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TRENDS IN EXTREME DAILY RAINFALL AND TEMPERATURE IN SOUTHEAST ASIA AND THE SOUTH PACIFIC: 1961–1998

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ABSTRACT

Trends in extreme daily temperature and rainfall have been analysed from 1961 to 1998 for Southeast Asia and the South Pacific. This 38-year period was chosen to optimize data availability across the region. Using high-quality data from 91 stations in 15 countries, significant increases were detected in the annual number of hot days and warm nights, with significant decreases in the annual number of cool days and cold nights. These trends in extreme temperatures showed considerable consistency across the region. Extreme rainfall trends were generally less spatially coherent than were those for extreme temperature. The number of rain days (with at least 2 mm of rain) has decreased significantly throughout Southeast Asia and the western and central South Pacific, but increased in the north of French Polynesia, in Fiji, and at some stations in Australia. The proportion of annual rainfall from extreme events has increased at a majority of stations. The frequency of extreme rainfall events has declined at most stations (but not significantly), although significant increases were detected in French Polynesia. Trends in the average intensity of the wettest rainfall events each year were generally weak and not significant. Copyright © 2001 Royal Meteorological Society.

KEY WORDS: Australasia; climate change; climate extremes; precipitation; Southeast Asia; South Pacific; temperature

1. INTRODUCTION

Extreme weather or climate events can have major impacts on society, the economy and the environment. Karl *et al.* (1999) assessed changes in climate extremes over many parts of the world during the past century. They reported a reduction in the number of extremely cold days, including fewer frosts and freezes, and an increase in the number of extremely hot days. As well, minima had increased more rapidly

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than maxima. Extreme precipitation had increased in the US, China, Australia, Canada, Norway, Mexico, Poland and the Former Soviet Union (Groisman *et al.*, 1999). No clear tropics-wide trends have emerged in the number of tropical storms; Nicholls *et al.* (1998) found a slight increase in the number of intense tropical cyclones in the Australian region since 1969, while Landsea *et al.* (1996) reported a decline in the number of intense Atlantic hurricanes over a similar period. There is little evidence of a change in extra-tropical storms, but only a limited amount of data have been analysed.

Fewer studies have examined trends in climate extremes, other than changes in mean values, largely a result of the extra demands this places on data quality and quantity. Even a relatively small amount of missing data, whilst not necessarily affecting the mean significantly, immediately raises the possibility that an extreme event has been missed. Also, when investigating trends in the extreme ends of a climatic distribution, the likelihood of complications resulting from erroneous data is increased because outliers can be incorrectly considered as true data extremes (or genuine extremes may be rejected as outliers). Applying consistent analyses across a wide region also requires that the criteria used to define extreme events are meaningful across the entire region. What is considered extreme in one part of the region might be considered quite routine in another. Further data issues in monitoring extreme events are discussed in Nicholls (1995).

Little is known about trends in extreme temperature or rainfall in the Asia-Pacific region. To some extent, this is because the region covers a broad range of countries, some of which have poor data availability, quality and consistency. The region is particularly vulnerable to changes in climate extremes as a result of its generally high population density, exposure to tropical cyclones, strong links between rainfall and the El Niño–Southern Oscillation, low-lying islands, coral reefs, and fire-prone environments. In addition, the Interdecadal Pacific Oscillation (Power *et al.*, 1999) is an important source of climate variation in the region.

In 1998, the Asia-Pacific Network (APN) for Global Change Research funded a workshop on climate extremes, hosted by the Australian Bureau of Meteorology Research Centre (BMRC). A major aim of the workshop was to encourage regional participation in international studies on monitoring and detecting changes in climate extremes (Manton and Nicholls, 1999). The meeting included representatives from 14 countries: Australia, Fiji, French Polynesia, Indonesia, Japan, Malaysia, Myanmar, New Caledonia, New Zealand, Papua New Guinea, the Philippines, Samoa, Thailand and Vietnam. A significant outcome of the workshop was the desire of all participants to contribute to an analysis of Asia-Pacific trends in extreme climate for the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). It was intended that this analysis should be consistent and relevant across the region, and simple to calculate.

