INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **29**: 1906–1925 (2009)
Published online 10 July 2009 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/joc.1979

Changes in means and extreme events of temperature and precipitation in the Asia-Pacific Network region, 1955–2007

Gwangyong Choi,[a,k]* Dean Collins,[b] Guoyu Ren,[c] Blair Trewin,[b] Marina Baldi,[d†] Yoshikazu Fukuda,[e] Muhammad Afzaal,[f] Theeraluk Pianmana,[g] Purevjav Gomboluudev,[h] Pham Thi Thanh Huong,[i] Norlisam Lias,[j] Won-Tae Kwon,[a] Kyung-On Boo,[a] Yu-Mi Cha[a] and Yaqing Zhou[c]

[a] *Climate Research Laboratory, National Institute of Meteorological Research, Korea Meteorological Administration, 45 Gisangcheong-gil, Dongjak-gu, Seoul 156-720, Republic of Korea*
[b] *National Climate Centre, Bureau of Meteorology, GPO Box 1289, Melbourne 3001, Australia*
[c] *Laboratory for Climate Studies, National Climate Centre, China Meteorological Administration, 46 Zhongguancun Nandajie, Beijing 100081, China*
[d] *National Institute of Water and Atmospheric Research Ltd., 269 Khyber Pass Rd, Newmarket, Auckland, New Zealand*
[e] *Climate Prediction Division, Global Environment and Marine Department, Japan Meteorological Agency, 1-3-4 Otemachi, Chiyoda-ku, Tokyo 100-8122, Japan*
[f] *Research and Development Division, Pakistan Meteorological Department, Sector H-8/2, PO Box 1214, Islamabad, Pakistan*
[g] *Climatological Group, Meteorological Development Bureau, Thai Meteorological Department, 4353 Sukhumvit Road, Bangna, Bangkok 10260, Thailand*
[h] *Forecast Research Laboratory, Institute of Meteorology and Hydrology, National Agency for Meteorology, Hydrology and Environmental Monitoring, Juulchiny Gudamj-5, Ulaanbaatar-46, Mongolia*
[i] *Climate Change Research Division, Center for Meteorology and Climate, Institute of Meteorology and Hydrology, 23/62 Nguyen Chi Thanh, Dong Da, Ha Noi, Vietnam*
[j] *Kuching Regional Meteorological Office, Kuching International Airport 93667, Kuching, Sarawak, Malaysia*
[k] *Department of Environmental Science, Kangwon National University, 192-1, Hyoja-dong, Chuncheon-si, Gangwon-do, 200-701, Republic of Korea*

ABSTRACT: In this study, spatial and temporal patterns of changes in extreme events of temperature and precipitation at 143 weather stations in ten Asia-Pacific Network (APN) countries and their associations with changes in climate means are examined for the 1955–2007 period. Averaged over the APN region, annual frequency of cool nights (days) has decreased by 6.4 days/decade (3.3 days/decade), whereas the frequency of warm nights (days) has increased by 5.4 days/decade (3.9 days/decade). The change rates in the annual frequency of warm nights (days) over the last 20 years (1988–2007) have exceeded those over the full 1955–2007 period by a factor of 1.8 (3.4). Seasonally, the frequencies of summer warm nights and days are changing more rapidly per unit change in mean temperatures than the corresponding frequencies for cool nights and days. However, normalization of the extreme and mean series shows that the rate of changes in extreme temperature events are generally less than that of mean temperatures, except for winter cold nights which are changing as rapidly as the winter mean minimum temperature. These results indicate that there have been seasonally and diurnally asymmetric changes in extreme temperature events relative to recent increases in temperature means in the APN region.

There are no systematic, regional trends over the study period in total precipitation, or in the frequency and duration of extreme precipitation events. Statistically significant trends in extreme precipitation events are observed at fewer than 30% of all weather stations, with no spatially coherent pattern of change, whereas statistically significant changes in extreme temperature events have occurred at more than 70% of all weather stations, forming strongly coherent spatial patterns.

KEY WORDS extreme climate indices; climate means; sensitivity of extreme climate events; Asia-Pacific Network (APN); climate change

Received 4 January 2009; Revised 2 June 2009; Accepted 3 June 2009

1. Introduction

Increases in extreme climate events, such as prolonged periods of hot days and intense heavy rainfall days, have greater negative impacts on human society and natural environments than changes in climate means. Several studies have reported how a single catastrophic precipitation event can devastate long-term accomplishments of human society within a short period (e.g. Zong and Chen, 2000). It is also well documented how greatly an extreme hot or cold temperature event can increase human mortality, as well as energy utilization (e.g. Huynen *et al.*, 2001; UNEP, 2004). There have been many studies in recent

* Correspondence to: Gwangyong Choi, Department of Environmental Science, Kangwon National University, 192-1, Hyoja-dong, Chuncheon-si, Gangwon-do, 200-701, Republic of Korea.
E-mail: tribute@hanmail.net
† On leave from Institute of Biometeorology – CNR, Rome, Italy.

decades that have examined changes in monthly, seasonal, and annual climate means for the purpose of capturing the fingerprints of climate change due to anthropogenic modification of atmospheric chemistry. In contrast, systematic and extensive studies about changes in extreme climate events covering broad regions (e.g. continental or hemispheric scale) have been a much more recent development, primarily due to difficulties in collecting high spatial and temporal resolution climatic data across international boundaries.

In recent years, climate scenario data simulated by global climate models (GCMs) have begun to be employed in projecting changes in extreme climate events in the warmer 21st century. However, several studies (e.g. Meehl *et al*., 2007; Sillmann and Roeckner, 2008; Alexander and Arblaster, 2009) have pointed out, through comparisons of simulated climatic data with observed data, that the difficulties climate models have in simulating present day extreme events provide additional uncertainty in projecting future changes in extreme climate events. These circumstances accentuate the importance of continuously monitoring changes in extreme climate events based on observed *in situ* climatic data.

Since the late 1990s, many efforts have been made to assess changes in spatial and temporal patterns of extreme climate events using observational climatic data. Analyses of long-term climatic characteristics of extreme events, including their intensity, duration, and frequency, are needed for developing mitigation and adaptation plans. In these efforts, data from a greater number of long-term weather stations across more extensive regions are indispensable to the detection of global-scale changes in climate extremes. However, there are many difficulties in obtaining reliable long-term climatic data due to financial and institutional barriers, including limitations imposed by many countries on exchanging data sets with daily or higher resolutions, as well as poor maintenance of data observation and archive practices. In general, there are, in developing countries, greater difficulties in maintaining observation networks and archiving quality-controlled data in an appropriate format due to lack of funding, technology, and human resources, as well as political instability or armed conflict in some regions. As a result, many stations have only short records or long periods of missing data, and many valuable long-term climatic data, including those archived throughout colonial periods. In some countries that only became independent during the 20th century, data remain in a non-digital format and not readily available for use in analyses (Page *et al*., 2004). A further difficulty was that no standard definitions of extreme climate indices were agreed by the international community until the late 1990s, which has also delayed the required monitoring efforts of extreme climate events across large regions. Some extreme events (e.g. extended heatwaves and cold spells) are still lacking accepted, universally applicable indices to describe them (Trewin, 2009).

To address these problems, a number of international workshops have taken place, many of them under the auspices of the joint Expert Team on Climate Change Detection and Indices (ETCCDI) [This Expert Team is a joint team of the World Meteorological Organization (WMO)'s Commission for Climatology (CCl), the World Climate Research Program's Project on Climate Variability and Predictability (CLIVAR), and the joint WMO-Intergovernmental Oceanographic Commission for Oceanography and Marine Meteorology (JComm)]. As a result, since the start of the 21st century internationally agreed extreme climate indices have become available for many regions, and numerous international collaborations monitor changes in extreme climate events from regional (Manton *et al*., 2001; Peterson *et al*., 2002; Klein Tank and Können, 2003; Aguilar *et al*., 2005; Griffiths *et al*., 2005; Moberg and Jones, 2005; New *et al*., 2006; Vincent *et al*., 2005; Klein Tank *et al*., 2006) to global (Frich *et al*., 2002; Alexander *et al*., 2006) scales. In particular, as a pioneering effort to examine observed trends in extreme climate events, the Asia-Pacific Network (APN) workshops have shown an effective model for other similar workshops as to how common analysis methods can be used to provide a consistent analysis of extremes across a large region. Since the first APN workshop on extreme climate was held in December 1998, many regional workshops for detecting extreme climate events have been organized successfully in areas such as North Africa, Central and South America, and the Middle East (Peterson and Manton, 2008). Among many previous papers, Alexander *et al*. (2006) provided the latest, most comprehensive analysis regarding global-scale changes in extreme climate events through combining results obtained by many regional meetings on extreme climates, including the APN workshops, as well as other national and regional studies.

A number of articles have been published that have considered the sign and magnitude of changes in extreme temperature and precipitation events and their association with changes in climate means and atmospheric circulation indices in the region of interest for this paper (e.g. Manton *et al*., 2001; Griffiths *et al*., 2003, 2005; Nicholls *et al*., 2005). These previous studies covered changes in climate extremes, mainly in south or southeast Asia and the south Pacific, for periods based on 1961–2000. For instance, a study covering southeast Asia and the tropical south Pacific region for the period 1961–1998 (Manton *et al*., 2001) reported that changes in extreme temperature events, such as increases in hot days and warm nights, as well as decreases in cool days and cold nights, have occurred coherently at many weather stations, whereas the sign and statistical significance of changes in extreme precipitation events varies from one region to another. Griffiths *et al*. (2003) showed that the trends of extreme rainfall events in the south Pacific for the period 1961–2000 are associated with the displacement of the south Pacific convergence zone. Nicholls *et al*. (2005) found an association between increases in

DOI: 10.1002/joc

hot days and warm nights in East Asia–West Pacific region and El Niño events in the preceding year. In these previous regional-scale studies, the trends of extreme climate indices in recent decades have been examined in detail, but systematic analyses showing the comparisons between seasonal or diurnal extreme climate change signals, and their relative linkages with changes in climate means, have been more limited (Griffiths *et al*., 2005). In particular, as the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007) stated, the direction and magnitude of changes in extreme climate are not necessarily identical to those in climate means. Thus, the exploration of the associations between extreme climate events and climate means is an important task for projecting future changes in extreme events using climate means, which are currently simulated more reliably by climate models than extreme events.

The latest (sixth) APN workshop was held in Seoul, Republic of Korea from 19 to 24 February 2008. Ten APN countries (Mongolia, China, Republic of Korea, Japan, Vietnam, Thailand, Pakistan, Malaysia, Australia, and New Zealand) participated in the workshop. The main goal of this workshop was to develop indices and indicators for monitoring trends in climate extremes and to apply them to the projection of future changes in climate extremes in the APN region. This collaborative workshop allowed authors to update the previous work by including climatic data from larger numbers of weather stations in the eastern Asia region, and extending the study period to 1955–2007. This article is a summary of the collaborative results of the sixth APN workshop. The key purpose of this paper is to examine spatial and temporal changes in extreme temperature and precipitation events across the APN region, and, more importantly, to examine their seasonal and diurnal associations with changes in climate means over the 1955–2007 period.

2. Data and methods

2.1. Study region and data quality

The ten countries participating in this project are located in the Asia-Pacific region and are spread across the domain of 55°N–55°S, 60°E–180°E (Figure 1), covering a range of climates. The study region includes tropical and subtropical climates, as well as mid-latitude climates, and extends from highly continental climates in western China, Mongolia, and central Australia, to highly maritime island climates in the Pacific. Many parts of the region have strong seasonal circulation variations, especially in southern and eastern Asia, where the summer and winter monsoons, and the Siberian high in winter, are major influences on climate, typically producing a marked summer maximum in total rainfall and likelihood of extreme rainfall events. Tropical cyclones are also a major influence on extreme rainfall in many parts of the region, both in the Northern and Southern Hemisphere. This study provides wide-ranging information on changes in extreme climate events through investigations across the APN regions with a variety of climates.

In this study, daily maximum and minimum temperature and precipitation data observed at 143 weather stations in ten Asia-Pacific Network countries are used to construct interannual time series of 20 extreme temperature indices and 11 extreme precipitation indices over the 1955–2007 period (Figure 1 and Table I). The number of stations provided by each of the ten participating countries ranged from 4 to 36. Australia and China, who each have several hundred operating stations, selected 36 and 32 weather stations, respectively, for use in this study, choosing those stations with long-term time series and little missing data to best represent the regional signals. Compared with Manton *et al*.'s study (2001), which was the first study about extreme climate events in the APN region, this study includes data from 60 additional stations and extends the time period of analysis by 15 years, with extensions at both the start and end of the series. More than 85% of the 143 stations have daily data with less than 10% missing records for the 1955–2007 period, although several stations in Pakistan and Vietnam are excluded due to frequent missing data and a lack of digitized daily data between 1955 and 1960.

