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CHANGE IN MEAN TEMPERATURE AS A PREDICTOR OF EXTREME TEMPERATURE CHANGE IN THE ASIA–PACIFIC REGION

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ABSTRACT

Trends (1961–2003) in daily maximum and minimum temperatures, extremes and variance were found to be spatially coherent across the Asia–Pacific region. The majority of stations exhibited significant trends: increases in mean maximum and mean minimum temperature, decreases in cold nights and cool days, and increases in warm nights. No station showed a significant increase in cold days or cold nights, but a few sites showed significant decreases in hot days and warm nights. Significant decreases were observed in both maximum and minimum temperature standard deviation in China, Korea and some stations in Japan (probably reflecting urbanization effects), but also for some Thailand and coastal Australian sites. The South Pacific convergence zone (SPCZ) region between Fiji and the Solomon Islands showed a significant increase in maximum temperature variability.

Correlations between mean temperature and the frequency of extreme temperatures were strongest in the tropical Pacific Ocean from French Polynesia to Papua New Guinea, Malaysia, the Philippines, Thailand and southern Japan. Correlations were weaker at continental or higher latitude locations, which may partly reflect urbanization.

For non-urban stations, the dominant distribution change for both maximum and minimum temperature involved a change in the mean, impacting on one or both extremes, with no change in standard deviation. This occurred from French Polynesia to Papua New Guinea (except for maximum temperature changes near the SPCZ), in Malaysia, the Philippines, and several outlying Japanese islands. For urbanized stations the dominant change was a change in the mean and variance, impacting on one or both extremes. This result was particularly evident for minimum temperature.

The results presented here, for non-urban tropical and maritime locations in the Asia–Pacific region, support the hypothesis that changes in mean temperature may be used to predict changes in extreme temperatures. At urbanized or higher latitude locations, changes in variance should be incorporated. Copyright © 2005 Royal Meteorological Society.

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KEY WORDS: Asia–Pacific; temperature; mean; extreme; variance; correlation; urbanization

1. INTRODUCTION

Speculation by media and the public as to whether significant changes in climate extremes have accompanied recent global warming often follows an extreme climate event, such as the severe flooding events in New Zealand during February 2004 (estimated to have been the second largest weather-related cost in New Zealand's history), or the record-breaking August 2003 heatwave in Europe, to which the World Meteorological Organization attributed over 21 000 deaths (Le Comte and Saunders, 2004).

The primary impacts of climate change on society result from extreme events (Katz and Brown, 1992), with changes in the frequency of extreme events having more impact than changes in mean climate (Mitchell *et al.*, 1990). The highly non-linear nature of the relationship between changes in mean temperature and the corresponding changes in extreme temperature events is well known (Mearns *et al.*, 1984; Wigley, 1985, 1988; Meehl *et al.*, 2000). Relatively small alterations in the mean state can result in a large change in the probabilities of extreme events. This effect is even more pronounced for successive extremes, e.g. a run of two extremes (Wigley, 1985). Figure 1, upper panel, depicts the effect of an increase in the mean of a hypothetical symmetric distribution on the probabilities of extreme events (shaded).

Changes in the variance are considered more important than changes in the mean when assessing the frequency of climate extremes, with greater sensitivity the more extreme an event is (Katz and Brown, 1992). This result can be generalized to non-normal distributions, with the frequency of extreme events relatively more dependent on the scale parameter than the location parameter (Katz and Brown, 1992). Figure 1, lower panel, shows the effect of a decrease in variance of a hypothetical symmetric distribution on the probabilities of extremes (shaded). In reality, a combination of a change in the location and scale parameter (in this case, mean and variance) may occur.

Several studies have analysed observed trends in temperature variability and found a general reduction based on daily to weekly data. Long-term decreasing trends were identified in high-frequency (daily to 5 day) temperature variability for the USA, the former Soviet Union, and China over the last 30–80 years (Karl *et al.*, 1995). Long-term decreases in day-to-day temperature variability have been found in Australia, particularly in the southeast (Collins *et al.*, 2000). Decreases in wintertime daily temperature variability across China and Korea have been identified since 1954, particularly for northeast China, and linked to changes in the variance of the Siberian high, related to the Arctic oscillation (Gong and Ho, 2004). Others have identified increases in temperature variance. Increased temperature variability has influenced recent European summer heatwaves (Schär *et al.*, 2004), and although 'symmetric' warming was observed in Europe over the full period 1946–99, consistent with a change in the mean only, an increasing variability in daily temperatures since 1976 was implied (Klein Tank and Können, 2003).

This study aims to quantify observed trends in temperature variance and the relationship between temperature mean and extremes, across the Asia–Pacific region, based on daily data. This is the first analysis undertaken across this complete area, with a view to identifying broad geographical coherency. The Asia–Pacific region has been targeted because small island states of the tropical Pacific Ocean, and some areas of Southeast Asia, are particularly vulnerable to the impacts of climate change, due to their small size, limited resources, or high population densities (IPCC, 2001a).

Projected increases in globally averaged surface temperature, due to enhanced greenhouse gas concentrations, range between 1.4 and 5.8 °C over the period 1990 to 2100 (IPCC, 2001b). It is very likely that land areas will warm more rapidly than this, particularly at northern high latitudes. In contrast, warming is expected to be less in Southeast Asia, and in particular in the Australasian region (IPCC, 2001b,c). The IPCC scenarios establish mean temperature estimates, but currently they do not address estimates of variance change. To date, the enhanced greenhouse effect in terms of changes in overall climate variance is not well understood, although climate simulations with enhanced atmospheric greenhouse gas concentrations suggest that a warmer climate could result in a decrease in high-frequency temperature variability (Karl *et al.*, 1995).

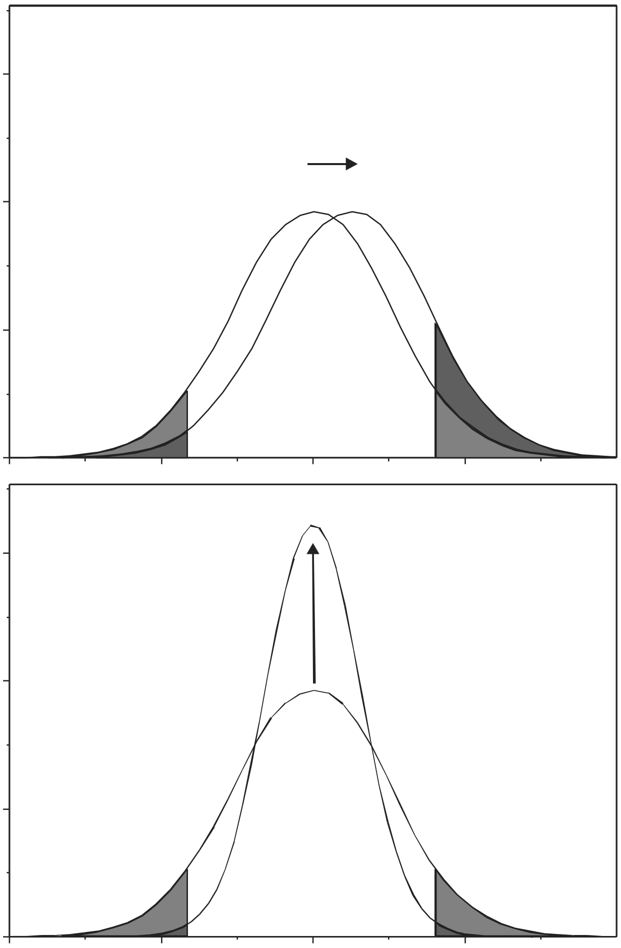

Figure 1. Two hypothetical forms of climate change are illustrated. In the upper panel, the location parameter (in this case, the mean) of the distribution increases. In the lower panel, the mean remains the same but the scale parameter (in this case, the variance) of the distribution decreases. Note how shifts in the location or scale parameter of the distribution change the probability of extreme events (shaded). In reality, a combination of changes in the location or scale parameter (in this case, mean and variance) may occur

Societal and environmental temperature-related impacts under greenhouse-gas-induced warming in the Asia–Pacific region could include (IPCC, 2001a) increased heat mortality, reduction in cold-temperature morbidity, increased tropical vector-borne diseases (such as dengue fever and malaria), increased fire risks, coral bleaching, increased urban pollution-related respiratory problems (related to hotter weather), and mixed impacts on agricultural and water resources.

Most climate impact studies use projected changes in mean climate to estimate likely changes to a particular sector, such as agricultural yield, energy demand, or mortality. Establishing a quantified relationship between mean temperature and extremes in Asia and the Pacific may make impact assessments of climate change in the region more robust.

The Asia–Pacific Network (APN) for Global Change Research has provided funding for several workshops on extremes since 1998, hosted by the Australian Bureau of Meteorology Research Centre (BMRC), aimed at regional participation in consistent analyses of climate extremes across Asia and the Pacific Ocean. This region historically has had lower data digitization and availability rates than many other parts of the globe. Representatives from at least a dozen countries attended each workshop. The results from the second workshop showed considerable spatial consistency within countries and across the Asia–Pacific region, in both the sign and magnitude of the trends in extreme temperature indices (the frequency of hot days, warm nights, cool days, and cold nights) (Manton *et al.*, 2001). The third APN workshop reviewed data storage and analysis capacity in the Asia–Pacific countries, and aimed to further exchanges of new information and software related to climate extremes. Metadata was the focus of the fourth workshop, providing an assessment of metadata, data quality and availability in the Asia–Pacific region (Page *et al.*, 2004).

The fifth APN extremes workshop was held in Australia in March 2004, at the BMRC. Members from 16 countries attended (Australia, China, Fiji, French Polynesia, Indonesia, Japan, Korea, Malaysia, New Caledonia, New Zealand, Papua New Guinea (PNG), Philippines, Samoa, Solomon Islands, Thailand, Vietnam), with data coverage between longitudes 87 °E and 139 °W, and from 46 °N to 47 °S. Three papers will be produced from this workshop. This paper focuses on the relationship between mean and extreme temperature in the Asia–Pacific region; a second (Nicholls *et al.*, 2005) examines the relationship between extreme daily temperatures in the Asia–Pacific region and the El Niño–southern oscillation, and a third will investigate extreme rainfall in the region.

2. DATA ANALYSIS METHOD

2.1. Climate station selection and urbanization issues

Each country's participant in the fifth APN extremes workshop updated daily maximum and minimum temperature data for a small number of stations in their country. The small number of stations per country used in the APN extreme workshops has an historical basis; station homogeneity testing and calculation of extreme indices are usually undertaken during the workshops to encourage capacity-building and uniform use of software and methodologies, so that there are time constraints on the analysis. Also, some developing or war-torn countries simply do not hold many long-term or good quality climate stations, which is particularly the case for small Pacific Island nations and parts of Southeast Asia. It is acknowledged that, for large or climatically diverse countries, a handful of stations is insufficient to describe trends in extremes within that country fully. For example, mainland China is the fourth largest country by land area in the world (www.ipedia.com/list_of_countries_by_area.html, accessed 12 February 2005), with an area of 9 596 960 km^2, but is described in this study by only five climate stations. One aim of the APN extremes workshops is for individual countries to repeat a more extensive analysis of extremes within their borders, using uniform indices and software and incorporating more stations. Many sub-regional studies on extremes have subsequently been published following APN extremes workshops (e.g. Collins *et al.*, 2000; Griffiths *et al.*, 2003; Zhai and Pan, 2003), which utilize a denser network of stations.

The stations used in the fifth APN extremes workshop were selected by participants according to the criteria laid down in previous extremes workshops at the BMRC; high quality, long records were desirable, with less than 20% of the daily values missing in each year. Stations were sought that were well maintained, had documented metadata, and were preferably at non-urban, single-site locations.

Most of the observed warming over the last 50 years has been attributed to the increase in greenhouse gas concentrations (IPCC, 2001b), but a proportion of the long-term land surface temperature warming trend may be related to non-climatic factors, such as the urban heat island (UHI) effect, since there has been a lower rate of warming observed over the last 20 years in the lower troposphere compared with the surface (Zhou *et al.*, 2004). The UHI is a well-documented human-induced climate modification. Land-use changes from urbanization significantly alter the natural surface conditions and atmospheric properties of a locality, changing the natural energy, momentum and hydrological balances, resulting in a distinct urban climate (Morris *et al.*, 2001). The temperature difference between urban and rural temperatures is known as the UHI, and this is greatest under clear-sky, low-wind situations (which often occur during wintertime at higher latitude locations).

The magnitude of the UHI has been previously quantified for both China and Korea, the two countries with the highest country-average population densities in this study. The maximum UHI in Seoul has increased by an estimated 0.56 °C over the period 1973–96 (Kim and Baik, 2002), whereas the estimated average annual urban bias in South Korea mean temperatures over the 1968–99 period was ~0.4 °C (Choi *et al.*, 2003). Determination of urbanization effects versus regional climate-change effects in apparent (recorded) temperature change in Korea was undertaken (Chung *et al.*, 2004), using two normal periods (1951–80 versus 1971–2000), and utilizing population data. Urbanization effects were found to be common in all months except April, and up to 0.5 °C of the reported increases in Korean night-time temperature were induced by urbanization (and not regional warming) in the later normal period compared with the earlier normal period. In contrast, it was estimated that the urbanization effect on daily maximum temperature change was small (Chung *et al*., 2004).

