atmos. 111, D05109.
Bengtsson, L., Hagemann, S., Hodges, K.I., 2004. Can climate trends be calculated from reanalysis data? J. Geophys. Res.-Atmos. 109 (D11), D11111.
Betts, A.K., Ball, J.H., Viterbo, P., 2003. Evaluation of the ERA-40 surface water budget and surface temperature for the Mackenzie River basin. J. Hydrometeorol. 4 (6), 1194–1211.
Dee, D.P., Uppala, S., 2009. Variational bias correction of satellite radiance data in the ERA-Interim reanalysis. Q. J. R. Meteorol. Soc. 135 (644), 1830–1841.
Dee, D.P., et al., 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc. 137 (656), 553–597.
Douglas, E.M., Vogel, R.M., Kroll, C.N., 2000. Trends in floods and low flows in the United States: impact of spatial correlation. J. Hydrol. 240, 90–105.
Easterling, D.R., et al., 1997. Maximum and minimum temperature trends for the globe. Science 277 (5324), 364–367.
Frauenfeld, O.W., Zhang, T.J., Serreze, M.C., 2005. Climate change and variability using European Centre for Medium-Range Weather Forecasts reanalysis (ERA-40) temperatures on the Tibetan Plateau. J. Geophys. Res.-Atmos. 110, D02101.
Huang, G., 2006. The assessment and difference of the interdecadal variations of climate change in northern part of China with the NCEP/NCAR and ERA-40 reanalysis data. Clim. Environ. Res. 11 (3), 310–320 (in Chinese with English abstract).
IPCC, 2007. Summary for policymakers of climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
Kalnay, E., et al., 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77 (3), 437–471.
Kang, S.C., Xu, Y.W., You, Q.L., Flugel, W.A., Pepin, N., Yao, T.D., 2010. Review of climate and cryospheric change in the Tibetan Plateau. Environ. Res. Lett. 5 (1), 015101.
Kistler, R., et al., 2001. The NCEP-NCAR 50-year reanalysis: monthly means CD-ROM and documentation. Bull. Am. Meteorol. Soc. 82 (2), 247–267.
Liu, B.H., Xu, M., Henderson, M., Qi, Y., Li, Y.Q., 2004. Taking China's temperature: daily range, warming trends, and regional variations, 1955–2000. J. Clim. 17 (22), 4453–4462.
Liu, X.D., Yin, Z.Y., Shao, X.M., Qin, N.S., 2006. Temporal trends and variability of daily maximum and minimum, extreme temperature events, and growing season length over the eastern and central Tibetan Plateau during 1961–2003. J. Geophys. Res.-Atmos. 111 (D19), D19109.
Ma, L.J., Zhang, T.J., Li, Q.X., Frauenfeld, O.W., Qin, D.H., 2008. Evaluation of ERA-40, NCEP-1, and NCEP-2 reanalysis air temperatures with ground-based measurements in China. J. Geophys. Res.-Atmos. 113, D15115.
Ma, L.J., Zhang, T., Frauenfeld, O.W., Ye, B.S., Yang, D.Q., Qin, D.H., 2009. Evaluation of precipitation from the ERA-40, NCEP-1, and NCEP-2 reanalyses and CMAP-1, CMAP-2, and GPCP-2 with ground-based measurements in China. J. Geophys. Res.-Atmos. 114, D09105.
New, M., et al., 2006. Evidence of trends in daily climate extremes over southern and west Africa. J. Geophys. Res.-Atmos. 111, D14102.
Peterson, T.C., Manton, M.J., 2008. Monitoring changes in climate extremes — a tale of international collaboration. Bull. Am. Meteorol. Soc. 89 (9), 1266–1271.
Peterson, T.C., et al., 2002. Recent changes in climate extremes in the Caribbean region. J. Geophys. Res.-Atmos. 107, D07113.
Peterson, T.C., Zhang, X.B., Brunet-India, M., Vazquez-Aguirre, J.L., 2008. Changes in North American extremes derived from daily weather data. J. Geophys. Res.-Atmos. 113 (D7), D07113.
Sen, P.K., 1968. Estimates of regression coefficient based on Kendall's tau. J. Am. Stat. Assoc. 63, 1379–1389.
Simmons, A.J., Jones, P.D., Bechtold, V.D., Beljaars, A.C.M., Kallberg, P.W., Saarinen, S., Uppala, S.M., Viterbo, P., Wedi, N., 2004. Comparison of trends and low-frequency variability in CRU, ERA-40, and NCEP/NCAR analyses of surface air temperature. J. Geophys. Res.-Atmos. 109, D24115.
Su, Z.X., Lu, S.H., Luo, S.W., 1999. The examinations and analysis of NCEP/NCAR 40 years global reanalysis data in China. Plateau Meteorol. 18 (2), 209–218 (in Chinese with English abstract).

Uppala, S.M., et al., 2005. The ERA-40 re-analysis. Q. J. R. Meteorol. Soc. 131 (612), 2961–3012.