Years in which more than 10% of daily data are missing at any individual weather station are excluded from analyses. To calculate departures from long-term climatology, the years 1971–2000 are used as a reference period. Data quality checks were carried out using the tools in the *RClimdex* software (Zhang and Yang, 2004), which identifies potentially unrealistic climatic records, including

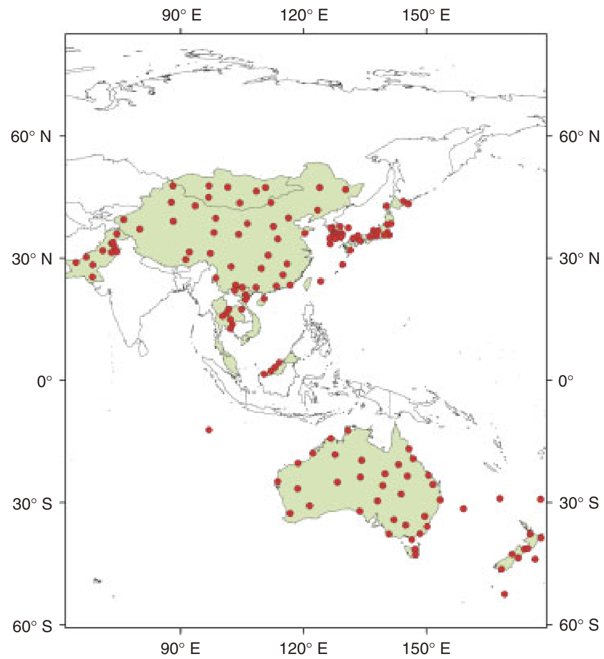

Figure 1. Location of the 143 weather stations across the ten APN countries included in this study. This figure is available in colour online at www.interscience.wiley.com/ijoc

DOI: 10.1002/joc

Table I. Data contributed by the ten APN countries.

Country	No of weather stations	Base data period	First year	Last year
Australia	36	1955–2007	1955	2005
China	32	1955–2007	1961	2007
Japan	18	1955–2007	1955	2007
Malaysia	4	1955–2007	1961	2007
Mongolia	6	1955–2006	1950	2006
New Zealand	10	1955–2007	1955	2007
Pakistan	11	1961–2006	1961	2006
Republic of Korea	14	1955–2007	1955	2007
Thailand	7	1955–2007	1955	2007
Vietnam	5	1961–2006	1961	2006
Overall	143		1955–2007	
Variables	Daily maximum and minimum temperatures, and daily precipitation			

The 'first year' and 'last year' given refer to the earliest and latest records contributed by each country, respectively.

negative values of daily maximum-minus-minimum temperatures, outliers (typically exceeding 4 standard deviations difference from the mean), and negative values of daily precipitation.

In addition to data quality control, a further issue potentially affecting the data sets is homogeneity, although many of the component stations from some countries (e.g. Australia) were selected for this study on the basis of their known data homogeneity. As a whole, however, the magnitude of change rates of extreme temperature events quantified in this study should be used with caution due to local, non-climatic factors such as urbanization. Many weather stations used in this study are currently located near or within regions where rapid urbanization, as a result of economic development, has occurred during the late 20th century. For instance, it has been documented that urbanization accounts for more than 30% of the overall warming of annual mean temperature observed in North China during the late 20th century (Zhou *et al*., 2004; Ren *et al*., 2008). The impact of factors such as urbanization will vary from one station to another. In this study, however, the removal of urbanization effects is not done due to the lack of metadata about weather stations, as well as systematic filtering methods. Thus, it is expected that local factors might lead to the overestimation of magnitudes of changes in extreme temperature indices at some stations, even though the consistency with trends at non-urban stations indicates that the sign of the trends may be reliable.

2.2. Extreme climate indices and methods of trend analyses

In this study, 20 extreme temperature (Table II) and 11 extreme precipitation (Table III) indices devised by the ETCCDI are utilized. Thirty-year (1971–2000) averages at individual weather stations are used as base line values for the extraction of anomaly time series. The *RClimdex* software developed by Zhang and Yang (2004) is used to construct time series of the indices, and to extract their linear trends and an assessment of statistical significance, for each individual weather station.

The extreme climate indices used in this study can be broadly categorized into a relative threshold (percentile) approach and an absolute threshold approach. For the temperature indices based on relative thresholds, the 30-year average 10th percentile values of daily temperatures at individual weather stations are calculated for each of the 365 days of the year. The long-term average percentile-based indices include cool days and nights for lower extremes and warm days and nights for higher extremes. The original unit (% of year) for these percentile-based extreme temperature indices is converted into days per year, which facilitates the comparisons with other temperature indices. Warm (wsdi) and cold (csdi) spell duration indicators consider the events of long-lasting runs of warm or cool days based on the percentile values. Monthly extreme temperature indices, as summarized in Table II, such as the highest and lowest daily maximum and minimum temperatures for the month (txx, txn, tnx, and tnn), and diurnal temperature range (dtr), are based on monthly maximum or minimum records at individual weather stations. Indices using fixed thresholds include summer days (su25), ice days (id0), tropical nights (tr25), frost days (fd0), and growing season length (gsl). Thresholds 5 °C above or below these threshold values are also used to define stronger/weaker extremes.

Similarly, for the precipitation indices based on relative thresholds, upper fifth (r95p) and first (r99p) percentile values are used to calculate the accumulation of very wet day or extremely wet day precipitation. Single day precipitation totals are considered (rx1day), and cumulative values for consecutive days at individual weather stations are used to define monthly maximum five-day precipitation (rx5day). To examine durational characteristics of extreme precipitation events, consecutive dry (cdd) and wet (cwd) days are used. Annual average characteristics of precipitation events are represented in annual total wet-day precipitation (prcptot) and simple daily intensity index (sdii). Extreme precipitation

DOI: 10.1002/joc

Table II. Twenty extreme temperature indices.

Abbreviation	Term	Definition
(su30) su25	Summer days	Annual count when TX (daily maximum temperature) (>30 °C) >25 °C
(id-5) id0	Ice days	Annual count when TX (<−5 °C) <0 °C
(tr20) tr25	Tropical nights	Annual count when TN(daily minimum temperature) (>20 °C) >25 °C
(fd-5) fd0	Frost days	Annual count when TN (<−5 °C) <0 °C
gsl	Growing season length	Annual count between first span after 1 January (1 July in SH) of at least 6 days with mean temperature >5 °C and first span after 1 July (1 January in SH) of at least 6 days with mean temperature <5 °C
txx (txn)	Max Tmax (Tmin)	Monthly maximum value of TX (TN)
tnx (tnn)	Min Tmax (Tmin)	Monthly minimum value of TX (TN)
TN10P (TN90P)	Cool (warm) nights	Percentage of days when TN <10th (TN >90th) percentile
TX10P (TX90P)	Cool (warm) days	Percentage of days when TX <10th (TX >90th) percentile
wsdi (csdi)	Warm (cold) spell duration indicator	Annual count of days with at least six consecutive days when TX >90th (TN <10th) percentile
dtr	Diurnal temperature range	Monthly mean difference between TX and TN

Table III. Eleven extreme precipitation indices.

Abbreviation	Term	Definition
rx1day (rx5day)	Max 1-day (5-day) precipitation amount	Monthly maximum 1-day (consecutive 5-day) precipitation
sdii	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined number of days with precipitation (PRCP) ≥1.0 mm) in the year
r10mm, r20mm, r30mm	Number of 10, 20, 30 mm precipitation days	Annual count of days when PRCP ≥10, 20, and 30 mm, respectively
cdd (cwd)	Consecutive dry (wet) days	Maximum number of consecutive days with PRCP <1 mm (PRCP ≥1 mm)
r95p (r99p)	Very (Extremely) wet day precipitation	Annual total PRCP when PRCP >95th (PRCP >99th) percentile
prcptot	Annual total wet-day precipitation	Annual total PRCP in wet days (PRCP ≥1 mm)

events exceeding absolute thresholds of precipitation are characterized by the number of days with precipitation exceeding 10 mm (r10mm), 20 mm (r20mm), or 30 mm (r30mm).

Linear trends in the time series of each index at each weather station over the study period are extracted using least square likelihood methods, but statistical significance for the trends in extreme climate indices is performed using the Kendall-tau test, which is a non-parametric method to effectively evaluate the trend of extreme climate events (Press *et al*., 1986). Linear trends averaged across 143 weather stations are regionally averaged to examine the overall trends across the ten APN countries and the significance of the regional and overall trends are examined using a t-test. In averaging the trends, however, no area-based weighting corrections are made, so areas with a high data density will be over-represented in the regional averages. Thus, spatial maps of the trends at individual weather stations are also provided in this study. Averages for each country and APN regional averages are calculated based on these daily records at individual weather stations with less than 10% missing climatic data. In addition to these extreme index data sets, time series of interannual anomalies of seasonal and annual average maximum and minimum temperatures are calculated at individual weather stations with respect to the 1971–2000 average values. In the calculation of seasonal values, the period between June and August (JJA) for weather stations in the Northern Hemisphere (NH) is considered as summer and that between December and February (DJF) is regarded as winter. The opposite is applied to weather stations in the Southern Hemisphere (SH). These definitions extend to stations near the Equator (e.g. in Malaysia), even though no significant distinction of thermal seasons exists in the tropical regions. Distribution maps are drawn considering the

DOI: 10.1002/joc

magnitude and statistical significance levels of each index at individual weather stations using the Geographic Information System (ArcGIS 9.3). Linear trends with p-value less than 0.05 are considered statistically significant in this study. In these spatial distribution maps, filled triangles represent statistically significant (95% confidence) trends over the 1955–2007 period. The direction of triangles indicates the sign of the changes, and the size of symbols represents the magnitude of the changes. Circle symbols are plotted when the p-value of Kendall's tau test is not available due to the event rarely or never occurring in the case of the fixed threshold-based indices (e.g. frosts near sea level in equatorial areas). In the case of growing season length, the circle symbols are drawn when its duration exceeds 364 days, an indicator that the temperature never falls below the growing season threshold.

Seasonal relationships between the changes in climate means and changes in extreme events across 143 weather stations are analysed using scatter plots and linear regression analyses. Trends in the scatter plots are extracted using the first eigenvector of the principal component analysis (also called empirical orthogonal function) that provides the maximum amount of joint variations of the independent and dependent variables (Wilks, 2006). To compare seasonal and diurnal differences in the sensitivity of changes in extreme events relative to changes in climate means, the original extreme and mean data at individual weather stations are normalized to a standard deviation unit.

3. Annual and seasonal changes in temperature means and extreme events

3.1. Temperature means and percentile-based extreme temperature events

Averaged over the APN region, annual mean maximum and minimum temperatures have increased by 0.17 °C/decade and 0.24 °C/decade since the mid-1950s, respectively (Figure 2). These increase rates are greater than the warming rate of the global mean surface temperature (0.13 ± 0.03 °C/decade) over the 50-year period from 1956 to 2005 (IPCC, 2007). The rate of increase of annual minimum temperatures is greater than that of annual maximum temperatures in most APN countries who participated in this study (Table IV). The largest difference in increase rates between annual minimum and maximum temperatures is found in Thailand, amounting to more than 0.20 °C/decade, whereas the difference is relatively small in island countries surrounded by oceans such as Japan (0.06 °C/decade) and New Zealand (0.09 °C/decade). In contrast, in Vietnam and Australia, the increase rates of annual maximum temperature for the stations studied are greater by 0.03–0.04 °C/decade than those of annual minimum temperature. These results may differ from national analyses based on more complete networks, although in the case of Australia they are broadly consistent with national analyses which show identical trends for maximum and minimum temperatures over the 1955–2007 period.