This led to a second workshop in December 1999, also funded by the APN and hosted by BMRC, attended by representatives from the same 14 countries plus the Solomon Islands. At this workshop, extreme rainfall and temperature trends were analysed by applying common quality control and analysis techniques across the region. While other variables could have been considered, rainfall and temperature were judged in the 1998 workshop as being the variables with the longest and most reliable records, and the most relevant for comparison with other international studies. This paper reports the results of the analyses conducted as a result of this second workshop. Quality control and analysis techniques are described in the next section, followed by trend results in the third section, and a discussion of the results in the fourth.

2. DATA ANALYSIS METHODS

2.1. Climate station selection

Representatives from the national climate service of each country participating in the workshop provided daily rainfall and maximum and minimum temperature data for a small number of stations in their country. The stations satisfied the following criteria:

- The records were as long as possible, and included the standard reference period of 1961–1990.
- Less than 20% of the daily values were missing in each year.
- The stations were of high-quality, preferably non-urban, and well maintained.
- The station, in most cases, had a documented history of changes such as those involving instrumentation, observation practices and the station's immediate environment (metadata).
- In most cases, the station had been located at a single site during the period of record.

Whilst participants were free to choose the stations that they felt best met these criteria, obvious candidates were those stations already selected for inclusion in the country's Reference Climate Station (RCS) network or the Global Climate Observing System (GCOS) Surface Network (GSN) (Peterson *et al.*, 1997). The primary purpose of such stations is to identify long-term climate trends and, consequently, these stations will have been chosen for having long, continuous and homogeneous records, for having minimal influence from urbanization, and for generally being high-quality stations.

2.2. Quality control

Inhomogeneities or discontinuities in a climate record can be caused by any change to the station or its operation, including site location, exposure, instrumentation, or observational practice. These discontinuities will not only affect mean climatic values, but also the extremes of the climatic distribution, and may affect the extremes differently to the mean (Trewin and Trevitt, 1996). Numerous studies have used procedures such as visual examination of data, neighbouring station checks, and statistical tests to identify and adjust for inhomogeneities in seasonal or annual mean temperature and total rainfall (e.g. Lavery *et al.*, 1992, 1997; Torok and Nicholls, 1996; Peterson *et al.*, 1998). A few studies (e.g. Trewin, 2000) have made adjustments at the daily time-scale and allowed for different magnitudes of discontinuity at different parts of the temperature or rainfall distribution. Ideally, this would have been done for the climate records used in this analysis, but this was beyond the scope of the workshop. However, attempts were made to minimize the influence of inhomogeneities on the results of the analysis.

The daily time-series from each station were first examined visually to identify any obvious outliers, trends and potential discontinuities. Annual mean series (annual total for rainfall) were then produced from the daily rainfall and maximum and minimum temperature time-series, and examined for discontinuities using a software package known as Multiple Analysis of Series for Homogenization (MASH) (Szentimrey, 1997). The MASH technique calculates the difference between series at a candidate station and at a number of climatically-similar reference stations to identify statistically significant shifts in the annual mean values of the candidate series. Potential break points were identified using MASH, and compared with available metadata.

MASH quantifies the adjustment needed to create a homogeneous annual mean series. However, applying these adjustments to all daily data during a year is not an appropriate method of producing a homogeneous daily data series. The magnitude of the discontinuity will vary at different times of the year, and it is not known how an adjustment for the mean should be translated into an adjustment for the more extreme values in the distribution. If no major discontinuities were detected for a station, then it was accepted for analysis. If a discontinuity could be related to some change suggested by the station metadata, then the station was rejected. If a discontinuity could not be related to metadata, it was assumed that the climatic shift was real. The results presented here are derived from the most homogeneous data identified at the workshop.

Finally, only stations where each year of record had at least 308 days of data available were included. This criterion equates to a probability of at least 50% that all of the four most extreme events for that year would be present in the data set.