A significant urbanization effect on the winter surface temperature in southeast China was observed during 1979–98 (Zhou *et al*., 2004), in line with an increase in the proportion of Chinese urban population from 18% to 39% over that time. An estimated 68% of the observed decline in winter daily temperature range (DTR) in southeast China could be attributed to urbanization (Zhou *et al*., 2004), due to winter minimum temperatures increasing faster than maximum temperatures, and an estimated increase in mean surface temperature of 0.05 °C per decade was attributed to urbanization. This latter estimate is much larger than previous calculations of the UHI magnitude in southeast China, which estimated an annual increase of ∼0.011 °C per decade due to urbanization over the period 1951–2001 (Li *et al*., 2004). However, the latter estimate is consistent with the rapid urbanization over the more recent period, and the latter study's focus on the winter season.

Table I shows the estimated country-wide average population densities for Asian countries analysed in this paper (only the top seven are shown). It is evident that China and South Korea are highly urbanized overall, with country-average population densities of approximately 500 km^{-2} or greater. Japan, the Philippines and Vietnam also show high country-average population densities, with greater than 200 km^{-2}.

Population densities in towns or cities that contain climate stations used in this study are listed in Table II, in the five countries from Table I with country-average population density greater 200 km^{-2}. Based on estimated town/city population and population density, 20 stations were subjectively marked as urbanized or highly urbanized, using the following decision rule: if both population ≥300 000 and population density ≥300 km^{-2}, then the station was deemed to be 'highly urbanized'. If one, but not both, of the conditions were met, the station was described as 'urbanized'. Note that for both categories the stations may, in fact, be located on the periphery of urban areas, such as at airports. The population density condition is comparatively conservative, e.g. some studies have defined urban stations as having population densities greater than 1000 km^{-2} (Choi *et al*., 2003); yet, other studies, when defining station urbanization solely on population, have used a range of population criteria: e.g. Easterling *et al*. (1997) used a population of 50 000 as the critical value for urban stations.

Tests for outliers, inhomogeneities or discontinuities in the climate records had been performed for all stations in previous workshops, and also during this workshop, using nearest-neighbour analysis techniques (for further details on quality control see Manton *et al*. (2001)). Despite these efforts it is still possible that undetected discontinuities have resulted in spurious results for a small number of stations. Discontinuities in climate records can result from changes to the station or its operation, e.g. changes in site location, observation

Table I. Rank of the largest population densities in Asia (country average).[a] List only includes the top seven densities from countries actually analysed in this study. Based on country census data collected between 1999 and 2003

Country	Average population density (km^{-2})
China	627
South Korea	491
Japan	336
Philippines	282
Vietnam	242
Thailand	121
Malaysia	69

[a] Source: www.ipedia.com [2–22 February 2005].

practice, exposure, or instrumentation, and can affect both the mean and extremes of a climatic distribution (Trewin and Trevitt, 1996).

In conclusion, a set of 89 stations (Appendix A and Figure 2) was used in the analysis, including the 20 urbanized records (identified in Table II). The urbanized stations were included both to identify any major differences in trends or behaviour between urbanised and less-urbanized sites, and because trends at these urbanized stations may be representative of other urbanized areas (with similar population densities and percentage of urban population) in their vicinity (since quality control and comparative checks were passed). It is important to note that area-averaged trends were not calculated, so the urbanization effects at one site do not influence results at other stations. It is acknowledged that UHI effects, including a possible decline in

Table II. Population and density in towns/cities containing stations used in this study. List only includes the five most densely populated countries from Table I. Places marked with * or ** are subjectively assessed as 'urbanized' or 'highly urbanized', respectively, based on both raw population and estimated density data

Town/City	Approximate population (2003)	Estimated population density (km^{-2})	Data source[a]
China			
Urumqi*	1 500 000	131	2,3,r
Yinchuan*	400 000	156	4, r
Beijing**	13 800 000	822	5,6, r
Chendu**	9 400 000	804	7,8, r
Guang Zhou**	10 000 000	1337	9, r
Korea			
Gangneong	230 000	221	10
Seoul**	10 000 000	16 975	11
Ulleungdo	11 000	150	12
Daegu**	2 500 000	2873	10
Jeonju**	620 000	3008	10
Busan**	3 900 000	4862	11
Japan			
Wakkanai	42 700	56	1
Abashiri	42 600	90	1
Nemuro	32 000	63	1
Akita**	318 000	691	1
Yamagata*	255 000	670	16
Wajima	25 000	96	1
Choshi*	77 000	915	1
Hachijojima	Unknown	Unknown	
Hamada	47 000	286	1
Shionomisaki	Unknown	Unknown	
Oita**	441 000	1222	1
Yonagunijima	Unknown	Unknown	
Miyakojima*	34 000	519	16
Naha**	307 000	7878	1
Minamidaitojima	Unknown	Unknown	
Chichijima	Unknown	Unknown	
Minamitorishima	Unknown	Unknown	
Philippines			
Basco	7000	192	1, r
Tuguegarao	121 000	~110	1, 13, 14
Baguio*	272 000	5556	1, r

Table II. (*Continued*)

Town/City	Approximate population (2003)	Estimated population density (km^{-2})	Data source[a]
Vietnam			
Phu-Lien*	73 000	2470	15
Pleycu*	170 500	755	15
Vanly*	279 100	1213	15
Ha-noi**	2 672 000	2901	15

[a] Sources, all accessed 2–22 February 2005:
1: www.ipedia.com.
r: External paper reviewers.
2: www.ecdc.net.cn/events/asian_europe/index_5/1.htm.
3: http://en.wikipedia.org/wiki/Urumqi.
4: http://english.sohu.com/2004/07/05/25/article220852525.shtml (2004).
5: http://www.geohive.com/cd/link.php?xml=cn&xsl=xs1.
6: http://en.wikipedia.org/wiki/Beijing.
7: http://www.world-gazetteer.com/fr/fr_cn.htm.
8: http://www.cts.com.cn/esite/chengducity/capital.htm.
9: http://www.demographia.com/db-guangzhou.htm.
10: http://kosis.nso.go.kr/cgi-bin/sws_888.cgi.
11: http://kosis.nso.go.kr/cgi-bin/sws_888.cgi?ID=DT_1B04003&IDTYPE=3&A_LANG=2&FPUB=4&SELITEM=.
12: http://kn.koreaherald.co.kr/SITE/data/html_dir/2002/08/24/200208240008.asp.
13: PAGASA, Philippines.
14: http://www.census.gov.ph/data/pressrelease/2002/pr0292tx.html.
15: Climate-Meteorological Research Center, Institute of Meteorology and Hydrology, Ha Noi, Vietnam.
16: http://www.stat.go.jp/data/kokusei/2000/kihon1/index.htm (in Japanese).

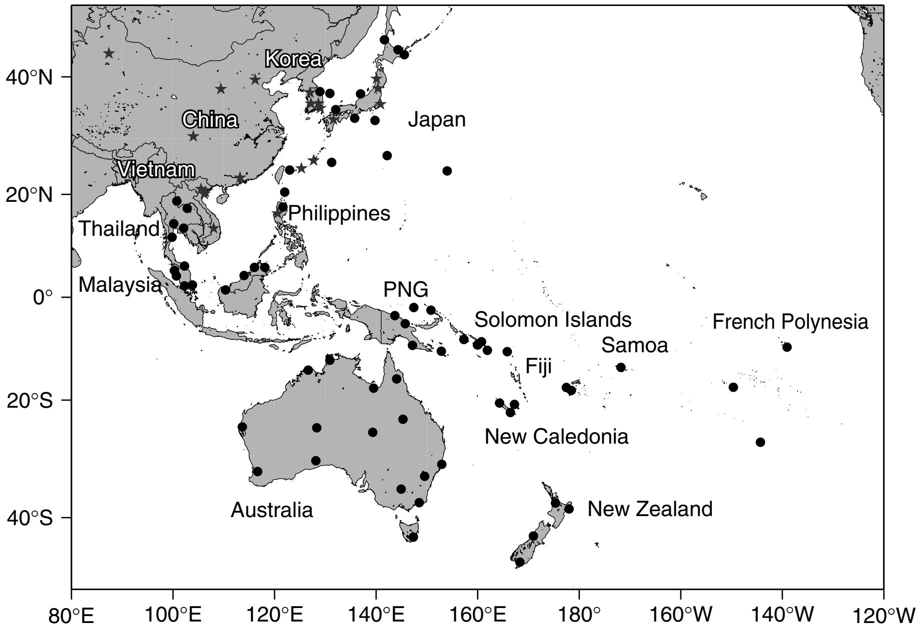

Figure 2. Location of stations (●) used in this study. Stations defined in Table II as 'urbanized' or 'highly urbanized' are shown as (⋆)

DTR and standard deviation due to urbanization, probably affect trends at the urbanized sites, and that this should be noted when interpreting the results at these stations.

For a particular year to be included in the analyses it needed to have at least 308 days of data available. This equates to a greater than 50% probability that all four of the most extreme events for that year would be included in the data set (Manton *et al.*, 2001). Most stations had data from 1961 to 2003, and this period was used to investigate trends in the extremes, means and variance, as well as the relationship between mean temperature and extremes. A small proportion of stations did not have data for the complete period (e.g. Samoa, Solomon Islands and PNG; see Appendix A), and this should be noted when interpreting the results.

2.2. Analysis methods

Extreme-temperature indices can be defined in a number of ways; using arbitrary thresholds (e.g. Jones *et al.*, 1999; Klein Tank and Können, 2003) or by using statistical quantities, such as percentiles (e.g. Plummer *et al.*, 1999; Manton *et al.*, 2001; Klein Tank and Können, 2003). The use of arbitrary thresholds, such as the number of days above 35 °C, is suitable for regions that have little spatial climate variability. This study, however, covers a broad region, latitudes 46 °N–47 °S, and there is no single temperature threshold that would be considered extreme over the entire region. For this reason, this study uses extreme indices based on percentiles. The 1st and 99th percentiles for each calendar year were calculated using all non-missing days, the 1st percentile corresponding to the fourth lowest value and the 99th percentile to the fourth highest, per year. Mean percentile values were also calculated over the period 1961–2003. To illustrate why percentile values were used (rather than fixed temperature thresholds), the minimum temperature mean 1st percentile (averaged over the period 1961–2003) was compared between Noumea, New Caledonia (located in a tropical, maritime climate) and Urumqi, China, which experiences a continental climate. The minimum temperature mean 1st percentile was 15.1 °C at Noumea and −24.0 °C at Urumqi.

Four extreme indices were calculated for each year:

- Hot days – frequency of days with maximum temperature above the 1961–2003 mean 99th percentile.
- Cool days – frequency of days with maximum temperature below the 1961–2003 mean 1st percentile.
- Warm nights – frequency of days with minimum temperature above the 1961–2003 mean 99th percentile.
- Cold nights – frequency of days with minimum temperature below the 1961–2003 mean 1st percentile.

The daily temperature time-series were also used to compute an annual averages and annual standard deviations for maximum temperature and minimum temperature. The means and annual standard deviations were calculated from 365 or 366 data points, without removing the annual cycle, in order to represent changes in the shape of the distribution of annual daily temperatures. This means that the standard deviation, as defined here, can inadvertently reflect changes due to a change in the mean (or a shift in the annual cycle), and at higher latitude locations it will largely be a measure of seasonal temperature range.

The mean and standard deviation indices calculated for each year were:

- Tmin – the mean minimum temperature;
- Tmax – the mean maximum temperature;
- SD Tmin – the standard deviation of minimum temperature;
- SD Tmax – the standard deviation of maximum temperature.

Annual time-series of the indices were calculated for each station. Trends in the annual indices were calculated using linear regression for each station, using all available years of record between 1961 and 2003. Trends and relationships between changes in the extremes, mean and standard deviation of the minimum and maximum temperature distributions were compared through (Pearson) correlation analysis and graphically. Because the correlations are based on series that were not detrended, changes in mean state, as well as interannual variability, are reflected in the correlation.