According to analyses of seasonal change rates (Figure 2), the rates of increase of average winter (DJF in the NH and JJA in the SH) maximum and minimum temperatures over the APN region are greater than those in summer. In winter, the rates of increase in maximum and minimum temperatures over the APN region are 0.22 and 0.33 °C/decade, respectively, whereas the corresponding increases in summer maximum and minimum temperatures are 0.11 and 0.16 °C/decade, respectively. The increase rate of minimum temperature is generally greater than that of maximum temperature in both summer and winter, indicating larger changes in mean temperatures by night than by day. However, the sign and magnitude of changes in seasonal maximum and minimum temperatures varies spatially from one country to another (Table IV). In Australia, the rate of increase of winter maximum temperature (0.11 °C/decade) is greater than that of minimum temperature (0.09 °C/decade), which is the opposite of the APN regional trends. Moreover, in

Table IV. Linear trends (°C/decade) in annual, winter and summer maximum and minimum temperatures in individual countries of the APN region, 1955–2007.

Climate means	Trends of maximum temperature			Trends of minimum temperature		
Countries	Winter	Summer	Annual	Winter	Summer	Annual
Mongolia	0.442*	0.429*	0.300*	0.322*	0.398*	0.380*
China	0.276*	0.092*	0.195*	0.476*	0.169*	0.327*
Republic of Korea	0.371*	0.047	0.236*	0.348*	0.117*	0.255*
Japan	0.103	0.115	0.124*	0.225*	0.149*	0.189*
Vietnam	0.250*	0.187*	0.242*	0.273*	0.178*	0.206*
Pakistan	0.168	−0.036	0.124*	0.258*	−0.024	0.198*
Thailand	0.161*	0.203*	0.164*	0.559*	0.261*	0.361*
Malaysia	0.192*	0.162*	0.157*	0.236*	0.255*	0.230*
Australia	0.113*	0.080	0.127*	0.085	0.122*	0.094*
New Zealand	0.115*	−0.012	0.044	0.172*	0.109*	0.129*

Trends marked with (*) are statistically significant at the 95% level.

DOI: 10.1002/joc

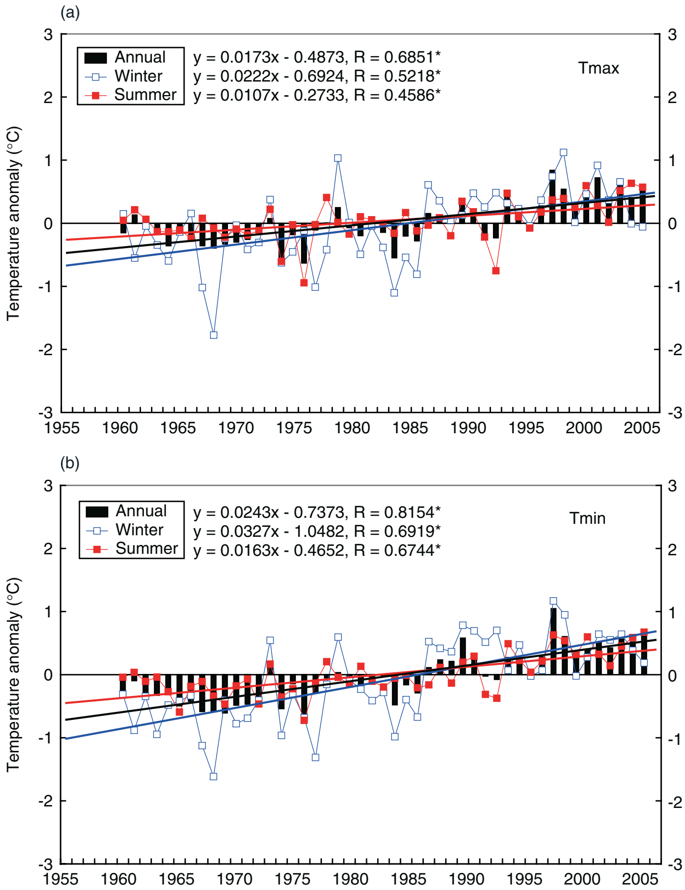

Figure 2. Changes in mean (a) maximum and (b) minimum temperatures over the APN region, for annual, winter and summer periods. Trends marked with (*) are significant at the 95% level. This figure is available in colour online at www.interscience.wiley.com/ijoc

Mongolia, the increase rate of winter (summer) maximum temperature is greater by 0.12 °C/decade (0.03 °C/decade) than that of minimum temperature. In general, trends in mean maximum and minimum temperatures are weaker in island countries, such as New Zealand and Japan, than they are in countries that have a significant number of stations in continental locations, such as Mongolia, China and Thailand. These differences are apparent both in summer and in winter, and for both maximum and minimum temperatures. The main exception to this rule is Australia, which shows relatively weak trends compared with the other APN countries, despite the continental location of many of the stations.

The significant changes in annual, seasonal maximum and minimum temperature means are associated with noticeable changes in the frequency of extreme temperature events in the APN region over the 1955–2007 period (Figure 3). Linear trend analyses of each extreme temperature index averaged across 143 weather stations show that the average frequency of cool nights (days) has decreased across the APN region by 6.4 days/decade (3.3 days/decade), whereas the frequency of warm nights (days) has increased by 5.4 days/decade (3.9 days/decade) over the 1955–2007 period. In the time series of these extreme temperature indices (Figure 4), curve-fitted functions generally fit the data better than linear regressions, suggesting that the rate of change of extreme temperature events has accelerated in the later part of the study period. Although there is also some evidence of this nonlinearity for mean temperatures as well, it is much more apparent when extremes are considered. Analysing individual indices, it is clear that the rate of change of the frequency of warm and cool days and warm nights has accelerated substantially since the late 1980s, whereas the frequency of cool nights has decreased approximately linearly since the mid-1950s. Over the last 20 years (1988–2007), the annual frequency of warm nights (days) has increased by 11 days/decade (11.2 days/decade), whereas that of cool nights (days) has decreased by 4.2 days/decade (4.6 days/decade). The rates of increase of the annual frequency of warm days and nights in the last 20 years are two or three times those over the entire study period. In addition, comparisons of the probability distribution function (PDF) of the annual percentage of cool nights and warm days in each of three 20-year subsets of the full 53-year period under consideration suggest that there have been systematic shifts in the mean and variance of the frequency of extreme temperature events in recent decades (Figure 5). The mean of the PDF of cool nights has gradually decreased over the three 20-year periods with a reduction in variance, whereas the mean frequency of warm days has increased abruptly between the second 20-year period (1968–1987) and the

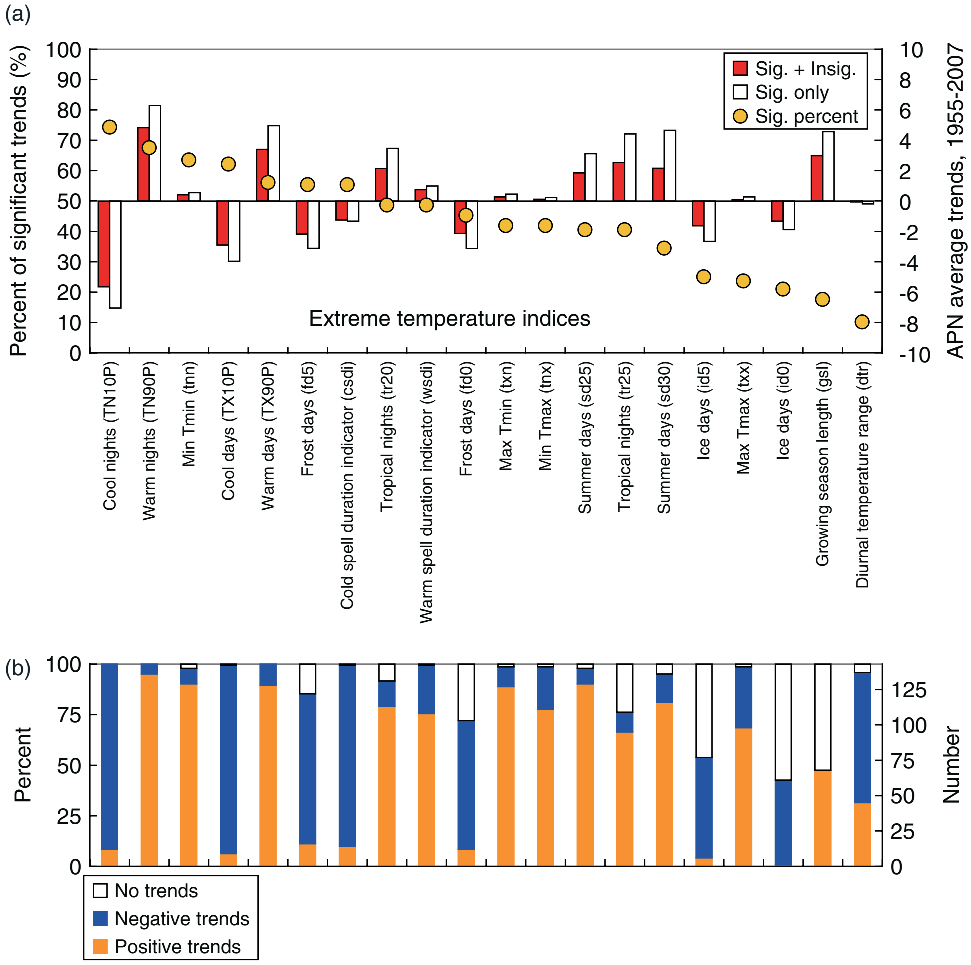

Figure 3. (a) Trends in 20 extreme temperature events averaged over the APN region. Filled circles indicate the percentage (left-hand scale) of the 143 stations that show a significant (95% level) trend for that index. Filled and white bars show the trend (right-hand scale) in that index averaged over all stations (filled) and only over those stations with significant trends (white). The unit of indices is days/decade except for Max Tmax (txx), Max Tmin (txn), Min Tmin (tnn), and Min Tmax (tnx) whose unit is °C/decade. (b) Percentage of all stations with negative and positive trends for each index. Stations where trends cannot be calculated due to the non-occurrence of the event are shown as 'no trends'. This figure is available in colour online at www.interscience.wiley.com/ijoc

recent 20-year period (1988–2007), with variance also increasing.

Spatial distribution maps of trends in these indices at the individual stations provide more detailed information of how the magnitude of rates of change in extreme climate events varies from one weather station to another (Figure 6). Statistically significant trends consistent with overall warming (increased frequency of warm days and nights, decreased frequency of cool days and nights) have occurred at approximately 70% of the stations considered (Figure 3(a)), with trends in the annual frequency of these events locally exceeding 20 days/decade for nighttime extremes, and 10 days/decade for daytime extremes. Opposite trends are found at about 10% of stations (Figure 3(b)), but almost none are significant. At most stations, the change rates of nocturnal extreme temperature events are greater than those of the daytime extreme temperature events, consistent with the regional results described earlier.

The strongest changes in extremes are observed in northern tropical regions including Malaysia and Thailand. In these countries, the maximum decrease rate in the annual frequency of cool nights amounts to −22 days/decade, whereas the maximum increase rate of annual frequency of warm nights rises to 25 days/decade. In contrast, trends of the annual frequency of cool and warm nights in western Australia are weak and mostly statistically insignificant, and weak trends are also observed for cool and warm days in southern China and central Australia. In terms of proximity to the oceans, the interannual variability of these percentile-based extreme temperature indices is lower in island countries such as New Zealand than those in inland countries such as Mongolia. The standard deviation of the annual frequency of cool nights over the 1955–2007 period is 3.8 days in New Zealand but 4.8 days in Mongolia.