Based on the homogeneity testing and quality control, data for a set of 91 high-quality stations (Appendix A and Figure 1) were prepared for analysis. As most of the stations have data from 1961–1998, this period was used to investigate trends in extremes. A small proportion of stations did not have data for the complete period (see Appendix A). This should be borne in mind when the results of the analysis of trends are discussed. It should also be remembered that although we believe the data set

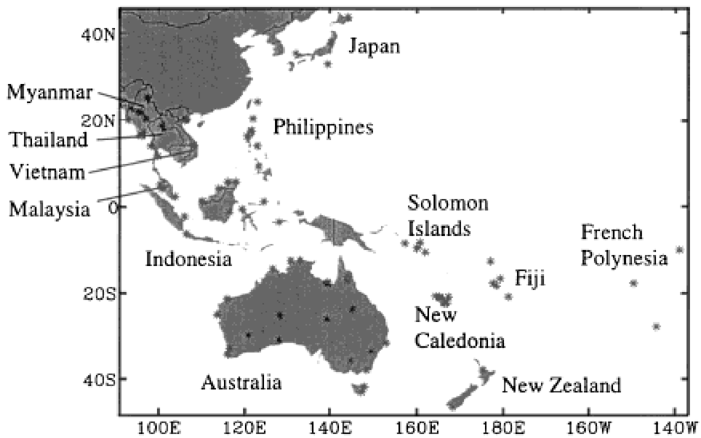

Figure 1. Locations of stations (*) used in this study

used here is the best available, at the present time, other unidentified inhomogeneities probably exist in these data. Future work may refine the data set further.

2.3. Analysis methods

Numerous extreme rainfall and temperature indices have been used in previous studies. Some indices involved arbitrary thresholds, such as the number of days each year with daily rainfall exceeding 25.4 mm or 50.8 mm (Groisman *et al.*, 1999), or the number of winter days below 0°C (Jones *et al.*, 1999). These are suitable for regions with little spatial variability in climate, but arbitrary thresholds are inappropriate for regions spanning a broad range of climates. For example, in a country like Australia that covers latitudes 12°–44°S, there is no single temperature or rainfall threshold that would be considered extreme in all regions. For this reason, some studies have used extreme indices based on statistical quantities such as the 10th or 90th percentile (e.g. Plummer *et al.*, 1999). These upper and lower percentiles are extreme in all regions, but vary in absolute magnitude from site to site. For example, the 99th percentile of daily rainfall exceeds 100 mm in summer and autumn over north-eastern Australia, but falls below 30 mm in the south (Hennessy *et al.*, 1999).

As this study covers a broad region, extreme climate indices were based on the 1st and 99th percentiles. The percentiles were computed using all non-missing days. For rainfall, this included rain days and dry days. As there are 365 days in a year, the 1st percentile is the 4th lowest value, and the 99th percentile is the 4th highest. We have chosen the following eight indices of extremes:

- Frequency of daily rainfall exceeding the 1961–1990 mean 99th percentile (*extreme frequency*).
- Average intensity of events greater than or equal to the 99th percentile each year, i.e. in the four wettest events (*extreme intensity*).
- Percentage of annual total rainfall from events greater than or equal to the 99th percentile, i.e. received in the four wettest events (*extreme proportion*).
- Frequency of days with at least 2 mm of rain (*rain days*).
- Frequency of days with maximum temperature above the 1961–1990 mean 99th percentile (*hot days*).
- Frequency of days with minimum temperature above the 1961–1990 mean 99th percentile (*warm nights*).
- Frequency of days with maximum temperature below the 1961–1990 mean 1st percentile (*cool days*).
- Frequency of days with minimum temperature below the 1961–1990 mean 1st percentile (*cold nights*).

Other indices, e.g. total rainfall, the 5th and the 95th percentile, were also calculated. Where appropriate, the results from these other indices are discussed.

The threshold of 2 mm rainfall in the definition of 'rain days' was used to avoid artificial trends. Such trends can arise from a tendency of some observers to fail to report small rainfall amounts (Lavery *et al.*, 1992). Also, the threshold for reporting rainfall can alter with changes in observing equipment or observer instructions (Nicholls and Kariko, 1993). Groisman *et al.* (1999) also used a threshold to select 'rain days' to avoid such problems.