The graphical depiction of trends in Figures 3 to 10 raises important questions about null hypothesis significance testing (NHST). Several papers have summarized the limitations of NHST and outlined some

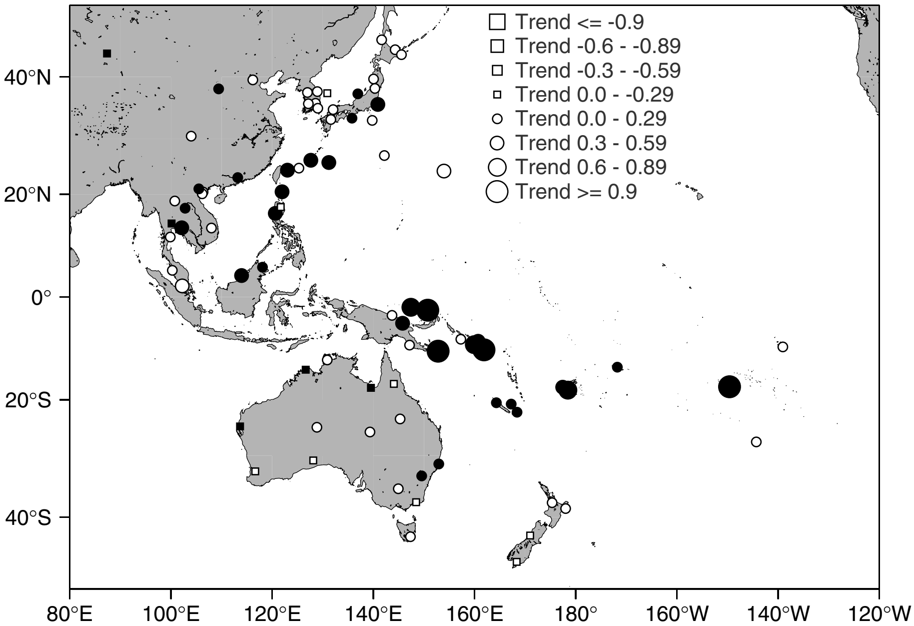

Figure 3. Trends in hot days 1961–2003. Trends as indicated in the scale (days per year). Trends associated with $p \leq 0.05$ ($p > 0.05$) are indicated by a black (white) symbol. Trends range between −0.2 days per year and +2.2 days per year

alternatives (e.g. Nicholls, 2000). NHST establishes a null hypothesis H_0, e.g. that there is no correlation between two variables. The observed correlation over a period of time is then found between the two variables, and tables used to calculate p, the probability that this correlation or a more extreme correlation would arise if a sample of the same size were drawn from a population with zero correlation. If p is less than 0.05 (or any other arbitrary cut-off), then the correlation is labelled 'significant' (and H_0 is rejected). One effect of NHST is to reduce the amount of information available (to either 'significant', or 'not significant'), so that information is lost in this type of display. Also, it is possible that a specific effect does not reach the 5% significance level simply because of a small sample size – with NHST affected as much by the size of the sample as much as by the strength of the effect being tested (Nicholls, 2000). Even if the null hypothesis is not rejected, it cannot be concluded that the null hypothesis is true.

Many studies that search for climate trends are of an exploratory nature, whereby trends are calculated over the entire data population (e.g. Manton *et al*., 2001). When there exists an alternative hypothesis (such as that there *is* a correlation), arising from initial data examination, the use of these data as a 'random' sample is invalidated under classic NHST (Nicholls, 2000). NHST was originally designed for 'debunking' studies (to discredit a certain theory), whereas many 'confirmatory studies' actually start with a hypothesis that there is an effect, often based on earlier research, and the purpose of the 'confirmatory test', therefore, is to estimate the strength of this effect. NHST in this situation might, therefore, be inappropriate – because the earlier work almost guarantees that the null hypothesis is not true – and other methods, such as confidence intervals, permutation tests and cross-validation might be more useful (Nicholls, 2000).

In conclusion, owing to the relatively small sample size in this study (~42 years), the 'confirmatory' nature of this work (expanding on the Manton *et al.* (2001) research), and the fact that we are more interested in what may be physically or socially important effects, such as spatial coherence in the sign and magnitude of trends across a region rather than concentrating on statistical significance, the magnitudes of all trends (and correlations) have been plotted in all figures in this paper. However, an attempt to address conventional NHST requirements has been undertaken for the reader, using the non-parametric Kendall–tau test. Trends have been clearly identified, if below an arbitrary test level ($p < 0.05$, null hypothesis rejected).

3. RESULTS

3.1. Trends in temperature indices

Updated trends in temperature indices are shown in Table III. Over half of the 89 stations (55%) showed a statistically significant increase in warm nights (although the UHI effect may be at least partly responsible at urbanized stations), and a significant increase in hot days was observed at 40% of sites analysed.

Six stations showed significant decreases in hot days: Lata (Solomon Islands), Suphan Buri (Thailand), Urumqi (China), and three Australian stations (Kalumburu, Carnarvon, and Burketown). Two stations showed a significant decrease in warm nights: Tuguegarao (Philippines) and Urumqi (China).

Compared with the trends in hot days over the period 1961–98 (Manton *et al.*, 2001), the spatial pattern for the period 1961–2003 (Figure 3) remains consistent, with decreases at northern and western stations of Australia, isolated sites in Thailand and New Zealand, and increases predominating elsewhere. The largest increases in hot days (Figure 3) are located in the South Pacific islands from the Solomon Islands to Fiji, and also Papeete in French Polynesia. Over the additional 5 years, the number of stations with 'significant' hot-day trends has increased (with four additional stations showing significance). Carnarvon (Australia) and Suphan Buri (Thailand) now have significant decreases in hot days, and two Malaysian sites now show significant increases.

Similarly, updated trends in warm nights (Figure 4) are spatially consistent with those seen over the period 1961–98 (Manton *et al.*, 2001), but with two additional Australian stations now showing significant increases. The biggest trends in warm-night frequency are seen in Malaysia, and from the Solomon Islands to Papeete (French Polynesia).

Updated trends in cool days (Table III) were significantly negative at over half of the stations (52%); notably, there were no significant increases. The largest decreases in cool days occurred in Korea (at urbanized sites), the Philippines, Malaysia and the Solomon Islands (Figure 5). The majority of stations analysed had significant decreases in cold nights (63%), with no significant increase in cold-night frequency at any station. The largest decreases in the frequency of cold nights (Figure 6) were observed in PNG, Malaysia and Thailand. The updated trends in cool days and cold nights are spatially consistent with the earlier results (Manton *et al.*, 2001).

Nearly all stations experienced an increase in maximum (Tmax) and minimum (Tmin) temperature over the period 1961–2003, with significant trends at 64% and 79% of sites respectively (Table III). Only one location showed a significant decrease in Tmax (Tuguegarao, Philippines), and one site a significant decrease in Tmin (Orbost, Australia). The largest trends in Tmax (Figure 7) were observed in the region from the Solomon Islands to Fiji (longitudes 150 °E to 180°), and at some sites in Korea, Thailand and Malaysia. Conversely, the trends in Tmin (Figure 8) were largest at some stations in Australia, Malaysia and Samoa, and at urban sites in China and Korea.

Interestingly, the percentages of significant increases in the mean (of both maximum and minimum temperature, 64% and 79% respectively) are larger than the percentages of significant increases in the frequency of extremes (hot days and warm nights: 40% and 55% respectively). Theory would suggest that small changes in the mean state can result in large changes in the probabilities of extreme events (Wigley, 1985), but that does not appear to be in evidence here. This may reflect that the extreme frequency series are noisy, or that changes in standard deviation are having an impact.

Table III. Index trends observed over the period 1961–2003 (see Appendix A for exact details). The number of stations in each category is given, with the percentage out of the total number of stations given in brackets. The total number (89) includes urbanized stations (Table II). Trends associated with $p \leq 0.05$ are labelled significant

	Hot days	Cool days	Warm nights	Cold nights	Tmax	Tmin	SD Tmax	SD Tmin
Significant increase	36 (40%)	0 (0%)	49 (55%)	0 (0%)	57 (64%)	70 (79%)	3 (4%)	2 (2%)
Significant decrease	6 (7%)	46 (52%)	2 (2%)	56 (63%)	1 (1%)	1 (1%)	17 (19%)	27 (30%)

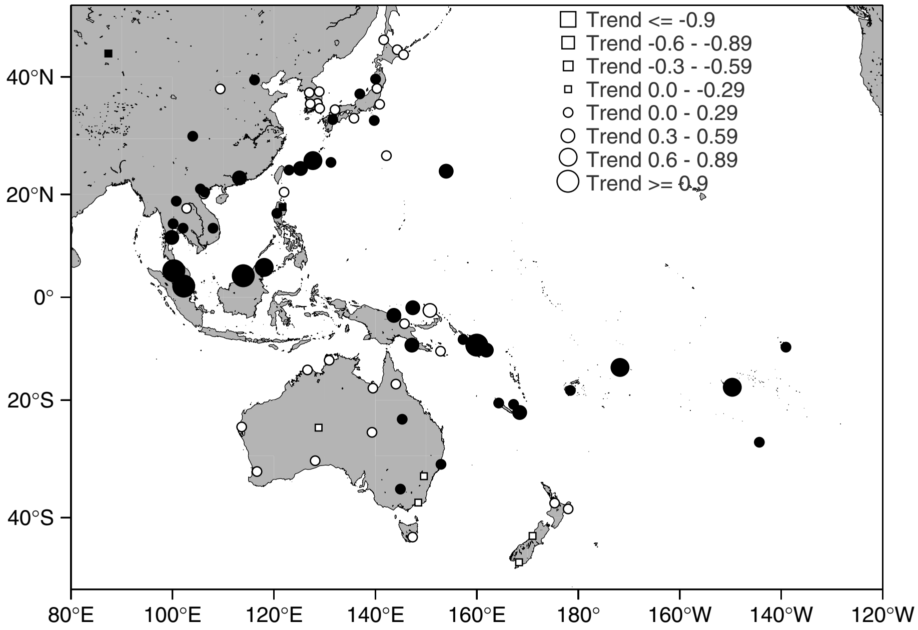

Figure 4. Trends in warm nights 1961–2003. Symbols as in Figure 3. Trends range between −0.2 days per year and +2.2 days per year

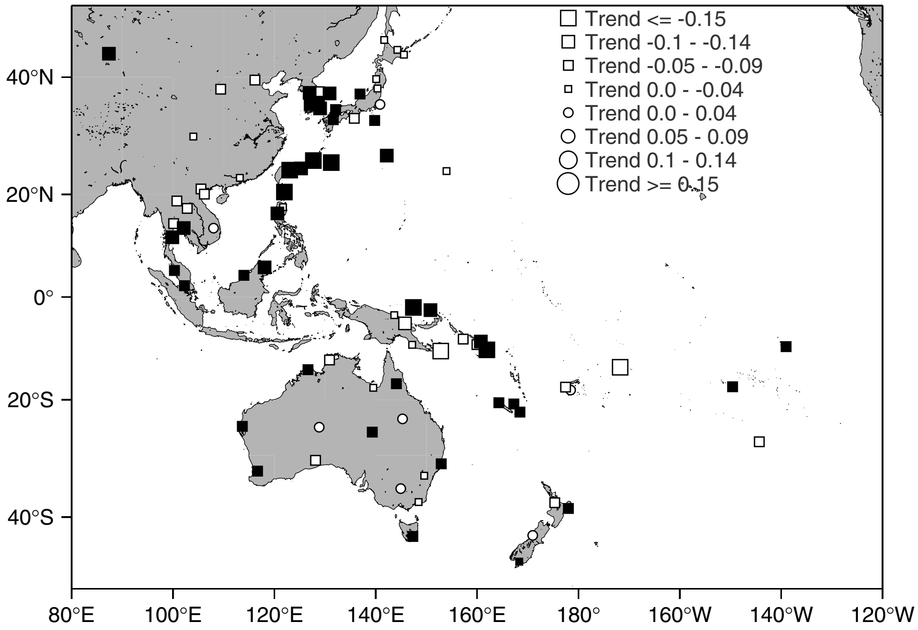

Figure 5. Trends in cool days 1961–2003. Symbols as in Figure 3. Trends range between −0.2 days per year and +0.03 days per year

Significant decreases were observed in SD Tmax and SD Tmin at 19% and 30% of locations respectively (Table III). Urbanization effects are likely to have at least partly influenced results, with the largest decreases in both SD Tmax and SD Tmin occurring at the urbanized sites in China and Korea (Figures 9 and 10). Three significant increases in SD Tmax were observed, in Fiji and the Solomon Islands (Figure 9). Significant increases in SD Tmin (Figure 10) were measured at Malacca (Malaysia) and Honiara (Solomon Islands).