3.2. Fixed threshold-based extreme temperature events and duration indicators

Fixed threshold-based extreme temperature events generally show trends over the 1955–2007 period, which are consistent with those of the percentile-based indices. As

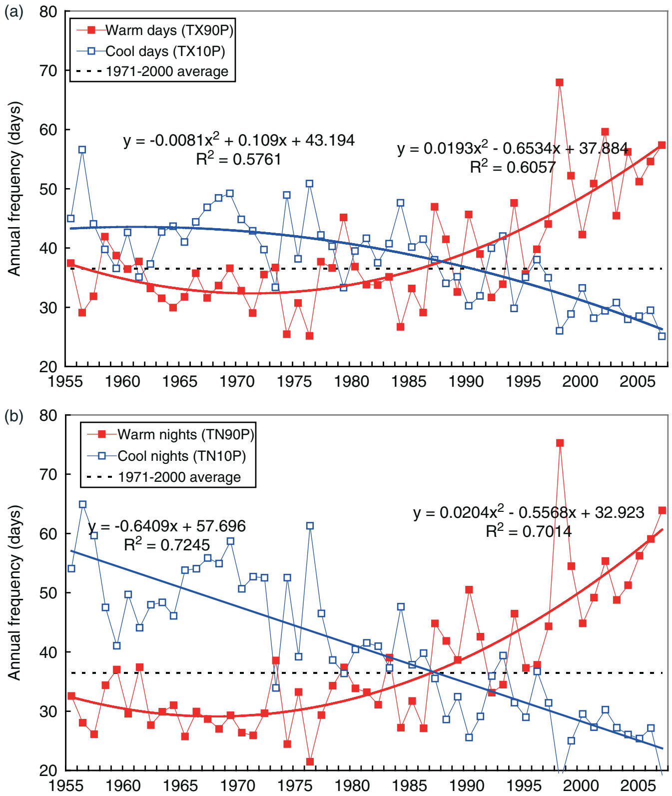

Figure 4. Regional average change in (a) warm days (TX90P) and cool days (TX10P), and (b) warm nights (TN90P) and cool nights (TN10P), averaged across ten APN countries, 1955–2007. This figure is available in colour online at www.interscience.wiley.com/ijoc

illustrated in Figure 3, the frequency of cold extremes, on the basis of fixed thresholds such as ice days and frost days, has decreased over the APN region, whereas the frequency of warm extremes such as summer days and tropical nights has increased over the 1955–2007 period.

The frequency of frost days, when daily minimum temperature falls below 0 °C, has decreased by −2.1 days/decade over the APN region, whereas tropical nights, when daily minimum temperature exceeds 25 °C, have increased in frequency by 2.5 days/decade. Consistent with these trends, ice days, when daily maximum temperature fails to reach 0 °C, have decreased in frequency by −1.3 days/decade, whereas summer days, when daily maximum temperature exceeds 25 °C, have increased in frequency by 1.9 days/decade. The percentages of weather stations with significant trends of these absolute threshold-based temperature indices over the 1955–2007 period range from 20% to 60%, which is a smaller proportion than the 70% found for percentile-based indices. Stations for which no trend is calculated in an index due to the event's absence or rarity at that station (see Section 2.2) are excluded from the calculation of these aggregates. Annual indices based on the monthly maximum or minimum of daily maximum or minimum temperatures (txx, txn, and tnx) generally show weaker trends, with only 25–40% of stations showing significant trends (Figure 3). As these indices are based on a single event in each year, they tend to show more interannual

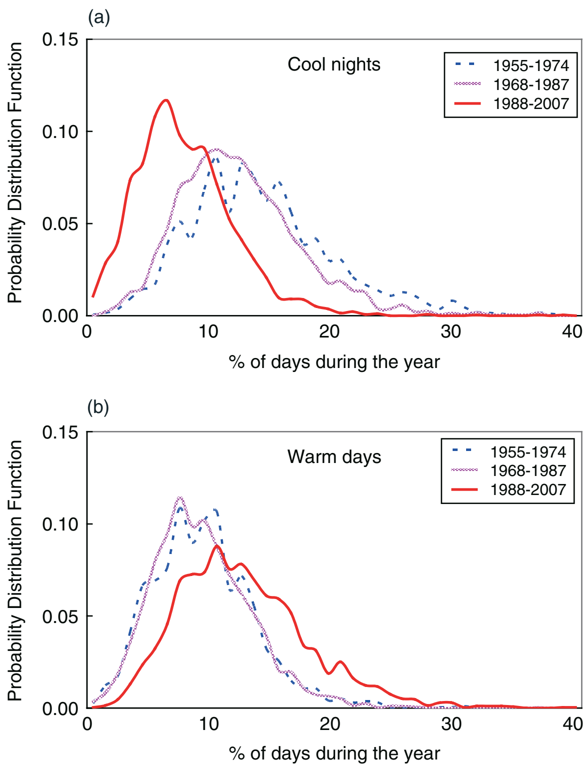

Figure 5. Probability distribution function of annual frequency of (a) cool nights (TN10P) and (b) warm days (TX90P) for 143 weather stations across the APN region for three 20-year periods: 1955–1974 (dotted line), 1968–1987 (light solid line), and 1988–2007 (dark solid line). This figure is available in colour online at www.interscience.wiley.com/ijoc

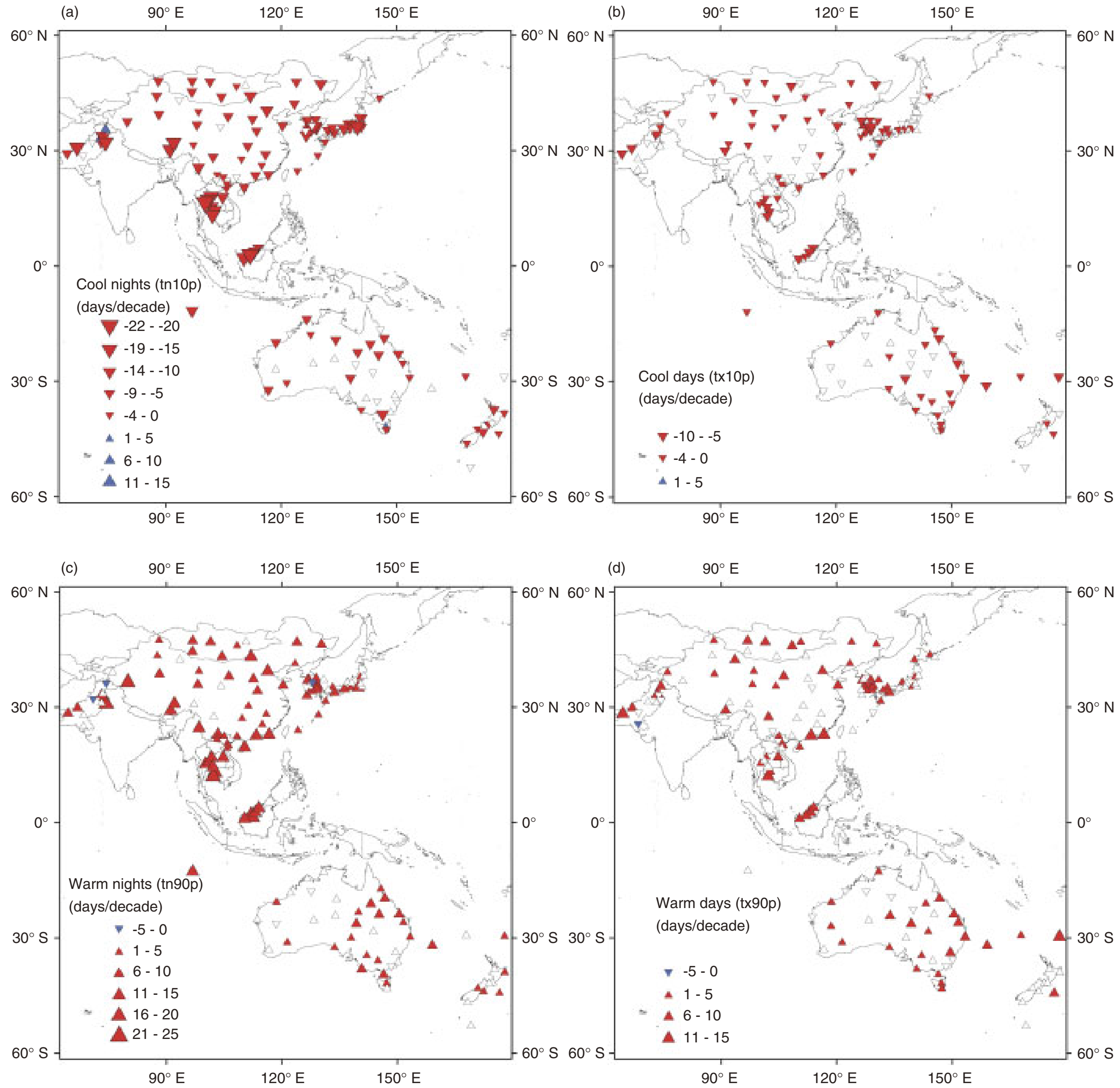

Figure 6. Spatial patterns of trends (days/decade) in percentile-based annual extreme temperature events at 143 individual weather stations across the APN region, 1955–2007: (a) cool nights (TN10P), (b) cool days (TX10P), (c) warm nights (TN90P), and (d) warm days (TX90P). Filled symbols represent statistically significant (95%) trends. The direction of triangles indicates the signs of the changes, and the size of symbols represents the magnitude of the changes. This figure is available in colour online at www.interscience.wiley.com/ijoc

variability than other indices based on multiple events during a year.

Considering the spatial distribution of trends in the fixed-threshold indices, the decrease rate of frost days in the extratropical region varies from 1 to 10 days/decade, whereas the decrease rate of ice days ranges between 1 and 5 days/decade (Figure 7). In those regions where tropical nights and summer days occur, tropical nights are increasing at a rate between 1 and 25 days/decade (locally exceeding 25 days/decade in Thailand), whereas summer days are increasing in frequency by 1–10 days/decade. Overall, nocturnal extreme temperature events based on fixed thresholds show more spatial variations than daytime events. Maps of the trends of these fixed-threshold indices at individual weather stations also indicate where these events are rare and no trends can be quantified. As the distribution of open circles in Figure 7(a)–(d) demonstrate, low temperature events such as ice days and frost days rarely occur in the tropical climate zone, whereas tropical nights and summer days rarely occur in the arctic or alpine climate zone, or in high mid-latitudes (e.g. New Zealand) or highlands (e.g. Mongolia and the Tibet Plateau).

Changes are also observed in duration indices, including growing season length and cold or warm spell duration indicators, as well as in range indices such as diurnal temperature range (Figure 8). At most weather stations in the extratropical climate zones, the growing seasons have lengthened over the 1955–2007 period at the rate of 1–10 days/decade, and statistically significant trends are observed in northeast Asia (Figure 8(a)). This index is not valid at most tropical and subtropical stations. The cold spell duration indicator, which is defined as the number of days contained within periods with at least six consecutive cool nights, and the warm spell duration indicator, which is defined as the number of days contained

DOI: 10.1002/joc

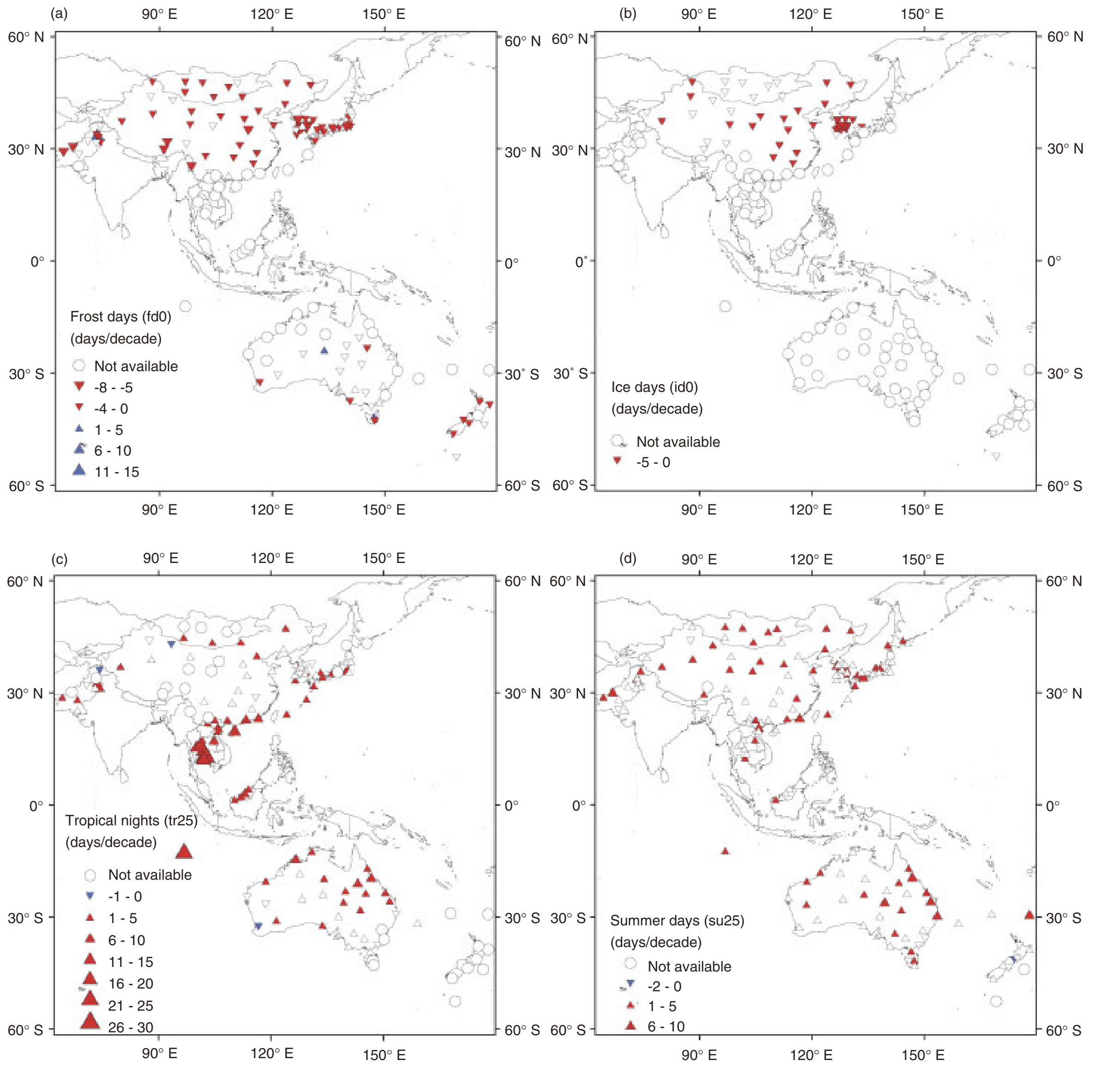

Figure 7. Same as in Figure 6, but for threshold-based indices including (a) frost days (fd0), (b) ice days (id0), (c) tropical nights (tr25), and (d) summer days (su25). Open circles represent locations where that extreme is rare. This figure is available in colour online at www.interscience.wiley.com/ijoc