An annual time-series of each index was computed for each station, without removing the seasonal cycle of temperature or rainfall. This means that changes in the hot day index will tend to be representative of changes in the hottest season, so changes in hot days during other seasons are effectively excluded. Hence, the indices convey information about events with the most extreme magnitude each year. From a practical viewpoint, the indices target events that, presumably, would have the greatest impact. If we had removed the seasonal cycle before computing indices, our time-series would have shown trends in extremes from seasons that are not the hottest, coldest or wettest for the year. These would be difficult to interpret in terms of practical impacts, although such an approach would have the advantage of increasing the sample size.

3. EXTREME RAINFALL AND TEMPERATURE TRENDS

3.1. Regional patterns of trends

Before describing the direction and magnitude of trends at each station in each country, we present an overview of the geographical pattern of trends in each index. This provides a clear picture of the spatial variation in the direction of trends and their statistical significance. The Kendall-tau test was used to test significance of the trends. All trends noted as significant were significant at the 95% level.

3.1.1. Rainfall. Annual total rainfall in the region has generally decreased between 1961 and 1998 (not shown). This decrease is associated with the predominance of El Niño events since the mid-1970s (Trenberth and Hoar, 1997). Total rainfall only increased significantly in southern New Zealand and some stations in French Polynesia. The number of rain days (with at least 2 mm of rain) has decreased significantly throughout most of Southeast Asia, and the western South Pacific (Figure 2).

Trends in the extreme rainfall indices were less spatially coherent than were those for rain days and (as is shown later) extreme temperature. The frequency of extreme rainfall events has declined at the majority of stations, although significant increases in this index were detected in French Polynesia (Figure 3). There

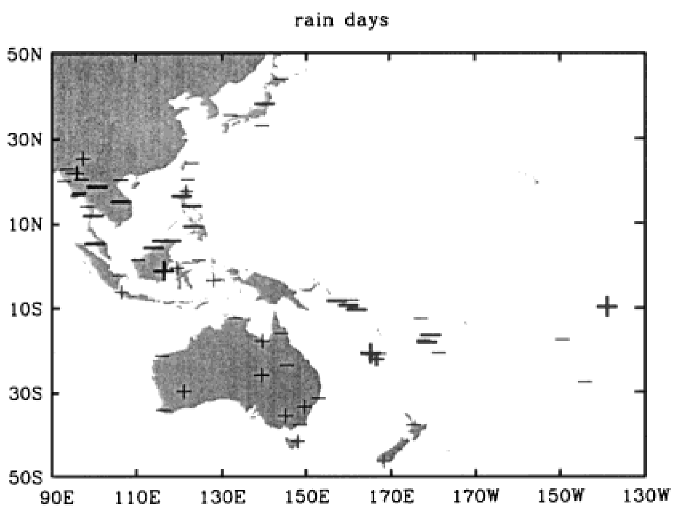

Figure 2. Trend in the frequency of days with at least 2 mm of rain (*rain days*). The sign of the linear trend is indicated by +/− symbols at each site; bold indicates significant trends (95%). Data from 1961–1998

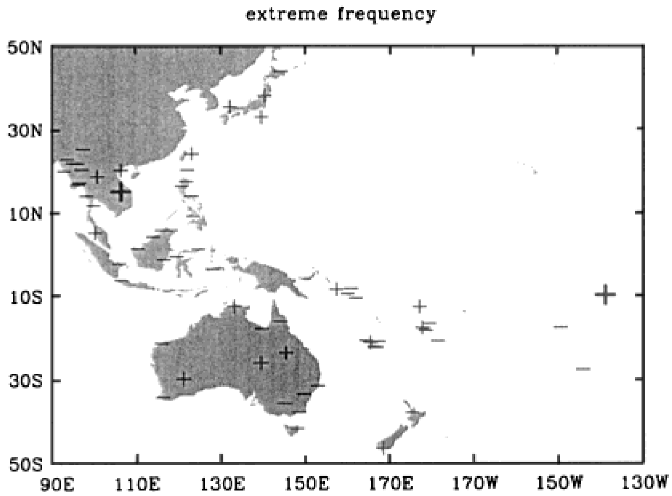

Figure 3. Trend in the frequency of daily rainfall exceeding the 1961–1990 mean 99th percentile (*extreme frequency*). The sign of the linear trend is indicated by +/− symbols at each site; bold indicates significant trends (95%). Data from 1961–1998