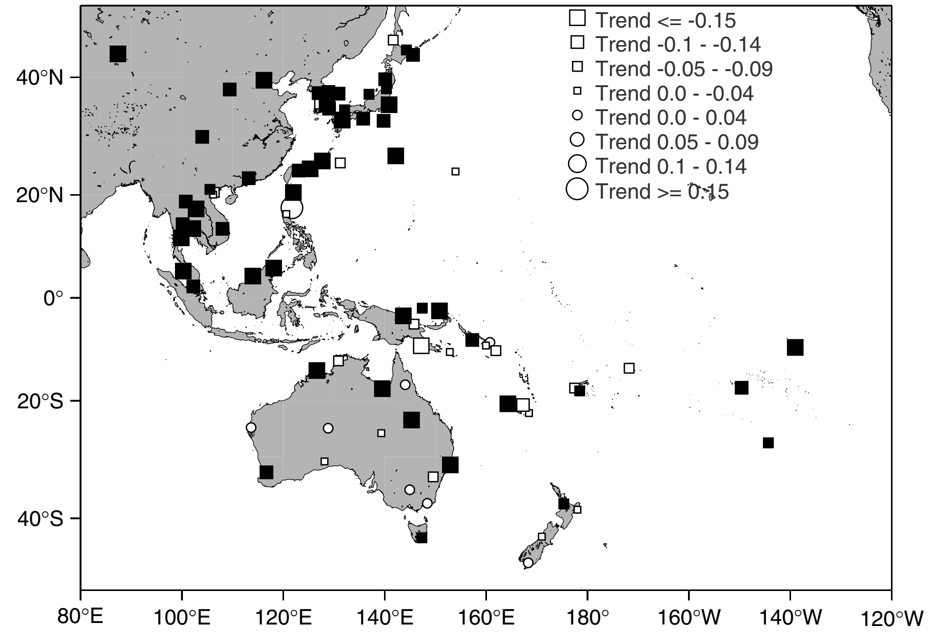

Figure 6. Trends in cold nights 1961–2003. Symbols as in Figure 3. Trends range between −0.5 days per year and +0.2 days per year

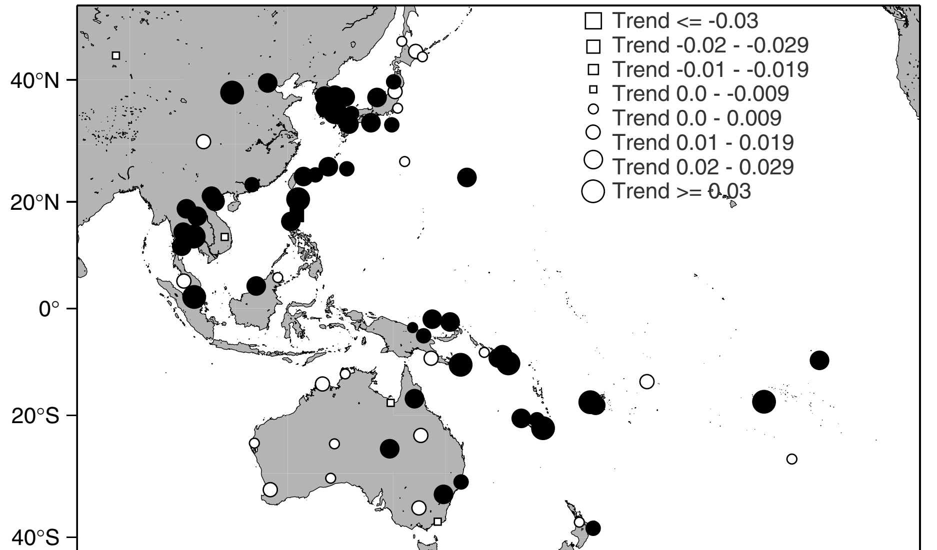

Figure 7. Trends in Tmax 1961–2003. Trends as indicated in the scale (°C per year). Trends associated with $p \leq 0.05$ ($p > 0.05$) are indicated by a black (white) symbol. Trends range between −0.04 °C per year and +0.05 °C per year

3.2. Categorizing stations by distribution changes

The summary section of Table IV lists the number (and percentage) of stations in particular (broad) categories of change for the 69 stations defined as non-urban in this study. Overall, the most common form of

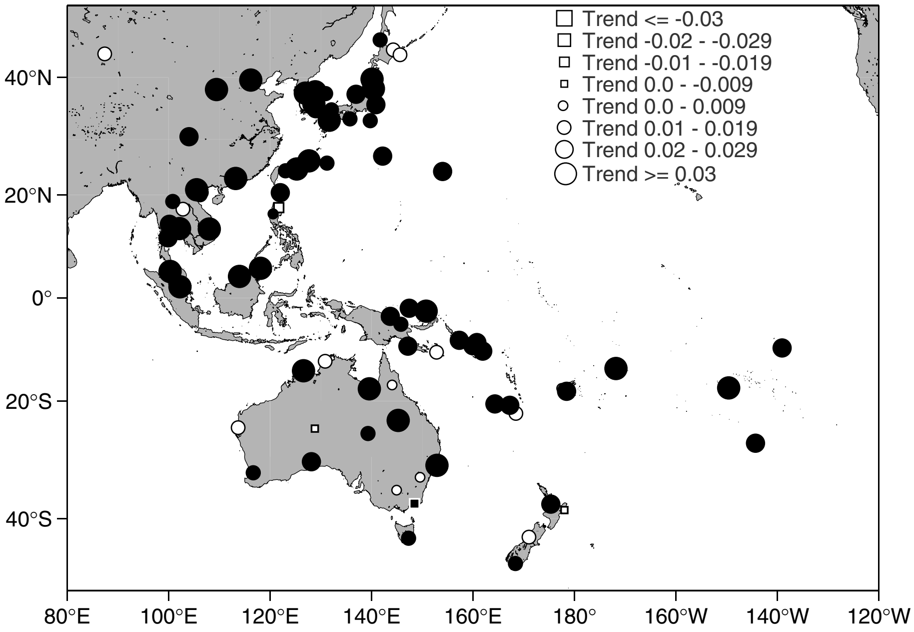

Figure 8. Trends in Tmin 1961–2003. Symbols as in Figure 7. Trends range between −0.02 °C per year and +0.07 °C per year

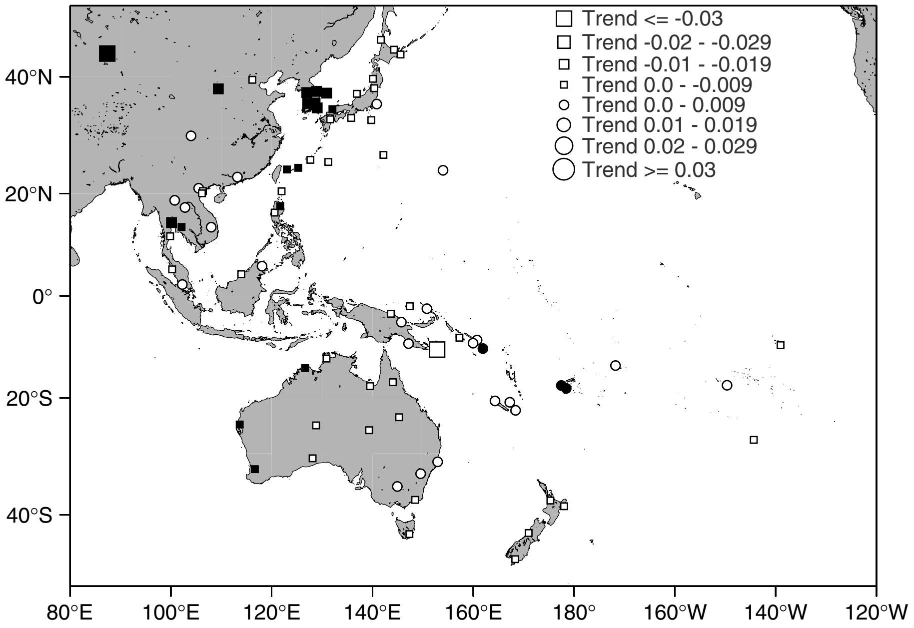

Figure 9. Trends in SD Tmax 1961–2003. Symbols as in Figure 7. Trends range between −0.038 °C per year and +0.006 °C per year

distribution change at non-urban sites, for both maximum and minimum temperature, involved a significant shift in the mean and one or both extremes (the tails of the distribution). This occurred in 57% and 68% of cases respectively. In comparison, Table V shows significant distribution changes at the 20 sites identified as urbanized. Overall, the most common form of distribution change at these urban sites remains the same as for the non-urban stations (a significant change in the mean and one or both extremes), with 55% and 85% of

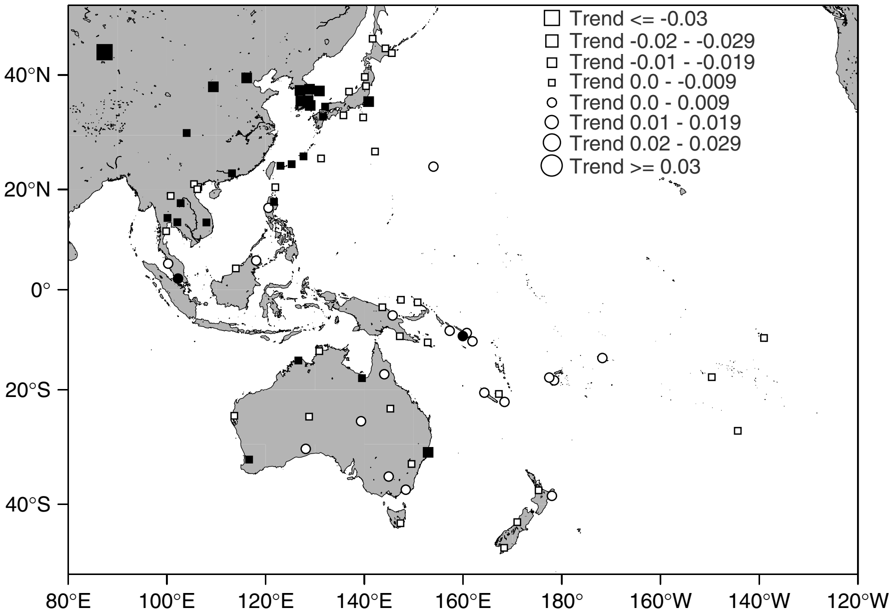

Figure 10. Trends in SD Tmin 1961–2003. Symbols as in Figure 7. Trends range between −0.044 °C per year and +0.005 °C per year

the sample showing this category of change for maximum and minimum temperatures respectively. However, several key differences between urban and non-urban stations emerge. The distribution change in minimum temperature is strongly influenced by urbanization effects, with a reduction in the 'no change' category for minimum temperature from 13% at non-urban sites (Table IV), to 0% at urbanized stations (Table V). Table V shows a clear increase in significant standard deviation changes at the urbanized sites, when compared with the non-urban stations. Significant change in SD Tmax occurred in 20% of cases at non-urban sites, compared with 35% in the urban sample. More noticeably, a significant change in SD Tmin was observed for 22% of non-urban stations, compared with 70% for urban sites, consistent with the typical reduction in urban DTR, primarily due to increased minimum temperatures.

The locations of stations (both urban and non-urban) with the most common category of distribution change (a significant shift in the mean and one or both extremes) are shown in Figure 11 (maximum temperature) and Figure 12 (minimum temperature). Figure 11 shows, notably, that (urban) stations in Korea and inland China, and a few sites in Thailand and southern Japan, showed a significant change in standard deviation, in addition to changes in the mean and one or both extremes. However, the majority of sites in the equatorial Pacific Ocean, tropical Southeast Asia and eastern Australia show significant changes in Tmax and one or both extremes (Figure 11), without any change in variability (such as is portrayed in our simplified Figure 1, upper panel). Exceptions were sites in Fiji and the Solomon Islands.

Similarly, most island stations located in the equatorial regions displayed changes in Tmin and one or both extremes, without any influence from variability changes (Figure 12). Many stations in China and Korea (known to be urban), southern Japan, Thailand and Vietnam, were additionally affected by significant changes in the standard deviation, along with several coastal stations in Australia. Noticeably, the Solomon Island and Fiji sites, which had significant changes in SD Tmax, did not show such changes in SD Tmin.

More specifically, significant changes in the mean and *both* extremes occurred in 29% and 38% of cases at non-urban sites for maximum and minimum temperature respectively (summary section, Table IV). The proportions for urbanized sites were slightly different (10% and 40% respectively, Table V). This is a subset of the previous situation. Maximum temperature distribution changes of this type (at both urban and non-urban sites) were primarily located in the equatorial region, in coastal locations (Figure 13), between 25 °N and 23 °S (except Port Macquarie, Australia, and Wajima, Japan). The majority of stations with an observed change in Tmin and both extremes (Figure 14), but no change in variability, are located in the tropics, from

Table IV. Number of 'non-urbanized' stations (includes sites where urban status is unknown) that fall into the 'significant change' categories listed. Trends associated with $p \leq 0.05$ are labelled significant. The percentage of the total number of non-urban sites ($N = 69$) is given in parentheses, and a summary is given at the bottom of the table

Significant change category	Maximum temperature	Minimum temperature
No change in mean, extremes, or SD	15 (22%)	9 (13%)
Mean, both extremes only	16 (23%)	19 (28%)
Mean, CD/CN only	8 (12%)	6 (9%)
Mean, HD/WN only	6 (9%)	9 (13%)
Mean, SD, CD/CN only	2 (3%)	5 (7%)
Mean only	3 (4%)	6 (9%)
All variables	4 (6%)	7 (10%)
Mean, SD, HD/WN, only	3 (4%)	1 (1%)
HD/WN only	3 (4%)	3 (4%)
CD/CN only	3 (4%)	2 (3%)
SD, both extremes, only	2 (3%)	0 (0%)
Mean and SD only	2 (3%)	0 (0%)
SD, HD/WN only	0 (0%)	1 (1%)
Extremes only (both)	1 (1%)	0 (0%)
SD, CD/CN only	1 (1%)	1 (1%)
SD only	0 (0%)	0 (0%)
Summary results (2–5 ignore variance changes)		
1. No change	15 (22%)	9 (13%)
2. Mean, not extremes	5 (7%)	6 (9%)
3. Extremes (1 or 2), not mean	10 (14%)	7 (10%)
4. Mean and both extremes	20 (29%)	26 (38%)
5. Mean and extremes (1 or 2)	39 (57%)	47 (68%)
6. Change in SD	14 (20%)	15 (22%)

French Polynesia to Malaysia. Many stations in mainland Asia and southern Japan also showed corresponding significant changes in standard deviation, possibly influenced by urbanization effects.

About 22% (20%) of non-urban (urban) stations display no changes in maximum temperature distribution, i.e. no significant changes in mean, extremes or standard deviation (summary section, Tables IV and V). There was no obvious pattern in the geographical location of these stations. Some 13% (0%) of non-urban (urban) stations exhibited no change in minimum temperature, whether in mean, extremes or standard deviation (summary section, Tables IV and V). All but one of the stations showing no change in minimum temperature (Figure 15) was located in the Southern Hemisphere (with the majority in Australia and New Zealand). No clear geographical pattern was evident for stations with significant changes in 'mean, not extremes', or 'extremes (1 or 2), not mean' (summary section, Tables IV and Table V).