within periods with at least six consecutive warm days, show spatially consistent change patterns across the APN region (Figure 8(c) and (d)). The cold spell duration has decreased by 1–10 days/decade, whereas the warm spell duration has increased by 1–6 days/decade. Statistically significant trends of cold spell duration are observed mainly in the western Pacific and East Asia, whereas relatively few stations show statistically significant trends in warm spell duration. Trends in the mean diurnal temperature range are mixed, with both increases and decreases of up to 1 °C/decade observed at various stations.

3.3. Changes in extreme temperature events relative to changes in temperature means

Trends in four percentile-based extreme temperature indices at 143 weather stations are compared to examine the extent to which the magnitude of their changes are consistent with or different from each other at any given station (Figure 9). The slope of the first eigenvector fitted to the combination of change rates of annual cool nights against those of annual warm nights is −0.8 while that for cool days against warm days is −1.6 (Figure 9(a) and (b)). These ratios suggest that the decrease rate of annual frequency of cool nights is greater than the increase rate of warm nights across the APN region. The decrease rate of annual frequency of cool days is less than the increase rate of warm days. Moreover, steep slope values of the first eigenvector (Figure 9(c) and (d)) suggest that annual changes in temperature extremes appear more clearly in nocturnal events than in daytime ones, reinforcing the findings discussed earlier. The magnitudes of changes in warm and cool nights are typically more than double those of warm and cool days. These results show that diurnal changes in extreme temperature events in the APN region have occurred

DOI: 10.1002/joc

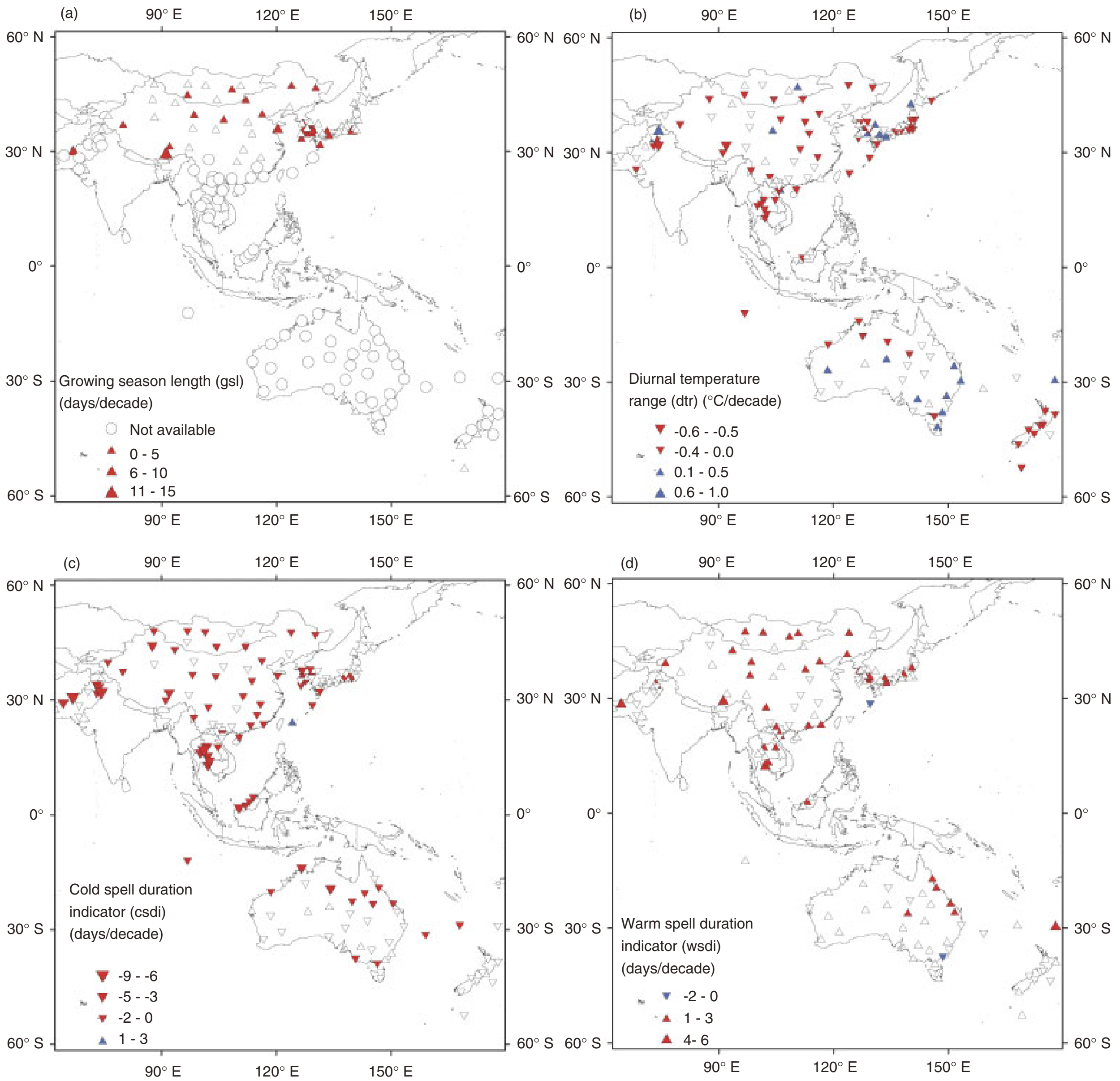

Figure 8. Same as in Figure 6, but for duration and range indicators of temperature including (a) growing season length (gsl), (b) diurnal temperature range (dtr), (c) cold spell duration indicator (csdi), and (d) warm spell duration indicator (wsdi). Open circles represent locations where that event is rare. This figure is available in colour online at www.interscience.wiley.com/ijoc

asymmetrically over the 1955–2007 period, with stronger signals at night than during the day.

A comparison of trends of extreme temperature events and means can demonstrate how sensitively seasonal and diurnal changes in extreme temperature events have responded to changes in climate means. In winter months (DJF for the NH, JJA for the SH), the decrease rate of the frequency of cool nights per unit increase in minimum temperature mean across the APN region is −8.4 days/°C (Figure 10(a)). In summer months (JJA for the NH, DJF for the SH), the rate of increase in the frequency of warm nights per unit increase in minimum temperature mean is 15.3 days/°C (Figure 10(c)). For maximum temperature, in winter months, the rate of decrease of the seasonal frequency of cool days per unit increase in maximum temperature mean is −9.0 days/°C, and in summer months, the rate of increase of the seasonal frequency of warm days per unit increase in maximum temperature mean is 11.4 days/°C (Figure 10(b) and 10(d)). These results suggest that change rates in extreme temperature events relative to changes in temperature means across the APN region are greater in summer than in winter.

For comparisons of seasonal and diurnal generalized sensitivities, seasonal temperature means and extreme temperature events are normalized using standard deviations at individual weather stations and the linear trends in the time series of normalized data for extreme temperature events are plotted against those for normalized seasonal temperature means (Figure 11). In the scatter plots, the first eigenvectors of the principal component analysis suggest that changes in low winter Tmin extremes (nights) are similar to changes in means, but other winter

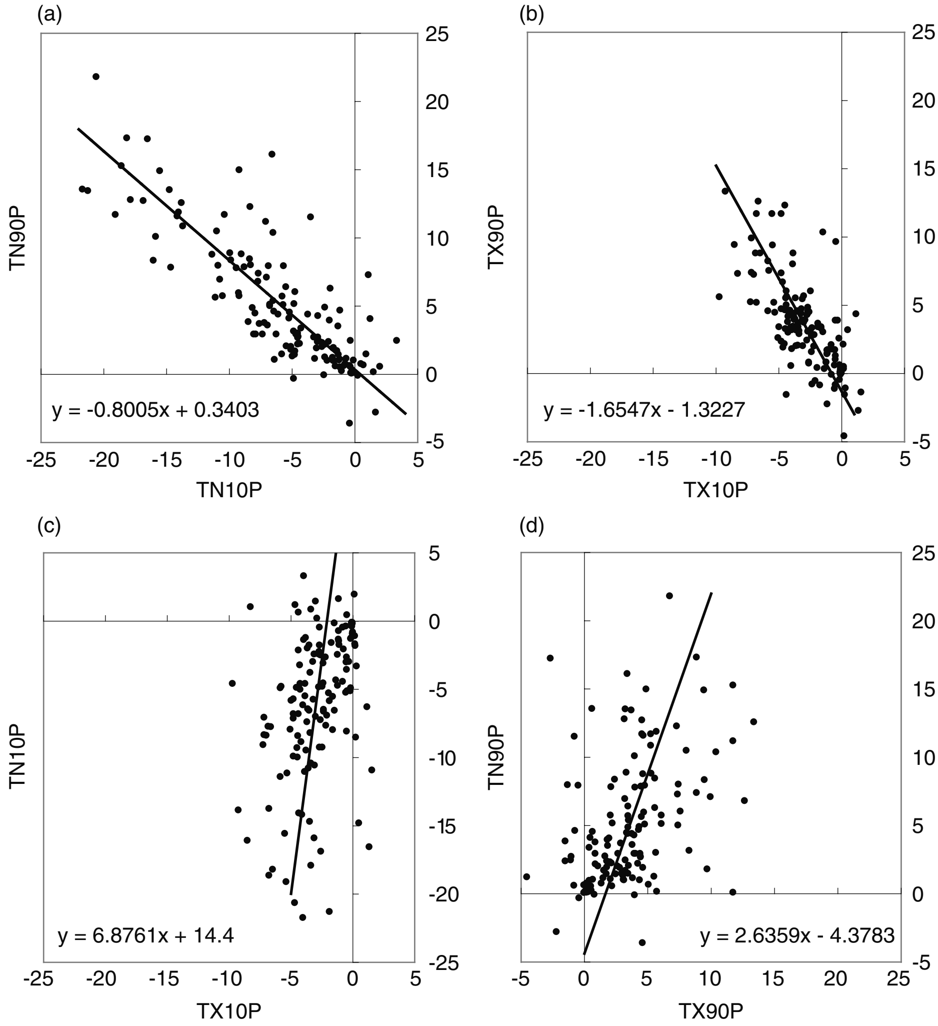

Figure 9. Comparisons of trends (days/decade) of extreme temperature events over the 1955–2007 across the APN region: cool nights (TN10P), cool days (TX10P), warm nights (TN90P), and warm days (TX90P). Each regression line indicates the first eigenvector of the principal component analysis.

and summer extreme events changes are less than seasonal temperature means. These results indicate that there have been seasonally and diurnally asymmetric changes in extreme temperature events relative to recent increases in temperature means in the APN region.