Ventura, V., Paciorek, C.J., Risbey, J.S., 2004. Controlling the proportion of falsely rejected hypotheses when conducting multiple tests with climatological data. J. Clim. 17 (22), 4343–4356.
Wang, J.X.L., Gaffen, D.J., 2001. Late-twentieth-century climatology and trends of surface humidity and temperature in China. J. Clim. 14 (13), 2833–2845.
Wang, S.W., Gong, D.Y., 2000. Enhancement of the warming trend in China. Geophys. Res. Lett. 27 (16), 2581–2584.
Wang, H.J., Sun, J.Q., Chen, H.P., Zhu, Y.L., Zhang, Y., Jiang, D.B., Lang, X.M., Fan, K., Yu, E.T., Yang, S., 2012. Extreme climate in China: facts, simulation and projection. Meteorol. Z. 21 (3), 279–304.
Wei, L., Li, D.L., 2003. Reliability of NCEP/NCAR reanalysis data in climatic change along Tibet railway. Plateau Meteorol. 22 (5), 488–494 (in Chinese with English abstract).
Wilks, D., 2006. On "field significance" and the false discovery rate. J. Appl. Meteorol. Climatol. 45 (9), 1181–1189.
Xie, A.H., Qin, D.H., Ren, J.R., Qing, X., Kang, S.C., Jiang, Y.Y., 2007. Reliability of NCEP/NCAR reanalysis data on Mount Qomolangma and Western Nyainqentanglha range. Acta Geograph. Sin. 62 (3), 268–278 (in Chinese with English abstract).
Xu, Y., Ding, Y.H., Zhao, Z.C., 2001. Confidence analysis of NCEP/NCAR 50-year global reanalyzed data in climate change research in China. Q. J. Appl. Meteorol. 12 (3), 337–347 (in Chinese with English abstract).
You, Q.L., Kang, S.C., Aguilar, E., Yan, Y.P., 2008. Changes in daily climate extremes in the eastern and central Tibetan Plateau during 1961–2005. J. Geophys. Res.-Atmos. 113, D07101.
You, Q.L., Kang, S.C., Li, C.L., Zhang, Q.G., Li, M.S., Liu, J.S., 2009. Reliability of NCEP/NCAR reanalysis data in the lake and glacier area in the Nam Co Basin. Meteorol. Mon. 35 (5), 66–73 (in Chinese with English abstract).
You, Q.L., Kang, S.C., Pepin, N., Flugel, W.A., Yan, Y.P., Behrawan, H., Huang, J., 2010. Relationship between temperature trend magnitude, elevation and mean temperature in the Tibetan Plateau from homogenized surface stations and reanalysis data. Glob. Planet. Chang. 71 (1–2), 124–133.
You, Q.L., Kang, S.C., Aguilar, E., Pepin, N., Flugel, W.A., Yan, Y.P., 2011. Changes in daily climate extremes in China and their connection to the large scale atmospheric circulation during 1961–2003. Clim. Dyn. 36, 2399–2417.
You, Q.L., Fraedrich, K., Ren, G.Y., Nicholls, N., Kang, S.C., 2013. Variability of temperature in the Tibetan Plateau based on homogenized surface stations and reanalysis data. Int. J. Climatol 33 (6), 1337–1347. http://dx.doi.org/10.1002/joc.3512.
Zhai, P.M., Sun, A.J., Ren, F.M., Liu, X.N., Gao, B., Zhang, Q., 1999. Chances of climate extremes in China. Clim. Chang. 42 (1), 203–218.
Zhang, Q., Qian, Y.F., 1999. Monthly mean surface albedo estimated from NCEP/NCAR reanalysis radiation data. Acta Geograph. Sin. 54 (4), 309–317 (in Chinese with English abstract).
Zhang, X.B., et al., 2005. Trends in Middle East climate extreme indices from 1950 to 2003. J. Geophys. Res.-Atmos. 110, D22104.
Zhang, X.B., Alexander, L., Hegerl, G.C., Jones, P., Tank, A.K., Peterson, T., Trewin, B., Zwiers, F., 2011. Indices for monitoring changes in extremes based on daily temperature and precipitation data. Wiley Interdiscip. Rev. Clim. Chang. 2, 851–870.
Zhang, Q., Kornich, H., Holmgren, K., 2012. How well do reanalyses represent the southern African precipitation? Clim. Dyn. http://dx.doi.org/10.1007/s00382-012-1423-z.
Zhao, T., Fu, C., 2006. Comparison of products from ERA-40, NCEP-2, and CRU with station data for summer precipitation over China. Adv. Atmos. Sci. 23 (4), 593–604.
Zhao, P., Zhou, Z.J., Liu, J.P., 2007. Variability of Tibetan spring snow and its associations with the hemispheric extratropical circulation and East Asian summer monsoon rainfall: an observational investigation. J. Clim. 20 (15), 3942–3955.
Zhao, T., Guo, W., Fu, C., 2008. Calibrating and evaluating reanalysis surface temperature error by topographic correction. J. Clim. 21 (6), 1440–1446.