From a more detailed assessment of maximum temperature variability at non-urban stations (upper section of Table IV), it is evident that the two most common changes in distribution for maximum temperature at non-urban sites were either no change (22%), or a shift in the mean, impacting on *both* tails of the distribution (23%), with no corresponding change in standard deviation (implying a simple shift in the location parameter of the distribution, such as portrayed in Figure 1, upper panel). A further 12% of the non-urban cases indicated a significant shift in mean and the left tail only (mean, CD only), and 9% of non-urban stations measured a change in the mean and right tail only (mean, HD only), with no significant changes in variability in either case. In summary, 44% of cases at non-urban sites with significant changes in the distribution of maximum temperature involved changes in the location parameter (mean), impacting on either one or both tails of the distribution (the extremes), with no influence from a significantly changed standard deviation.

Table V. Number of 'urbanized' stations ($N = 20$) that fall into the 'significant change' categories listed. Trends associated with $p \leq 0.05$ are labelled significant. The percentage of the total number of urban sites is given in parentheses, and a summary is given at the bottom of the table

Significant change category	Maximum temperature	Minimum temperature
No change in mean, extremes, or SD	4 (20%)	0 (0%)
Mean, both extremes only	2 (10%)	2 (10%)
Mean, CD/CN only	1 (5%)	1 (5%)
Mean, HD/WN only	2 (10%)	2 (10%)
Mean, SD, CD/CN only	5 (25%)	6 (30%)
Mean only	3 (15%)	1 (5%)
All variables	0 (0%)	6 (30%)
Mean, SD, HD/WN, only	1 (5%)	0 (0%)
HD/WN only	1 (5%)	0 (0%)
CD/CN only	0 (0%)	0 (0%)
SD, both extremes, only	1 (5%)	1 (5%)
Mean and SD only	0 (0%)	0 (0%)
SD, HD/WN only	0 (0%)	0 (0%)
Extremes only (both)	0 (0%)	0 (0%)
SD, CD/CN only	0 (0%)	0 (0%)
SD only	0 (0%)	1 (5%)
Summary results (2–5 ignore variance changes)		
1. No change	4 (20%)	0 (0%)
2. Mean, not extremes	3 (15%)	1 (5%)
3. Extremes (1 or 2), not mean	2 (10%)	1 (5%)
4. Mean and both extremes	2 (10%)	8 (40%)
5. Mean and extremes (1 or 2)	11 (55%)	17 (85%)
6. Change in SD	7 (35%)	14 (70%)

Interestingly, three stations showed no change in the mean maximum temperature, but had significant changes in variability, which impacted on both extremes (labelled 'SD, both extremes, only' in Tables IV and V). These stations, Kalumburu and Carnarvon (Australia), and Urumqi (China), showed a large decrease in variability, resulting in a significant decrease in the numbers of both cold and hot extremes (similar to our simplified Figure 1, lower panel). Urumqi also showed this type of change for minimum temperature.

A more detailed assessment of minimum temperature variability at non-urban stations (upper section of Table IV) shows that the most common distribution change for minimum temperature (28% of cases) was a shift in the mean and both extremes only (e.g. no change in standard deviation), again implying a simple shift in the location parameter. A further 9% of cases indicated a significant shift in mean and the left tail only, (mean, CN only), and 13% of stations displayed a change in the mean and right tail only (mean, WN only), with no significant change in variability in either case. This implies that 50% of significant changes in minimum temperature distribution at non-urban stations involved changes in the mean, impacting on either one or both tails of the distribution (the extremes), with no significant change in the standard deviation.

Notably, 10% of non-urban stations (Table IV) showed a significant shift in all minimum temperature variables (mean, extremes and standard deviation), in contrast to 30% of urbanized sites (Table V). This largely reflects the greater number of significant changes in the standard deviation of minimum temperature at urbanized sites.

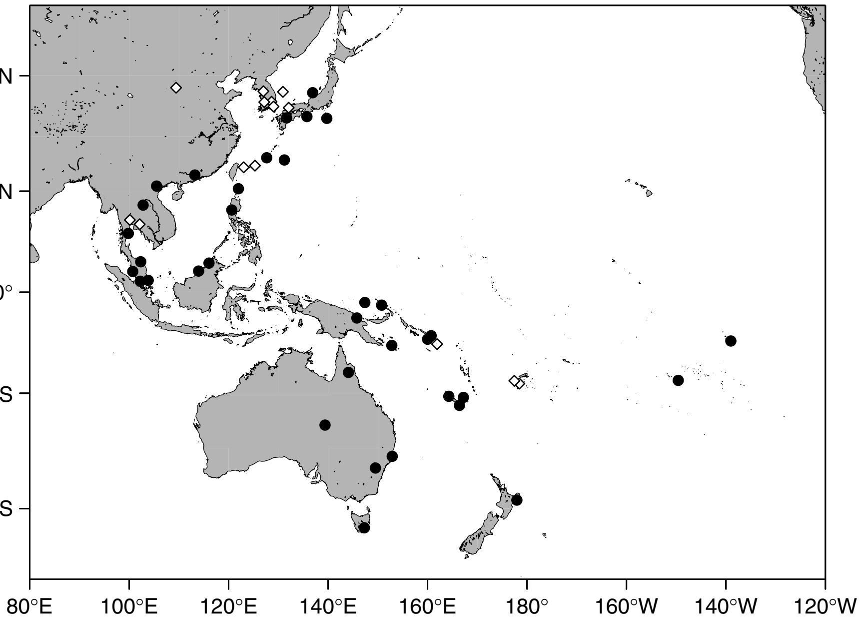

Figure 11. Locations of stations (both urban and non-urban) with significant changes in maximum temperature: mean and one or two extremes, but no significant change in SD Tmax (●), mean and one or two extremes, with significant change in SD Tmax (◊)

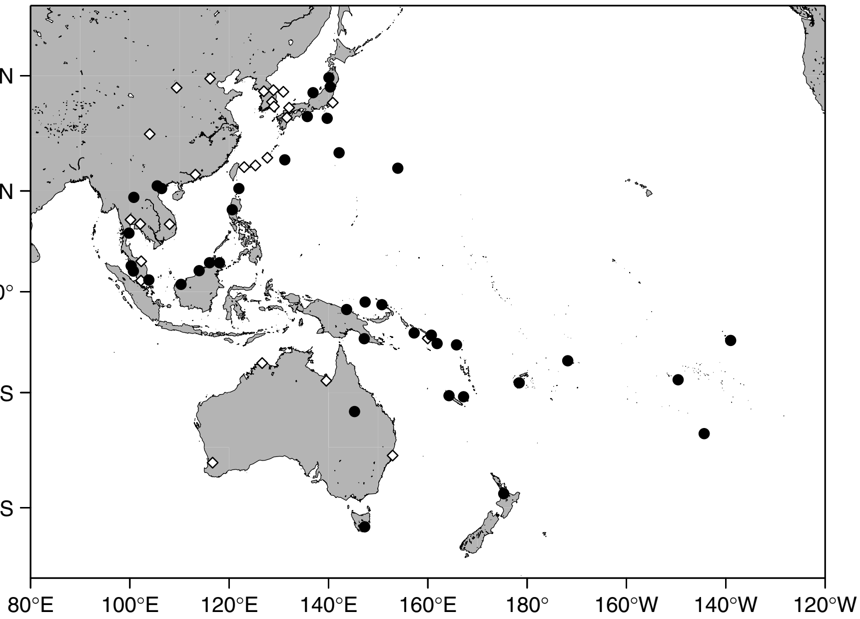

Figure 12. Locations of stations (both urban and non-urban) with significant changes in minimum temperature: mean and one or two extremes, but no significant change in SD Tmin (●), mean and one or two extremes, with significant change in SD Tmin (◊)

3.3. *Correlations between mean temperature and frequency of extremes*

Consistently strong relationships existed between the extreme temperature indices and measures of mean climate (Appendix B). Correlations between hot days and Tmax ranged between +0.17 and +0.89. Correlations were weakest in Australia (except in the southeast), in inland China and northern Japan

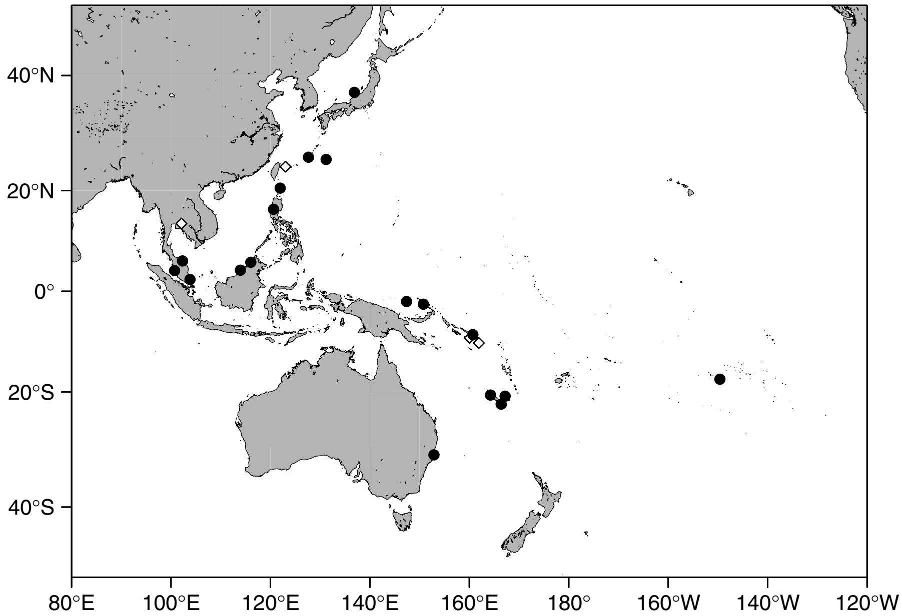

Figure 13. Locations of stations (both urban and non-urban) with significant changes in maximum temperature: mean and *both* extremes, but no significant change in SD Tmax (●), mean and both extremes, with significant change in SD Tmax (◊)

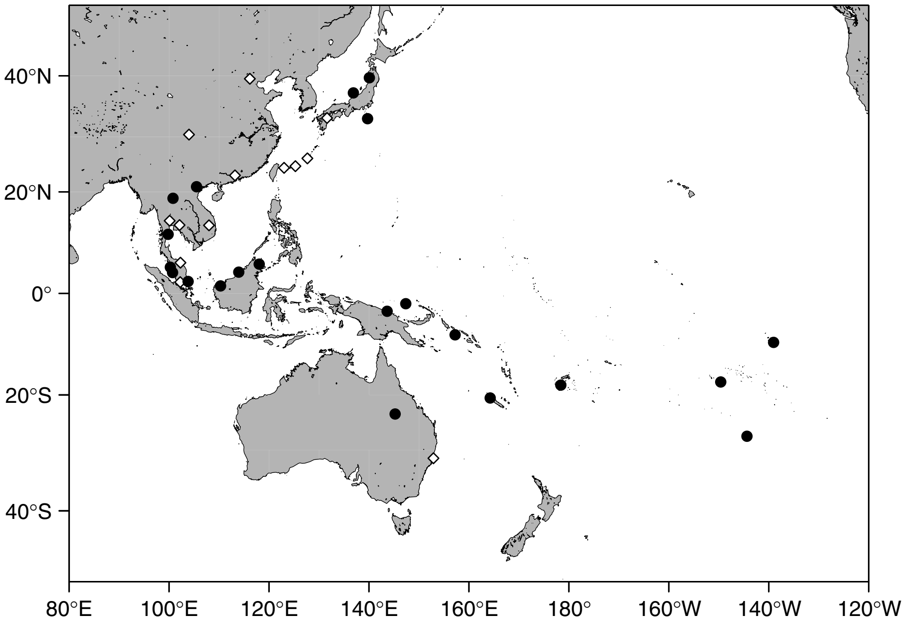

Figure 14. Locations of stations (both urban and non-urban) with significant changes in minimum temperature: mean and *both* extremes, but no significant change in SD Tmin (●), mean and both extremes, with significant change in SD Tmin (◊)

(Figure 16), and were very strong in Malaysia, PNG and parts of Thailand, Fiji, the Solomon Islands, and French Polynesia. The average correlation was +0.55 across all stations.