The sensitivity of changes in seasonal extreme temperature events to changes in temperature means varies from one country to another (Table V). The sensitivity of the winter frequency of cool days to changes in winter maximum temperature varies from −4.3 days/°C in China to −10.1 days/°C in Malaysia, whereas that of cool nights relative to changes in winter minimum temperature ranges from −1.1 days/°C in Pakistan to −20.2 days/°C in Malaysia. The sensitivity of the summer frequency of warm days to changes in summer maximum temperature varies from 6.1 days/°C in Australia to 14.8 days/°C in the Republic of Korea, whereas for warm summer nights relative to changes in summer minimum temperature it ranges from 5.6 days/°C in New Zealand to 16.4 days/°C in Malaysia.

In most cases, Northern Hemisphere countries show greater sensitivity of extremes to changes in means in summer than in winter, reflecting the generally spatial variability of changes in extreme temperature events in summer in those regions. In contrast, for Southern Hemisphere low latitude locations, the sensitivities are slightly greater in winter (noting that a sensitivity is not calculated for warm days in New Zealand, as mean summer maximum temperatures are cooling slightly there), reflecting the fact that in large parts of northern Australia winter temperatures are more variable than those in summer.

4. Annual and seasonal changes in precipitation totals and extremes

4.1. Annual and seasonal total precipitation

In the APN region, seasonal and annual precipitation do not show substantial, spatially coherent trends, unlike the situation for temperature means or extremes. In the time series of annual total precipitation averaged across the region, several high positive anomalies of annual precipitation are identified in 1975, 1998 and 1999, but there has been no obvious linear trend in annual

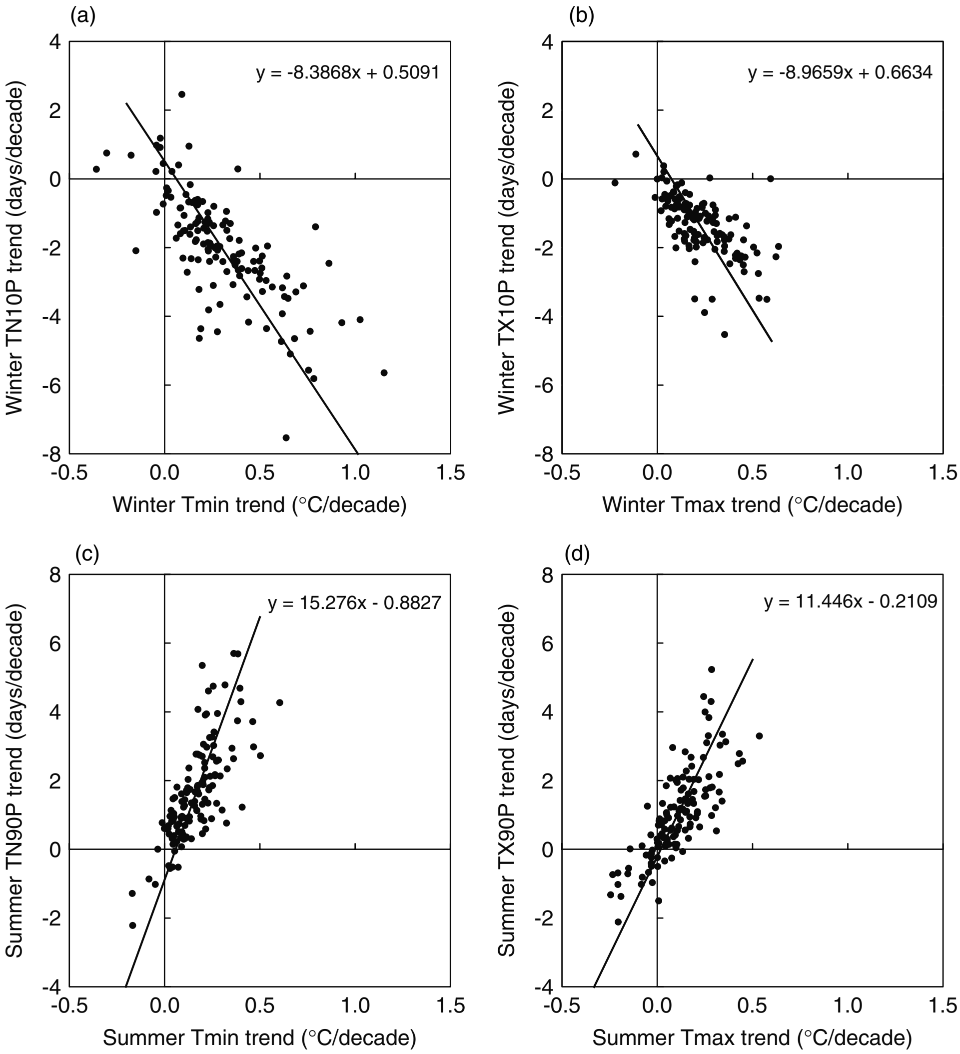

Figure 10. Summer and winter trends in extreme temperature events relative to changes in summer and winter extreme temperature means across the APN region, 1955–2007: cool nights (TN10P), cool days (TX10P), warm nights (TN90P), and warm days (TX90P). Each regression line indicates the first eigenvector of the principal component analysis.

Table V. Sensitivity (days/°C) of extreme temperature event frequency to changes in mean maximum and minimum temperatures for winter and summer, averaged over individual countries, 1955–2007.

Countries	Winter		Summer	
	Cool days/Tmax	Cool nights/Tmin	Warm days/Tmax	Warm nights/Tmin
Mongolia	−9.9	−5.1	6.4	7.1
China	−4.3	−5.2	10.5	10.7
Republic of Korea	−5.5	−6.0	14.8	11.0
Japan	−6.9	−9.9	11.6	11.2
Vietnam	−4.3	−6.8	8.2	12.1
Pakistan	−4.6	−1.1	N/A	N/A
Thailand	−7.3	−7.0	10.2	14.0
Malaysia	−10.1	−20.2	13.9	16.4
Australia	−7.0	−9.0	6.1	6.8
New Zealand	−6.9	−6.1	N/A	5.6

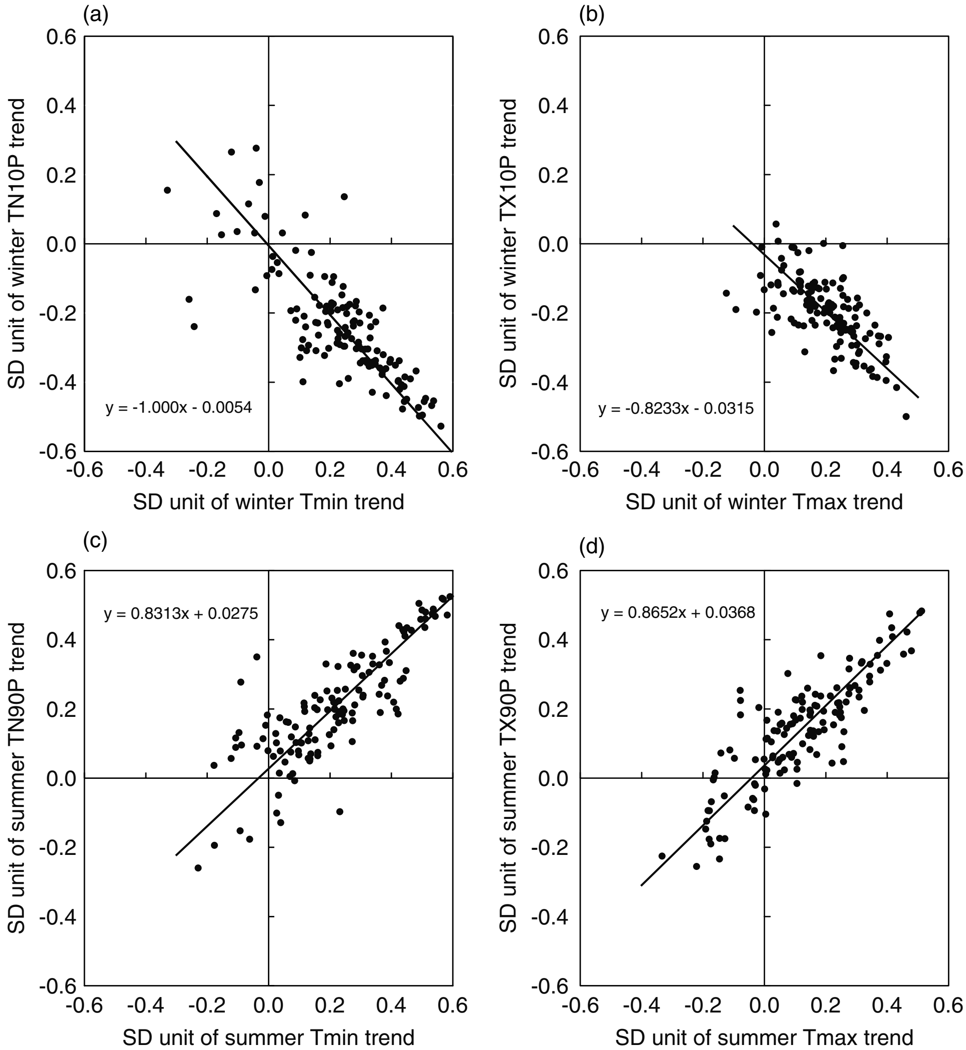

Figure 11. Generalized sensitivity of changes in summer and winter extreme temperature events relative to changes in summer and winter extreme temperature means across the APN region, 1955–2007: cool nights (TN10P), cool days (TX10P), warm nights (TN90P), and warm days (TX90P). All values of dependent and independent variables in the scatter plots indicate the trends derived from the time series of the normalized mean and extreme events using standard deviations (SD) at individual weather stations. Each regression line indicates the first eigenvector of the principal component analysis.

total precipitation (Figure 12). Summer total precipitation shows a slight (and insignificant) increasing trend, largely due to the positive anomalies since the mid-1990s, whereas winter total precipitation fails to show any significant change pattern.

Similarly, linear trends of annual and seasonal total precipitation in most countries are not statistically significant, with exceptions in the Republic of Korea and Mongolia (Table VI). Similar results concerning increases of summer precipitation in the Republic of Korea have also been reported in other studies. Choi *et al*. (2008) analysed the linear trends of precipitation indices extracted from 61 weather stations for the 1973–2007 period and found that increases in intensity of heavy rainfall events (exceeding 40 mm) are the major contributor to the increases of seasonal total precipitation in recent decades.

4.2. Extreme precipitation events

Time series analyses of extreme precipitation indices averaged across 143 weather stations also show that there have been no regionally systematic, statistically significant trends in the APN region over the 1955–2007 period (Figure 13). The regional average 5 day maximum precipitation shows an increasing trend of 0.82 mm/decade, but this is statistically insignificant. The simple daily intensity index shows an increasing trend at the rate of 0.09 mm/day per decade, but it is also statistically insignificant. The regional average number of 10 mm precipitation days shows an insignificant decreasing trend of 0.1 days/decade. In the case of duration-based indicators of wet and dry conditions, including consecutive wet (cwd) and dry (cdd) days, there are no observable regional trends with statistical significance.

Moreover, the spatial coherence that is observable for trends in percentile-based temperature indices (significant at approximately 70% of 143 weather stations) is not replicated in trends of precipitation events across the APN region. Of the 143 weather stations across the APN region, statistically significant trends in extreme

DOI: 10.1002/joc

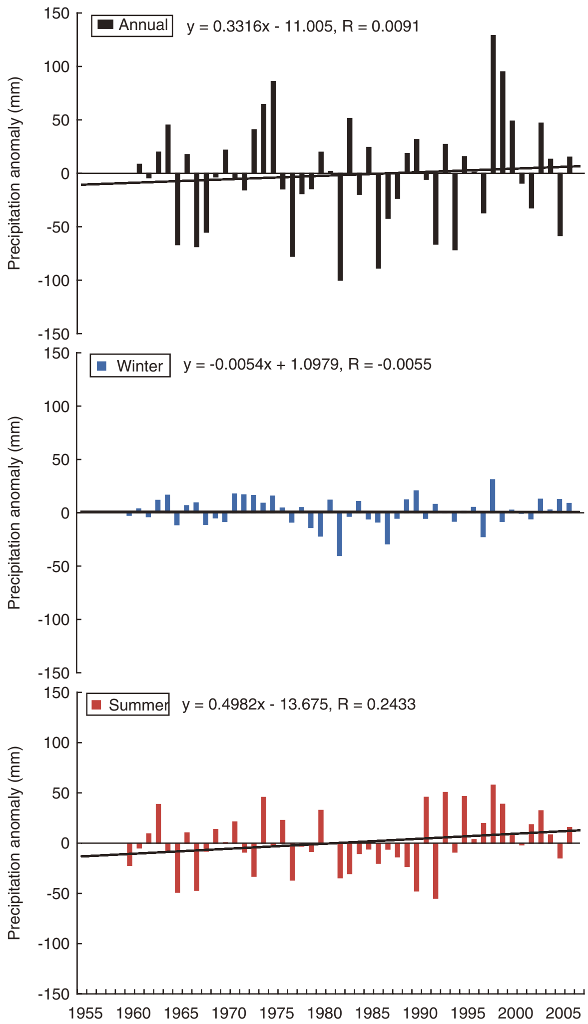

Figure 12. Same as in Figure 2, but for annual or seasonal total precipitation (mm). This figure is available in colour online at www.interscience.wiley.com/ijoc

Table VI. Linear trends (mm/decade) of annual, summer and winter total precipitation in individual countries of the APN region, 1955–2007.

Countries	Trends of total precipitation (mm/decade)		
	Annual	Winter	Summer
Mongolia	−4.4	0.5*	−5.9
China	3.3	1.5	1.6
Republic of Korea	24.5	−1.9	33.0*
Japan	−17.5	−3.2	−6.8
Vietnam	−44.2	−1.1	0.8
Pakistan	12.2	2.5	10.5
Thailand	−7.7	−0.8	0.9
Malaysia	25.6	4.1	5.6
Australia	1.5	−3.7	1.9
New Zealand	−7.7	−2.7	1.8

Trends marked with (*) are statistically significant at the 95% level.

precipitation indices are observed at less than 30% (Figure 13(a)). As illustrated in Figure 13(b), for most indices, the percentage of stations with positive trends is similar to that of stations with negative trends. Observation sites included in this study are not spatially dense enough to discuss the field significance of changes in extreme precipitation events. Generally, clustering patterns of statistically significant changes in extreme precipitation events are not observed across individual countries. However, it may be possible to observe local clustering patterns if higher spatial resolution data were available. Overall, very wet day (r95p) or extreme wet day (r99p) precipitation, and monthly maximum 1-day (rx1day) show significant trends at only 10–14% of weather stations, without any spatially consistent patterns in the sign (Figure 14). Similarly, few stations show statistically significant trends of duration-based indicators such as consecutive wet days (cwd) or consecutive dry days (cdd), with significant trends at less than 12% of stations and no systematic clustering patterns (Figure 14(c) and (d)).

At the regional scale, decreasing trends of very wet or extremely wet day precipitation, mostly non-significant, are found in northern China as well as in Mongolia (Figure 14(a) and (b)). The opposite trend is observed in southern and central China, as well as in the Republic of Korea, indicating north-south reversed patterns in East Asia. Such increases of summer precipitation in the Republic of Korea and the mid- to lower Yangtze basin, and decreases of annual and seasonal precipitation in northern China, have been reported in other studies (Choi *et al.*, 2008; Ding and Ren, 2008). Mostly insignificant positive trends of very wet day precipitation are observed in western Australia, whereas the reverse is true in eastern Australia, particularly on the east coast where some trends are significant.

It is concluded from these results that there have been no spatially coherent changes in the amount, frequency, intensity, and duration of extreme rainfall events across the APN region as a whole for the 1955–2007 period, but changes in extreme precipitation events have occurred on local scales or smaller regional scales than the entire APN region. These results suggest that future studies need to examine changes at a much finer spatial scale, based on more stations with *in situ* precipitation data.

5. Discussion and conclusions

One of the key findings of this study is that there have been spatially coherent but temporally asymmetric change patterns in extreme temperature events across the APN region over the 1955–2007 period, while significant changes in precipitation means and extreme events are observed only on small local scales. In general, extremes of minimum temperature, both high and low, have shown stronger trends over the period than extremes of maximum temperatures.

This study also indicates shortcomings of indices based on fixed thresholds in examining extreme climate events across regions with multiple climate zones, such as the

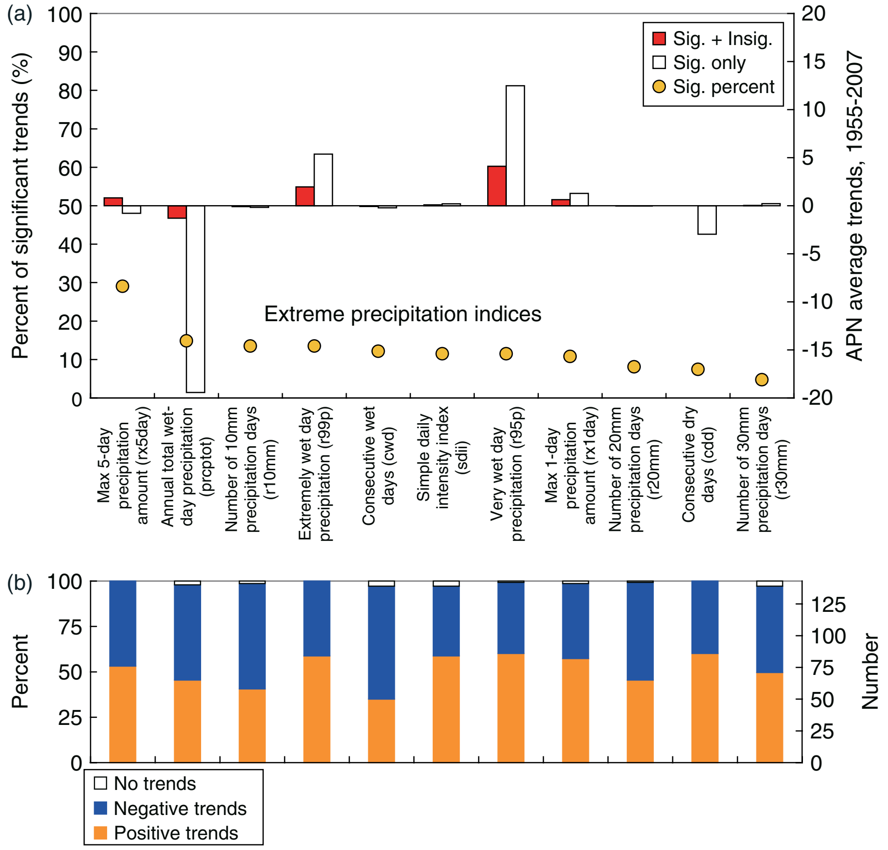

Figure 13. Same as in Figure 3 but for 11 extreme precipitation indices. Trends are in millimetre/decade except for r10mm, r20mm, r30mm, cwd and cdd, which are in days/decade. This figure is available in colour online at www.interscience.wiley.com/ijoc

APN region. For instance, ice days and frost days are rarely observed in the tropical regions between 25°N and 25 °S, and summer days rarely occur at high altitudes or in higher latitude regions. Similar conclusions regarding the impacts of latitude on frost days were documented by Alexander *et al*. (2006). As a result, the number of stations that show significant trends for fixed threshold-based extreme temperature indices such as frost days and tropical nights is less than the number of stations that show significant trends of percentile-based extreme temperature events, which show significant trends at 70% of weather stations.

In contrast to the largely significant and spatially coherent trends in the frequency of extreme temperature events across the APN region, most extreme precipitation indices show significant trends at only a small proportion (30% or less) of weather stations, and there are no spatially clustered change patterns. The signs of changes reported in this study are consistent with the findings by Manton *et al*. (2001) for southeast Asia, and the percentages of weather stations with significant trends in precipitation indices are also similar to the global averages reported by Alexander *et al*. (2006). Compared with Manton *et al*. (2001), however, this study provides more detailed information about the magnitude of seasonal trends, based on longer term data at a greater number of stations, as well as additional indices.

Some global models project that during the warmer 21st century, precipitation will decrease in the subtropical regions and become more concentrated in intense rainfall events with a greater risk of droughts (IPCC, 2007). In contrast, precipitation is projected to increase in the high latitude regions. Projected changes in mean precipitation may influence changes in precipitation extremes. This underlines the importance of ongoing monitoring of extreme temperature and precipitation events in those regions.

At regional and local scales, there are many influences on climate in addition to broad global changes, including urbanization and elevation, and proximity to water bodies. These influences can affect changes in extreme climate events. For instance, the magnitude of changes is generally small in island countries such as Japan and New Zealand compared with more continental locations. A similar result for a slightly different set of stations and participating countries is documented in Manton *et al*. (2001), showing the smallest changes in island countries including Fiji, Japan, and New Zealand. These patterns are consistent with the simulations of GCMs, which generally indicate slower warming on/near the ocean than in continental interiors (IPCC, 2007). The moist atmosphere near the oceans may subdue the occurrences of extreme temperature events due to its high heat capacity compared with the drier inland atmosphere.

This study provides useful information about changes in extreme climate events since the mid-1950s at 143 weather stations across ten APN countries. However, the magnitude of change rates quantified in this study should

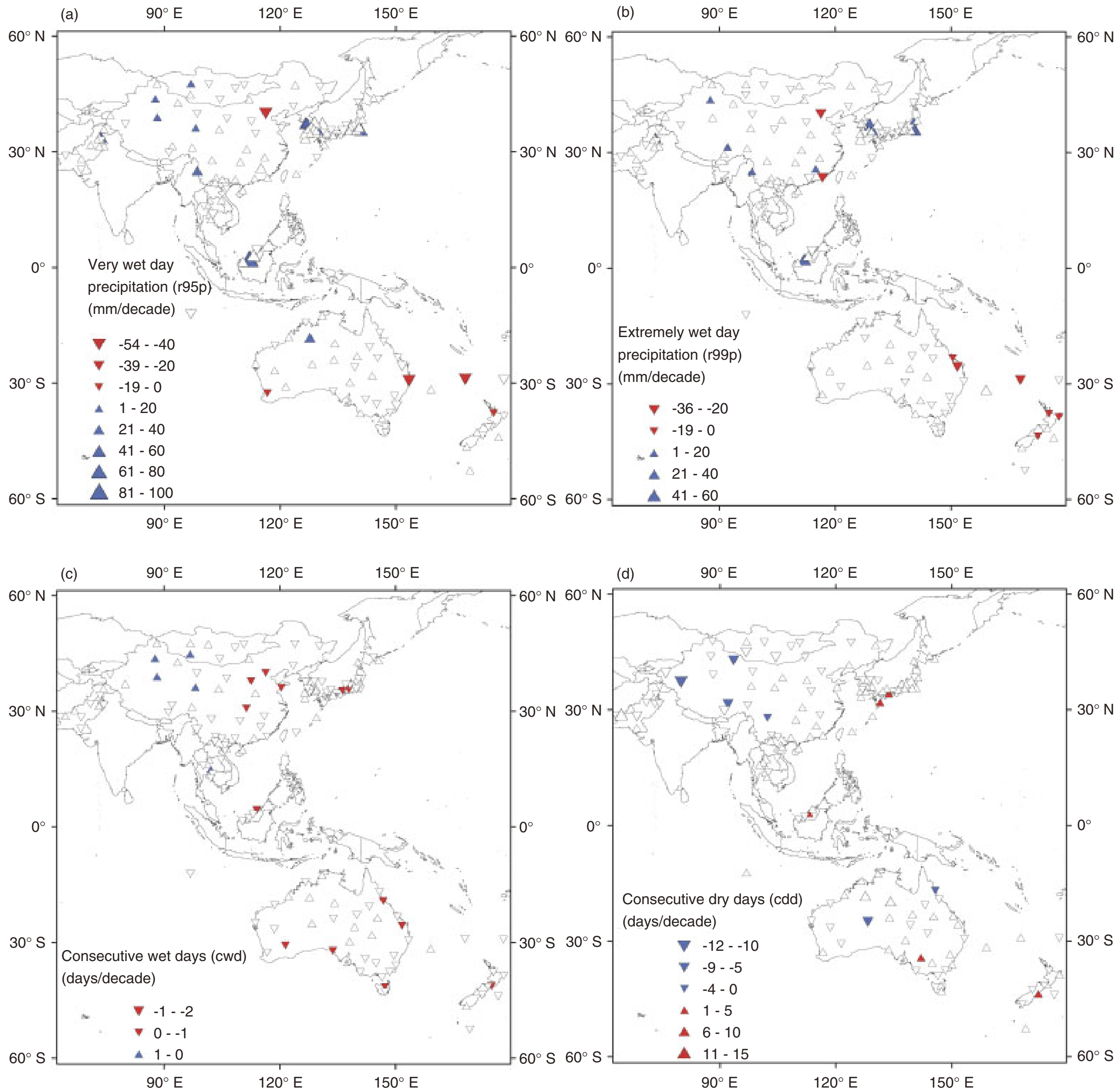

Figure 14. Same as in Figure 6, but for (a) very wet day precipitation (r95p), (b) extremely wet day precipitation (r99p), (c) consecutive wet days (cwd), and (d) consecutive dry days (cdd). This figure is available in colour online at www.interscience.wiley.com/ijoc

be used with caution due to data quality issues. In particular, urbanization might amplify the change rates of temperature-related extreme events. Many weather stations used in this study are currently located near or within regions where urbanization has occurred quickly as a result of rapid economic development. The removal of urbanization effects on temperature data was not conducted in this study due to a lack of suitable metadata. In future studies, there is a need to collect more metadata to classify weather stations into several groups (e.g. rural, small towns, and urban) based on observational environments, using criteria such as population of residential areas near stations and the percentage of high-density building within certain radii. In addition, further homogeneity checking is required to reduce potential bias of the data sets caused by other non climatic factors (Zhang *et al*., 2009).