The correlations between warm nights and Tmin (Figure 17) were weakest at known urban sites (inland China, northern Japan, Korea) and for some Australian and New Zealand sites. The relationship between

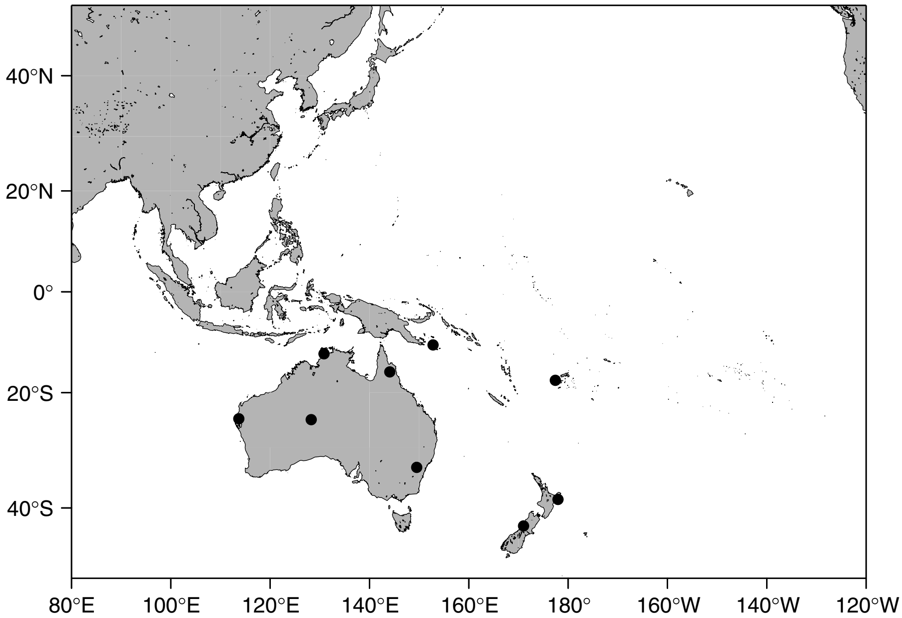

Figure 15. Locations of stations (both urban and non-urban) with no significant changes in minimum temperature (no changes in mean, extremes, or SD Tmin) (●)

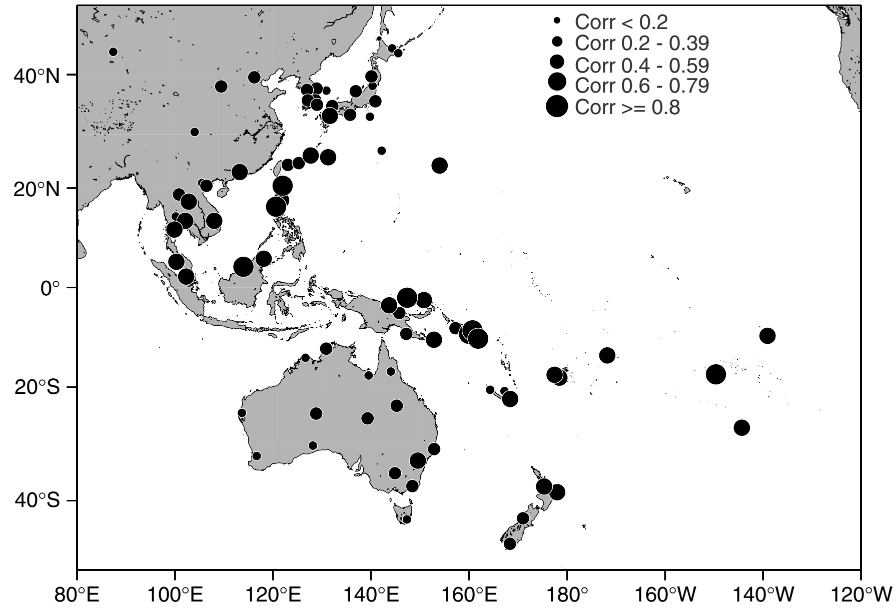

Figure 16. Correlation of hot days with Tmax. Correlations range between 0.17 and 0.89. Circle size is proportional to correlation magnitude (see scale)

warm nights and Tmin was consistently strong in the tropical Pacific Ocean and Southeast Asia, including Malaysia, parts of Thailand and in the Philippines. The average correlation across all locations was +0.54.

Correlations between cool days and Tmax ranged between −0.18 and −0.79, with an average correlation of −0.47. Correlations were weakest at higher latitudes (at some stations in Australia and New Zealand), and

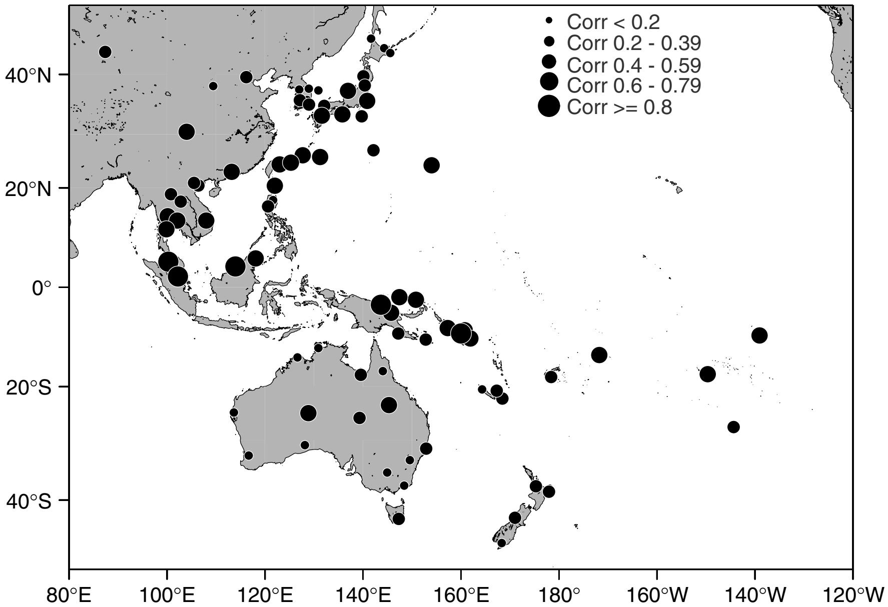

Figure 17. Correlation of warm nights with Tmin. Correlations range between 0.11 and 0.90. Circle size is proportional to correlation magnitude (see scale)

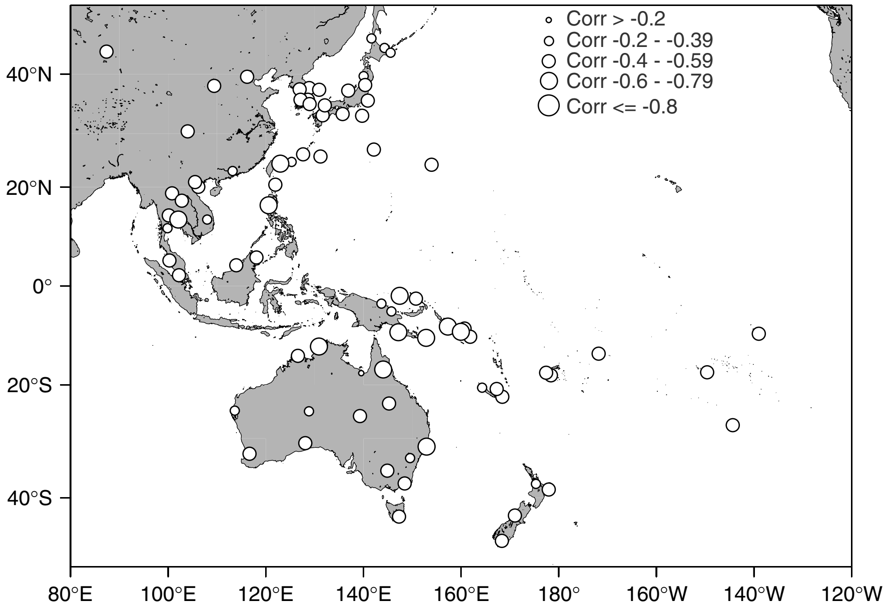

Figure 18. Correlation of cool days with Tmax. Correlations range between −0.79 and −0.18. Circle size is proportional to correlation magnitude (see scale)

in China and Japan (Figure 18), possibly influenced by urbanization effects. Correlations were strongest at island stations in the region from PNG to Fiji (the area of largest trends in Tmax).

The strongest relationship between cold nights and mean temperatures was seen in tropical locations (Figure 19) from French Polynesia to Malaysia, also Thailand and the Philippines. Correlations were again smallest at higher latitudes of both hemispheres, including China (where all sites were identified as urbanized),

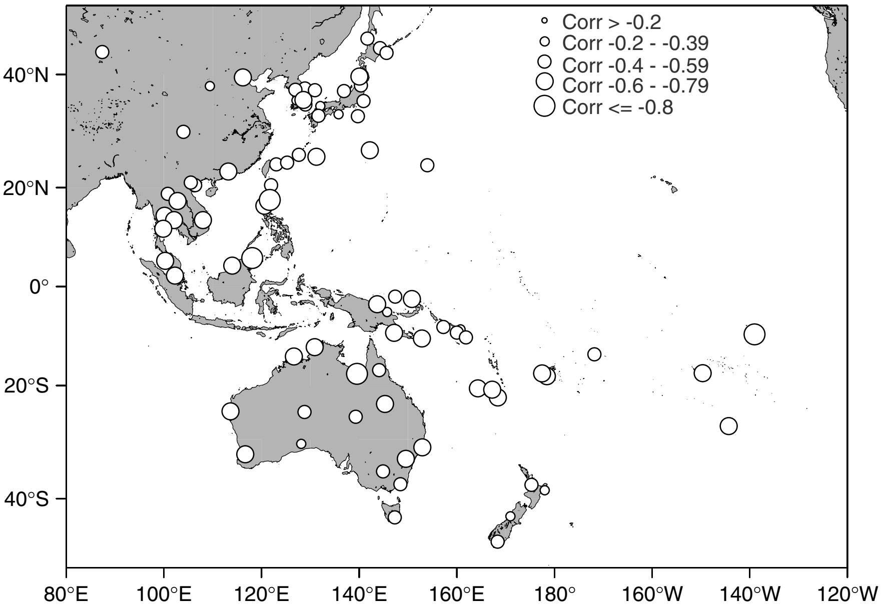

Figure 19. Correlation of cold nights with Tmin. Correlations range between −0.83 and −0.28. Circle size is proportional to correlation magnitude (see scale)

the western half of Australia and at some stations in New Zealand. The average correlation between cold nights and Tmin was −0.57.

Strong correlations between indices of mean climate and extreme climate in the islands of the tropical Pacific Ocean, and coastal locations of Malaysia, Thailand, the Philippines and southern Japan, indicate that the mean may be a useful predictor of changes in extreme climate in this region. However, correlations at higher latitudes, or at urbanized sites, were weaker.

4. ILLUSTRATIVE CASES

4.1. Changes in mean minimum temperature and extremes, no variability changes

A significant increase in Tmin was observed at Koumac, New Caledonia, since 1961, with a significant reduction in the number of cold nights and increase in warm-night frequency. No significant change in variability of minimum temperature was exhibited. This type of distribution change corresponds to 'mean, both extremes only' in Table IV, or a simplified shift in the mean (Figure 1, upper panel). A time series of minimum temperature indices at Koumac is shown in Figure 20. A steady increase in Tmin is evident (approximately 1 °C over the study period), with a steady decline in cold nights (by at least half). The increase in warm nights was more variable, but still significant (with an influential outlier in 2002).

Stations in the South Pacific, as well as sites in Malaysia and Japan, demonstrated this type of behaviour in minimum temperatures and extremes, although not all trends in the extremes were statistically significant. All New Caledonia stations also showed this type of distribution change for maximum temperatures (Figure 13).

4.2. Reduction in maximum temperature variability, fewer extremes

Carnarvon, Australia, is one of a number of coastal sites in northern and western Australia where a reduction in the variability of maximum temperature, but no change in mean climate, corresponded to a reduction in extremes. These reductions in the standard deviation and both extremes were significant at

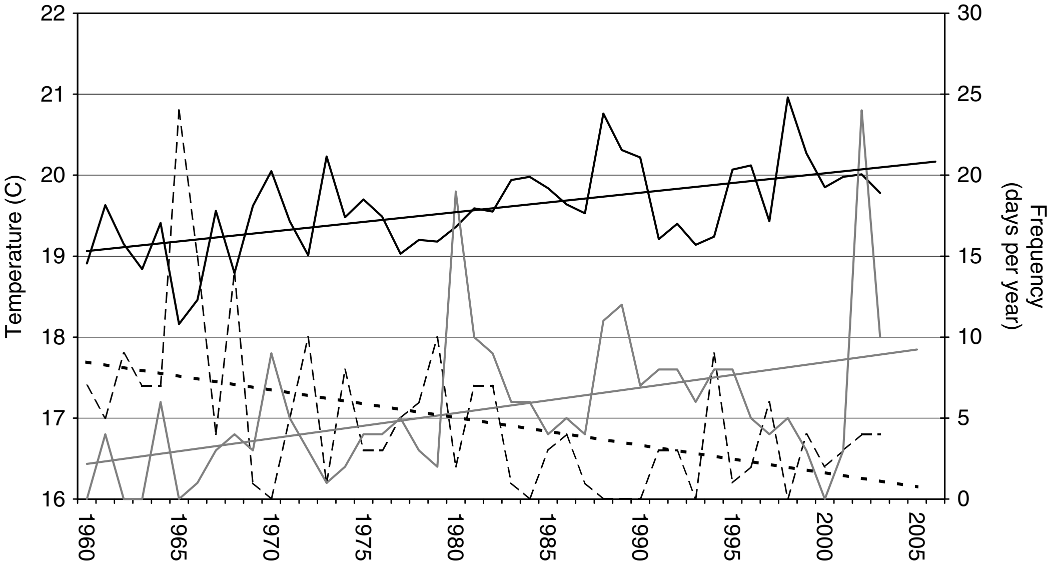

Figure 20. Koumac, New Caledonia. Time series of Tmin (solid black line), frequency of warm nights (solid grey line) and frequency of cold nights (dashed line). The frequency indices refer to the right-hand y-axis. Linear trends are also shown

Carnarvon, corresponding to 'SD, both extremes only' in Table IV, or the simplified lower panel in Figure 1. The decrease in both hot days and cool days can be clearly seen in Figure 21, although both series are noisy. There was no significant trend in Tmax. Two other Australian stations (i.e. Wandering and Kalumburu) demonstrated this type of behaviour in maximum temperatures, as well as the urbanized Chinese site of Urumqi (Table IV).

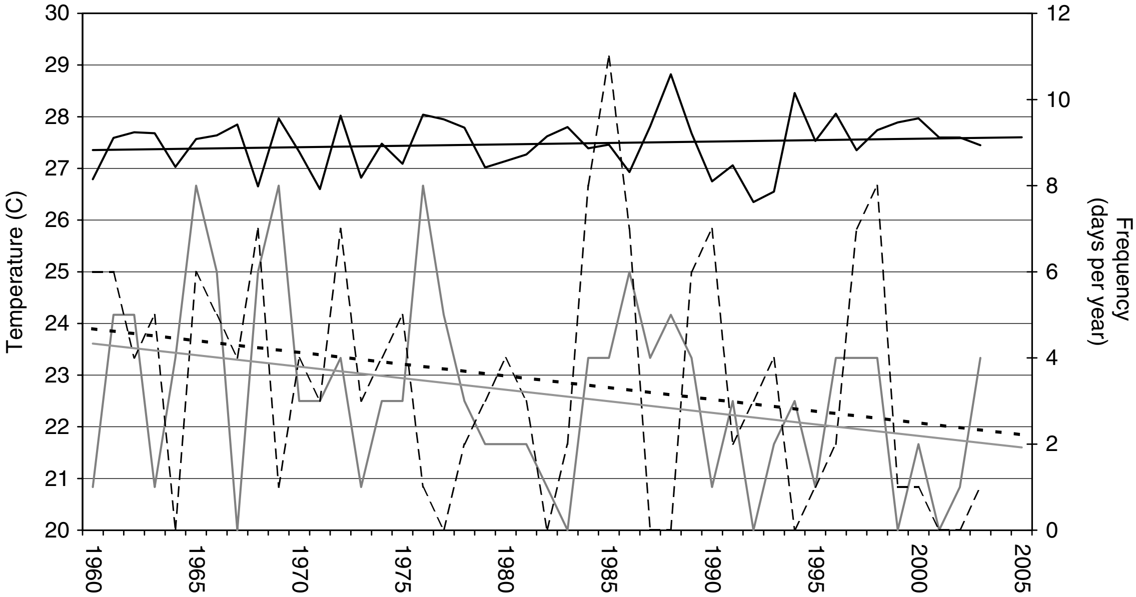

Figure 21. Carnarvon, Australia. Time series of Tmax (solid black line), frequency of hot days (solid grey line) and frequency of cool days (dashed line). The frequency indices refer to the right-hand y-axis. Linear trends are also shown

4.3. Increased mean maximum temperature and variability, more hot days

Several stations near to the South Pacific convergence zone (SPCZ), from 150 °E to 180° (in the Solomon Islands and Fiji), showed a large increase in mean maximum temperature and significant increases in variability, resulting in significant increases in hot days, but mixed trends for cool days.

Tmax has significantly increased at Lautoka, Fiji (Figure 22), in the order of 1.5 °C since 1961, with a corresponding (significant) increase in hot days, and a concurrent increase in variability (not directly shown). Cool days have decreased (but not significantly).

4.4. Increased mean minimum temperature, decrease in variability, fewer cold nights

Most stations in Korea, China and Japan, and several stations in Thailand (Suphan Buri and Chanthaburi), Vietnam (Pleycu) and coastal Australia, showed a significant increase in Tmin, with significant decreases in minimum temperature variability. The resulting impacts on extremes were consistent: all stations exhibited significant decreases in cold nights (which reflects both effects on the left-hand tail of the distribution), but only about half the sites showed an increase in warm nights. Urbanization effects are likely to have at least partly affected these results at the urban sites identified in this study.

Daegu, Korea, is a highly urbanized site that showed a strong increase in mean minimum temperature (approximately 1 °C since 1961), and a corresponding strong decrease in cold nights (Figure 23), which have become quite rare in the last decade. Although there was an increase in warm nights, the rate of increase was not significant.

5. DISCUSSION AND CONCLUSIONS

This paper has documented trends in daily temperature means, extremes and variability across the broad Asia–Pacific region, and found these trends to be spatially coherent within geographical areas.

The observed spatial coherency in trends in means, extremes, and variance indicates that useful results can be obtained through analysis of a broad geographical area, even where individual stations suffer from incomplete data, could benefit from improved homogeneity testing, or if trends are not statistically ‘significant’.

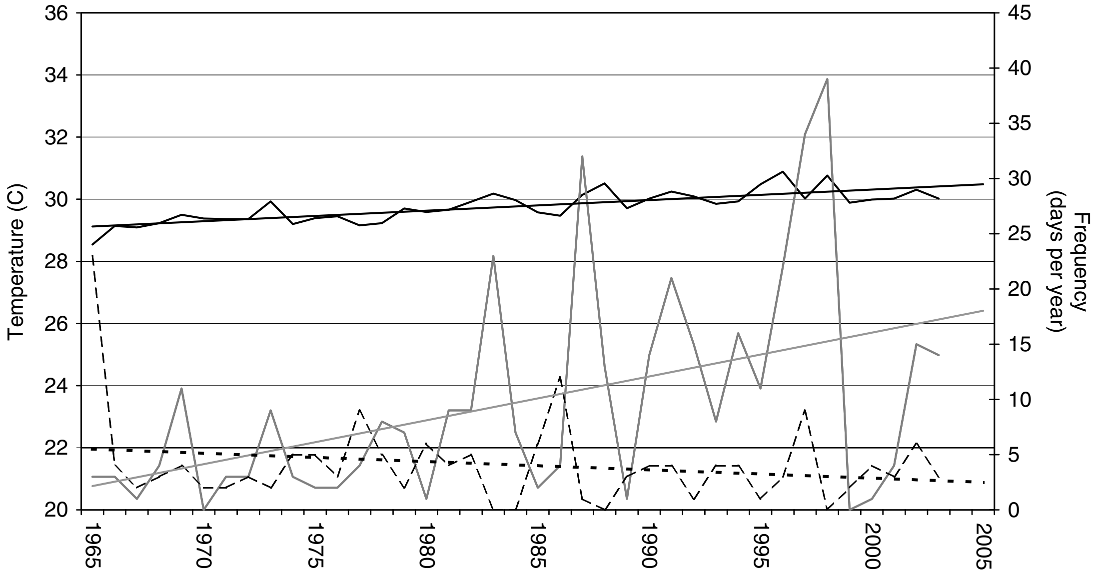

Figure 22. Lautoka, Fiji. Time series of Tmax (solid black line), frequency of hot days (solid grey line) and frequency of cool days (dashed line). The frequency indices refer to the right-hand y-axis. Linear trends are also shown

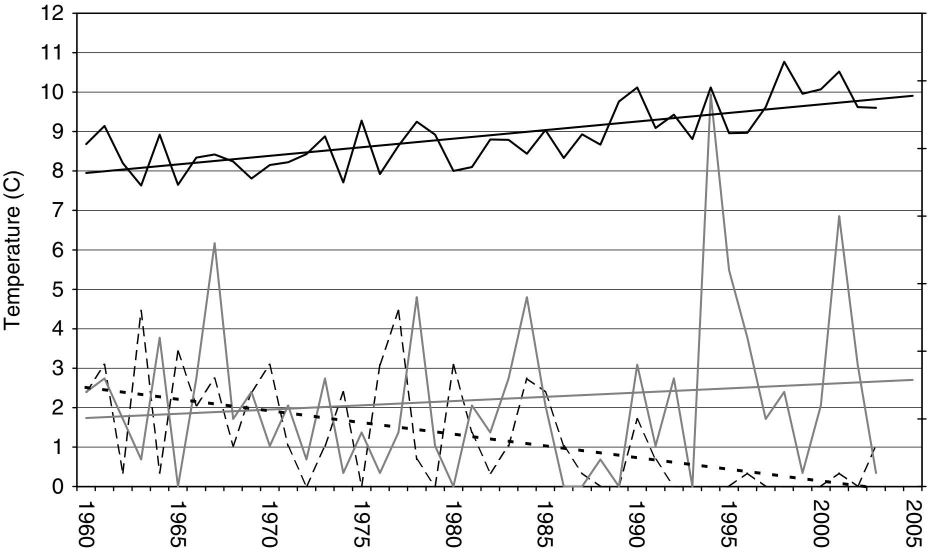

Figure 23. Daegu, Korea. Time series of Tmin (solid black line), frequency of warm nights (solid grey line) and frequency of cold nights (dashed line). The frequency indices refer to the right-hand *y*-axis. Linear trends are also shown

The majority of stations (79%) showed a significant increase in mean minimum temperature, and 64% exhibited a significant increase in mean maximum temperature. Mean minimum temperature increases were largest in China, Korea, Malaysia and parts of Australia. The largest increases in maximum temperature were observed in the region near the SPCZ, between Fiji and the Solomon Islands, and in Malaysia and Korea. Over half of the stations showed significant increases in warm nights, and decreases in cool days and cold nights. Hot days increased at 40% of the stations. Notably, no stations showed significant increases in cool days or cold nights. This updated and expanded set of extreme indices trends is generally consistent with previous work, but the level of significance has increased at several stations over the longer analysis period.

The urbanized stations identified in this paper typically showed large (and significant) increases in the mean and decreases in standard deviation of both maximum and minimum temperature, but trends in extremes were often much smaller (and insignificant).

The most common distribution change observed in the Asia–Pacific region over 1961–2003, at non-urban sites, involved a significant shift in the mean and either one or both extremes (the tails of the distribution), but with no significant change in standard deviation. This category accounted for 44% (50%) of significant distribution change cases for maximum temperature (minimum temperature) at non-urban sites.

For urbanized stations, the dominant distribution change observed involved a change in both mean and variance, impacting on either one or both distribution tails. This result was particularly evident for minimum temperature, but also applied to maximum temperature change.

Notable differences between non-urban and urban sites emerged when including standard deviation results: urbanized sites more commonly exhibited significant changes in the standard deviation of both maximum and minimum temperatures than non-urban sites did (by a factor of ~1.5 for maximum temperature and a factor of ~3 for minimum temperature). The significant decrease in standard deviation observed at urbanized sites in this study is consistent with previous studies in China and Korea, which showed that urbanization effects decreased variance, in particular for minimum temperatures. A moderate proportion of non-urban stations (13%) showed no minimum temperature distribution change over the analysis period, compared with no sites (0%) in the (smaller) urbanized sample, primarily reflecting urbanization (reduced standard deviation) effects.

Interestingly, a small number of non-urban sites in the region close to the SPCZ, between Fiji and the Solomon Islands, showed a significant increase in maximum temperature variability. Also, the majority of stations that showed no significant maximum temperature distribution change at all were located in Australia and New Zealand.

The strength of the correlations between mean temperature and extreme indices locations in the Asia–Pacific region, in particular at non-urban, maritime and tropical sites, indicates that the mean may be a useful predictor of changes in extreme climate. Correlations were largest in the tropical Pacific Ocean from French Polynesia to PNG, and in coastal Southeast Asia (Malaysia, the Philippines, southern Japan and at some sites in Thailand). Correlations were weaker at continental, higher latitude, or urbanized locations, e.g. in Australia (except in the southeast for hot days), inland China and Korea, and some sites in northern Japan.

The stations that displayed significant shifts in mean temperature, changes in one or both extremes and no corresponding significant changes in variance also exhibited a strong correlation between mean and extreme temperatures, and were primarily located in tropical, maritime and non-urban environments. For stations from French Polynesia to PNG, as well as in Malaysia and the Philippines, and some outlying islands of Japan, these results support the hypothesis that changes in the mean minimum temperature have the potential to be used to predict changes in extremes. This hypothesis also applies to maximum temperatures in the same geographical area (except for stations in Fiji and the Solomon Islands, near the SPCZ west of 180°). Note that, at the tropical island stations, standard deviation trends tend to be small, relative to observed trends in the mean. Although the frequency of extreme events is theoretically more sensitive to changes in the scale parameter (variance) than the location parameter, it is possible that the magnitude of the change in the mean can be sufficiently large, compared with the size of the change of the variance, to have a dominant effect still on extreme-event frequency (Katz and Brown, 1992).

At higher latitudes (Australia, New Zealand, and northern Japan), at urbanized sites (especially mainland China and Korea), and in the region from Fiji to the Solomon Islands, the use of the mean temperature alone as a proxy for changes in extremes is not recommended, because of significant urbanization effects and/or variability changes, lower correlations between means and extreme indices, or spatial inconsistencies in observed distribution changes (if changes were observed at all).

Future identification of the mechanisms behind these trends in extremes would be useful, including analysis of drivers of the increased maximum temperature variability in the SPCZ region (from Fiji to the Solomon Islands), and the reduction in maximum temperature variability at some coastal Australian stations. Further work on quantifying temperature distribution changes in the Asia–Pacific region would also assist future impact assessments of climate change.

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APPENDIX A: LIST OF STATIONS, THEIR LOCATION AND PERIOD OF RECORD

The data provided by the member countries covered part or all of the years in the ‘available’ column. The data used for analysis were in most cases shorter, bounded by the analysis period of 1961–2003 and, in some cases, limited by incomplete annual records.