Another important aspect that should be considered in future studies is the inclusion of more stations with reliable long-term data to quantify spatially weighed trends. At present, a high station density is potentially available in countries such as the Republic of Korea and Japan, but many valuable observations may be still paper-archived and effectively inaccessible in some countries in the APN region. Digitization of these data is important in improving the assessment of long-term climate change. Eventually, such quality-controlled data will allow further studies, including the association between changes in extreme climate events and broad-scale variability of the atmospheric circulation. Several previous studies on extreme events in different parts of the world have sought to find potential linkages between extreme temperature or precipitation events and large-scale atmospheric circulation (e.g. El Niño Southern Oscillation (ENSO) and

DOI: 10.1002/joc

North Atlantic Oscillation) or oceanic conditions (e.g. sea surface temperature (SST)) (e.g. Gershunov and Barnett, 1998; Haylock and Goodess, 2004; Aguilar *et al*., 2005; Griffiths *et al*., 2005; Nicholls *et al*., 2005; Scaife *et al*., 2008). However, more detailed studies are needed to fully understand the linkages between changes in extreme climate events and atmospheric circulation indices such as the Arctic Oscillation (AO) and the Pacific North American pattern (PNA). These future studies will permit better prediction systems for extreme climate events by considering their lead–lag relationships with atmospheric circulation patterns.

Future climate scenario data simulated by high-resolution regional climate models may also be useful in projecting future changes in extreme climate events, even though their uncertainty should also be considered through the comparison with *in situ* observational data. Regional climate scenario data may be able to fill the spatial gap between observation sites and provide fine-resolution data beyond what is currently available from the relatively low resolution global climate model outputs (Sillmann and Roeckner, 2008).

Acknowledgements

The authors are grateful for the funding support of the Asia-Pacific Network (Project No: ARCP2007-20NSG), the National Institute of Meteorological Research at the Korea Meteorological Administration (Project No: NMR-2009-B-2), and the Ministry of Sciences and Technology of China (Project No: 2007BAC29B02). We also deeply appreciate numerous weather observers in the APN countries who have made enormous efforts to collect the valuable data and made this study possible.

References

Aguilar E, Peterson TC, Ramírez Obando P, Frutos R, Retana JA, Solera M, González Santos I, Araujo RM, Rosa García A, Valle VE, Brunet India M, Aguilar L, Álvarez L, Bautista M, Castañón C, Herrera L, Ruano R, Siani JJ, Hernández Oviedo GI, Obed F, Salgado JE, Vázquez JL, Baca M, Gutíerrez M, Centella C, Espinosa J, Martínez D, Olmedo B, Ojeda Espinoza CE, Haylock M, Núñez R, Benavides H, Mayorga R. 2005. Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003. *Journal of Geophysical Research* **110**: D233107: DOI:10.1029/2005JD006119.

Alexander LV, Arblaster JM. 2009. Assessing trends in observed and modelled climate extremes over Australia in relation to future projections. *International Journal of Climatology* **29**: 417–435.

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research* **111**: D05109 DOI:10.1029/2005JD006290.

Choi G, Kwon WT, Boo KO, Cha YM. 2008. Recent spatial and temporal changes in means and extreme events of temperature and precipitation across the Republic of Korea. *Journal of the Korean Geographical Society* **43**: 681–700.

Ding YH, Ren GY (eds). 2008. *An Introduction of China Climate Change Science*. Beijing: Meteorological Press.

Frich P, Alexander LV, Della-Marta P, Gleason B, Haylock M, Klein Tank AMG, Peterson T. 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research* **19**: 193–212.

Gershunov A, Barnett TP. 1998. ENSO influence on intraseasonal extreme rainfall and temperature frequencies in the contiguous United States: observation and model results. *Journal of Climate* **11**: 1575–1586.

Griffiths GM, Chambers LE, Haylock MR, Manton MJ, Nicholls N, Baek H-J, Choi Y, Della-Marta PM, Gosai A, Iga N, Lata R, Laurent V, Maitrepierre L, Nakamigawa H, Ouprasitwong N, Solofa D, Tahani L, Thuy DT, Tibig L, Trewin B, Vediapan K, Zhai P. 2005. Change in mean temperature as a predictor of extreme temperature change in the Asia-Pacific region. *International Journal of Climatology* **25**: 1301–1330.

Griffiths GM, Salinger MJ, Leleu I. 2003. Trends in extreme daily rainfall across the South Pacific and relationship to the South Pacific Convergence Zone. *International Journal of Climatology* **23**: 847–869.

Haylock MR, Goodess CM. 2004. Inter-annual variability of European extreme winter rainfall and links with mean large-scale circulation. *International Journal of Climatology* **24**: 759–776.

Huynen MMTE, Martens P, Schram D, Weijenberg MP, Kunst AE. 2001. The impact of heat waves and cold spells on mortality rates in the Dutch population. *Environmental Health Perspectives* **109**: 463–470.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon S, Qin D Manning M Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds.). Cambridge University Press: Cambridge, UK; New York, NY, USA.

Klein Tank AMG, Können GP. 2003. Trends in indices of daily temperature and precipitation extremes in Europe, 1946–1999. *Journal of Climate* **16**: 3665–3680.

Klein Tank AMG, Peterson TC, Quadir DA, Dorji S, Zou X, Tang H, Santhosh K, Joshi UR, Jaswal AK, Kolli RK, Sikder AB, Deshpande NR, Revadekar JV, Yeleuova K, Vandasheva S, Faleyeva M, Gomboluudev P, Budhathoki KP, Hussain A, Afzaal M, Chandrapala L, Anvar H, Amanmurad D, Asanova VS, Jones PD, New MG, Spektorman T. 2006. Changes in daily temperature and precipitation extremes in central and south Asia. *Journal of Geophysical Research* **111**: D16105, DOI: 10.1029/2005JD006316.

Manton MJ, Della-Marta PM, Haylock MR, Hennessy KJ, Nicholls N, Chambers LE, Collins DA, Daw G, Finet A, Gunawan D, Inape K, Isobe H, Kestin TS, Lefale P, Leyu CH, Lwin T, Maitrepierre L, Ouprasitwong N, Page CM, Pahalad J, Plummer N, Salinger MJ, Suppiah R, Tran VL, Trewin B, Tibig I, Yee D. 2001. Trends in extreme daily rainfall and temperature in southeast Asia and the South Pacific: 1961–1998. *International Journal of Climatology* **21**: 269–284.

Meehl GA, Arblaster JM, Tebaldi C. 2007. Contributions of natural and anthropogenic forcing to changes in temperature extremes over the United States. *Geophysical Research Letters* **34**: L19709, DOI: 10.1029/2007GL030948.

Moberg A, Jones PD. 2005. Trends in indices for extremes in daily temperature and precipitation in central and western Europe, 1901–1999. *International Journal of Climatology* **25**: 1149–1171.

New M, Hewitson B, Stephenson DA, Tsiga A, Kruger A, Manhique A, Gomez B, Coelho CAS, Masisi DN, Kululanga E, Mbambalala E, Adesina F, Saleh H, Kanyanga J, Adosi J, Bulane L, Fortunata L, Mdoka ML, Lajoie R. 2006. Evidence of trends in daily climate extremes over southern and west Africa. *Journal of Geophysical Research* **111**: D14102, DOI: 10.1029/2005JD006289.

Nicholls N, Baek HJ, Gosai A, Chambers LE, Choi Y, Collins D, Della-Marta PM, Griffiths GM, Haylock MR, Iga N, Lata R, Maitrepierre L, Manton MJ, Nakamigawa H, Ouprasitwong N, Solofa D, Tahani L, Thuy DT, Tibig L, Trewin B, Vediapan K, Zhai P. 2005. The El Niño–Southern Oscillation and daily temperature extremes in east Asia and the west Pacific. *Geophysical Research Letters* **32**: L16714, DOI: 10.1029/2005GL022621, 2005.

Page CM, Nicholls N, Plummer N, Trewin B, Manton M, Alexander L, Chambers LE, Choi Y, Collins DA, Gosai A, Della-Marta P, Haylock MR, Inape K, Laurent V, Maitrepierre L, Makmur EEP, Nakamigawa H, Ouprasitwong N, McGree S, Pahalad J, Salinger MJ, Tibig L, Tran TD, Vediapan K, Zhai P. 2004. Data rescue in the southeast Asia and south Pacific region: challenges and opportunities. *Bulletin of the American Meteorological Society* **85**: 1483–1489.

Peterson TC, Taylor MA, Demeritte R, Duncombe DL, Burton S, Thompson F, Porter A, Mercedes M, Villegas E, Fils RS, Klein-Tank AMG, Martis A, Warner R, Joyette A, Mills W, Alexander L, Gleason B. 2002. Recent changes in climate extremes in the Caribbean region. *Journal of Geophysical Research* **107**(D21): 4601, DOI: 10.1029/2002JD002251.

Peterson TC, Manton MJ. 2008. Monitoring changes in climate extremes: A tale of international collaboration. *Bulletin of the American Meteorological Society* **89**: 1266–1271.

Press WH, Flannery BP, Teukolsky SA, Vetterling WT. 1986. *Numerical Recipes: The Art of Scientific Computing*. Cambridge University Press: Cambridge.

Ren G, Zhou Y, Chu Z, Zhang A, Guo J, Liu X. 2008. Urbanization effect on observed surface air temperature trend in North China. *Journal of Climate* **21**: 1333–1348.

Scaife AA, Folland CK, Alexander LV, Moberg A, Knight JR. 2008. European climate extremes and the North Atlantic Oscillation. *Journal of Climate* **21**: 72–83.

Sillmann J, Roeckner E. 2008. Indices for extreme events in projections of anthropogenic climate change. *Climatic Change* **86**: 83–104.

Trewin BC. 2009. A new index for monitoring changes in heatwaves and extended cold spells. *Ninth International Conference on Southern Hemisphere Meteorology and Oceanography*, Melbourne, 9–13 February 2009.

UNEP (United Nations Environmental Programme). 2004. Impacts of summer 2003 heat wave in Europe. *Environment Alert Bulletin* **2**: 1–3.

Vincent LA, Peterson TC, Barros VR, Marino MB, Rusticucci M, Carrasco G, Ramirez E, Alves LM, Ambrizzi T, Berlato MA, Grimm AM, Marengo JA, Molion L, Moncunill DF, Rebello E, Anunciação YMT, Quintana J, Santos JL, Baez J, Coronel G, Garcia J, Trebejo I, Bidegain M, Haylock MR, Karoly D. 2005. Observed trends in indices of daily temperature extremes in South America: 1960–2000. *Journal of Climate* **18**: 5011–5023.

Wilks DS. 2006. *Statistical Methods in the Atmospheric Sciences*. 2nd eds. Academic Press: New York.

Zhang X, Yang F. 2004. RClimDex (1.0) user manual. (Available at http://cccma.seos.uvic.ca/ETCCDMI/software.shtml).

Zhang X, Zwiers FW, Hegerl G. 2009. The influences of data precision on the calculation of temperature percentile indices. *International Journal of Climatology* **29**: 321–327.

Zhou LM, Dickinson RE, Tian YH, Fang JY, Li QX, Kaufmann RK, Tucker CJ, Myneni RB. 2004. Evidence for a significant urbanization effect on climate in China. *Proceedings of the National Academy of Sciences* **101**: 9540–9544.

Zong Y, Chen X. 2000. The 1998 flood on the Yangtze, China. *Natural Hazards* **22**: 165–184.