Table AI.

Country	Station	Latitude (decimal)	Longitude (decimal)	Temperature (available)	Temperature (used)
Australia	Kalumburu	14.30 °S	126.64 °E	1957–2003	1961–2003
	Carnarvon	24.88 °S	113.67 °E	1945–2003	1961–2003
	Wandering	32.67 °S	116.67 °E	1957–2003	1961–2003
	Forrest	30.83 °S	128.11 °E	1947–2003	1961–2003
	Giles	25.04 °S	128.29 °E	1957–2003	1961–2003
	Darwin	12.42 °S	130.88 °E	1941–2003	1961–2003
	Palmerville	16.00 °S	144.08 °E	1957–2003	1961–2003
	Burketown	17.74 °S	139.55 °E	1957–2003	1961–2003
	Barcaldine	23.55 °S	145.29 °E	1957–2003	1961–2003
	Birdsville	25.90 °S	139.35 °E	1957–2003	1961–2003
	Port Macquarie	31.43 °S	152.92 °E	1921–2003	1961–2003
	Bathurst	33.43 °S	149.56 °E	1921–2003	1961–2003
	Deniliquin	35.55 °S	144.95 °E	1957–2003	1961–2003
	Orbost	37.69 °S	148.46 °E	1957–2003	1961–2003
	Hobart	42.89 °S	147.33 °E	1944–2003	1961–2003
China	Urumqi	43.47 °N	87.37 °E	1951–2003	1961–2003
	Yinchuan	38.14 °N	109.42 °E	1951–2003	1961–2003
	Beijing	39.56 °N	116.17 °E	1951–2003	1961–2003
	Chendu	30.40 °N	104.01 °E	1951–2003	1961–2003
	Guang Zhou	23.08 °N	113.19 °E	1951–2003	1961–2003
Fiji	Lautoka	17.62 °S	177.45 °E	1965–2003	1965–2003
	Suva	18.15 °S	178.45 °E	1942–2003	1961–2003
French Polynesia	Atuona	9.80 °S	139.03 °W	1961–2003	1961–2003
	Faaa	17.55 °S	149.60 °W	1957–2003	1961–2003
	Rapa	27.62 °S	144.33 °W	1951–2003	1961–2003
Japan	Wakkanai	45.42 °N	141.68 °E	1961–2003	1961–2003
	Abashiri	44.02 °N	144.28 °E	1961–2003	1961–2003
	Nemuro	43.33 °N	145.58 °E	1961–2003	1961–2003
	Akita	39.72 °N	140.10 °E	1961–2003	1961–2003
	Yamagata	38.25 °N	140.35 °E	1961–2003	1961–2003
	Wajima	37.38 °N	136.90 °E	1961–2003	1961–2003
	Choshi	35.73 °N	140.87 °E	1961–2003	1961–2003
	Hachijojima	33.10 °N	139.78 °E	1961–2003	1961–2003
	Hamada	34.90 °N	132.07 °E	1961–2003	1961–2003
	Shionomisaki	33.45 °N	135.77 °E	1961–2003	1961–2003
	Oita	33.23 °N	131.62 °E	1961–2003	1961–2003
	Yonagunijima	24.47 °N	123.02 °E	1961–2003	1961–2003
	Miyakojima	24.78 °N	125.28 °E	1961–2003	1961–2003
	Naha	26.20 °N	127.68 °E	1961–2003	1961–2003
	Minamidaitojima	25.83 °N	131.23 °E	1961–2003	1961–2003
	Chichijima	27.08 °N	142.18 °E	1969–2003	1969–2003
	Minamitorishima	24.30 °N	153.97 °E	1970–2003	1970–2003
Korea	Gangneong	37.75 °N	128.90 °E	1912–2003[a]	1961–2003
	Seoul	37.57 °N	126.97 °E	1908–2003[a]	1961–2003
	Ulleungdo	37.48 °N	130.90 °E	1939–2003	1961–2003
	Daegu	35.88 °N	128.62 °E	1908–2003	1961–2003
	Jeonju	35.82 °N	127.15 °E	1919–2003	1961–2003
	Busan	35.10 °N	129.03 °E	1905–2003	1961–2003

Table AI. (*Continued*)

Country	Station	Latitude (decimal)	Longitude (decimal)	Temperature (available)	Temperature (used)
Malaysia	Bayan Lepas	5.30 °N	100.27 °E	1968–2003	1968–2003
	Kota Bharu	6.17 °N	102.28 °E	1968–2003	1968–2003
	Kuching	1.48 °N	110.33 °E	1968–2003	1968–2003
	Kota Kinabalu	5.93 °N	116.05 °E	1968–2003	1968–2003
	Malacca	2.27 °N	102.25 °E	1968–2003	1968–2003
	Miri	4.33 °N	113.98 °E	1968–2003	1968–2003
	Mersing	2.45 °N	103.83 °E	1968–2003	1968–2003
	Sandakan	5.90 °N	118.07 °E	1968–2003	1968–2003
	Sitiawan	4.22 °N	100.70 °E	1968–2003	1968–2003
New Caledonia	Koumac	20.56 °S	164.29 °E	1954–2003	1961–2003
	Nouméa	22.28 °S	166.45 °E	1951–2003	1961–2003
	Ouanaham	20.78 °S	167.24 °E	1960–2003	1961–2003
New Zealand	Gisborne	38.67 °S	178.01 °E	1940–2003	1961–2003
	Ruakura	37.78 °S	175.31 °E	1940–2003	1961–2003
	Hokitika	42.72 °S	170.99 °E	1900–2003	1961–2003
	Invercargill	46.42 °S	168.33 °E	1948–2003	1961–2003
Papua New Guinea	Kavieng	2.58 °S	150.80 °E	1973–2003	1973–2003
	Madang	5.22 °S	145.78 °E	1973–2003	1973–2003
	Misima	10.67 °S	152.83 °E	1975–2003	1976–2003
	Momote	2.05 °S	147.42 °E	1968–2003	1968–2003
	Port Moresby	9.45 °S	147.20 °E	1970–2003	1970–2003
	Wewak	3.58 °S	143.67 °E	1973–2003	1973–2003
Philippines	Baguio City	16.42 °N	120.60 °E	1961–2003	1961–2003
	Tuguegarao	17.62 °N	121.70 °E	1961–2003	1961–2003
	Basco	20.45 °N	121.97 °E	1961–2003	1961–2003
Samoa	Apia	13.82 °S	171.78 °W	1972–2003	1972–1995
Solomon Islands	Auki	8.78 °S	160.73 °E	1962–2000	1962–1999
	Henderson	9.42 °S	160.05 °E	1974–2000	1975–1999
	Honiara	9.42 °S	159.97 °E	1951–2000	1961–1999
	Kirakira	10.42 °S	161.92 °E	1965–2000	1965–1999
	Lata	10.70 °S	165.80 °E	1970–2000	1971–2000
	Munda	8.33 °S	157.26 °E	1962–2000	1962–2000
Thailand	Nan	18.78 °N	100.78 °E	1951–2003	1961–2003
	Udon Thani	17.38 °N	102.80 °E	1951–2003	1961–2003
	Suphan Buri	14.47 °N	100.13 °E	1953–2003	1961–2003
	Chanthaburi	13.62 °N	102.12 °E	1951–2003	1961–2003
	Prachuap Khiri Khan	11.83 °N	99.83 °E	1951–2003	1961–2003
Vietnam	Phu-Lien	20.48 °N	106.38 °E	1958–2003	1961–2003
	Ha-Noi	21.02 °N	105.51 °E	1961–2003	1961–2000
	Pleycu	13.58 °N	108.01 °E	1961–2003	1961–2003
	Vanly	20.07 °N	106.18 °E	1960–2003	1961–2003

[a] Missing data due to Korean War.

APPENDIX B: CORRELATIONS BETWEEN EXTREME INDICES AND TMAX/TMIN

Table BI.

Country	Station	Cool days and mean Tmax	Hot days and mean Tmax	Cold nights and mean Tmin	Warm nights and mean Tmin
Australia	Birdsville	−0.45	0.42	−0.48	0.58
	Palmerville	−0.70	0.34	−0.45	0.23
	Burketown	−0.18	0.30	−0.81	0.42
	Barcaldine	−0.56	0.48	−0.72	0.64
	Port Macquarie	−0.65	0.57	−0.78	0.53
	Bathurst	−0.35	0.68	−0.65	0.39
	Deniliquin	−0.42	0.55	−0.41	0.28
	Orbost	−0.43	0.43	−0.58	0.31
	Hobart	−0.49	0.39	−0.49	0.49
	Carnarvon	−0.33	0.22	−0.64	0.29
	Wandering	−0.55	0.24	−0.60	0.24
	Forrest	−0.47	0.30	−0.28	0.38
	Giles	−0.25	0.57	−0.51	0.70
	Darwin	−0.70	0.40	−0.69	0.36
	Kalumburu	−0.55	0.34	−0.63	0.26
China	Urumqi	−0.46	0.38	−0.47	0.40
	Yinchuan	−0.44	0.58	−0.33	0.30
	Beijing	−0.56	0.51	−0.71	0.55
	Chendu	−0.45	0.38	−0.46	0.70
	Guang Zhou	−0.29	0.62	−0.63	0.77
Fiji	Suva	−0.51	0.71	−0.71	0.59
	Lautoka	−0.53	0.67	−0.69	0.11
French Polynesia	Rapa	−0.49	0.64	−0.60	0.48
	Faaa	−0.48	0.85	−0.70	0.67
	Atuona	−0.55	0.72	−0.81	0.67
Japan	Hamada	−0.46	0.54	−0.38	0.60
	Yamagata	−0.50	0.36	−0.46	0.54
	Wakkanai	−0.40	0.17	−0.54	0.25
	Abashiri	−0.29	0.38	−0.46	0.22
	Nemuro	−0.31	0.39	−0.48	0.34
	Akita	−0.37	0.55	−0.63	0.53
	Wajima	−0.43	0.42	−0.59	0.67
	Choshi	−0.44	0.53	−0.53	0.61
	Hachijojima	−0.45	0.40	−0.47	0.49
	Shionomisaki	−0.46	0.54	−0.34	0.61
	Oita	−0.45	0.62	−0.51	0.73
	Yonagunijima	−0.63	0.56	−0.58	0.61
	Miyakojima	−0.37	0.51	−0.51	0.69
	Naha	−0.45	0.71	−0.58	0.73
	Minamidaitojima	−0.45	0.63	−0.64	0.60
	Chichijima	−0.56	0.37	−0.76	0.44
	Minamitorishima	−0.48	0.66	−0.47	0.64
Korea	Gangneong	−0.43	0.46	−0.52	0.24
	Seoul	−0.48	0.50	−0.54	0.33
	Ulleungdo	−0.54	0.32	−0.48	0.32
	Daegu	−0.54	0.53	−0.60	0.37
	Jeonju	−0.48	0.51	−0.35	0.41
	Busan	−0.51	0.57	−0.51	0.42

Table BI. (*Continued*)

Country	Station	Cool days and mean Tmax	Hot days and mean Tmax	Cold nights and mean Tmin	Warm nights and mean Tmin
Malaysia	Bayan Lepas	−0.41	0.76	−0.67	0.88
	Miri	−0.59	0.82	−0.66	0.85
	Sandakan	−0.40	0.72	−0.83	0.80
	Malacca	−0.45	0.72	−0.64	0.89
New Caledonia	Koumac	−0.37	0.38	−0.78	0.32
	Noumea	−0.45	0.68	−0.69	0.53
	Ouanaham	−0.48	0.37	−0.72	0.55
New Zealand	Ruakura	−0.29	0.67	−0.54	0.52
	Gisborne	−0.43	0.64	−0.36	0.47
	Hokitika	−0.55	0.56	−0.32	0.56
	Invercargill	−0.47	0.55	−0.47	0.32
Papua New Guinea	Kavieng	−0.58	0.78	−0.64	0.70
	Madang	−0.21	0.58	−0.36	0.63
	Misima	−0.79	0.60	−0.68	0.55
	Momote	−0.63	0.82	−0.53	0.76
	Port Moresby	−0.60	0.56	−0.76	0.59
	Wewak	−0.26	0.71	−0.74	0.84
Philippines	Basco	−0.57	0.83	−0.48	0.68
	Tuguegarao	−0.25	0.64	−0.81	0.39
	Baguio	−0.73	0.81	−0.61	0.56
Samoa	Apia	−0.47	0.72	−0.56	0.78
Solomon Islands	Munda	−0.72	0.47	−0.40	0.73
	Honiara	−0.61	0.82	−0.54	0.90
	Auki	−0.52	0.83	−0.36	0.67
	Kirra	−0.51	0.89	−0.55	0.67
Thailand	Nan	−0.48	0.52	−0.59	0.59
	Udon Thani	−0.44	0.67	−0.73	0.55
	Suphan Buri	−0.49	0.32	−0.67	0.62
	Chanthaburi	−0.63	0.70	−0.78	0.69
	Prachuap Khiri Khan	−0.40	0.74	−0.67	0.77
Vietnam	Phu-Lien	−0.39	0.42	−0.40	0.45
	Pleycu	−0.38	0.68	−0.63	0.63
	Vanly	−0.46	0.34	−0.30	0.35
	Ha-Noi	−0.48	0.31	−0.41	0.56

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