has been a weak decline (i.e. not statistically significant) in the average intensity of the highest four events each year over much of Southeast Asia (Figure 4). Weak increases in extreme intensity were found at some stations in Australia, Fiji, New Zealand and New Caledonia. Significant increases in extreme intensity were found at a couple of stations in French Polynesia and Japan. The proportion of annual rainfall from extreme events has generally increased, with a few stations exhibiting a significant increase (Figure 5).

3.1.2. Temperature. The number of hot days has increased at most stations (significantly at several stations), but there were significant decreases in northern Australia (Figure 6). Warm nights increased in frequency almost everywhere, and generally these increases were significant (Figure 7). Weak (not statistically significant) declines were found in southern Australia and New Zealand. Cool days (Figure 8) and cold nights (Figure 9) declined in frequency, with a few exceptions (almost entirely in Australia and New Zealand).

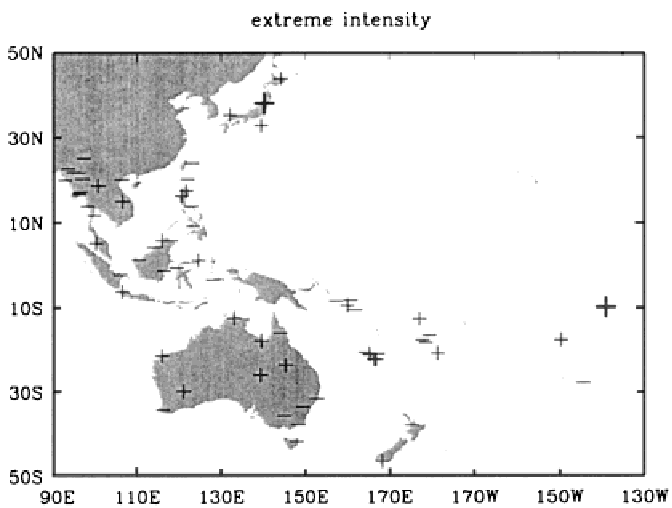

Figure 4. Trend in the average intensity of the events greater than or equal to the 99th percentile (*extreme intensity*). The sign of the linear trend is indicated by +/− symbols at each site; bold indicates significant trends (95%). Data from 1961–1998

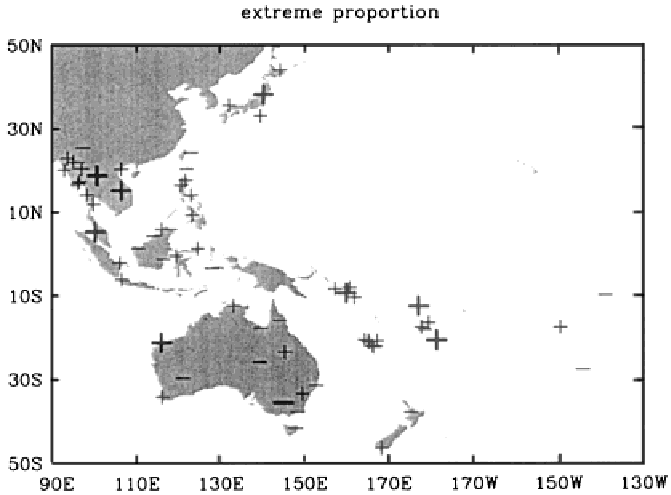

Figure 5. Trend in the percentage of annual total rainfall from the events greater than or equal to the 99th percentile (*extreme proportion*). The sign of the linear trend is indicated by +/− symbols at each site; bold indicates significant trends (95%). Data from 1961–1998

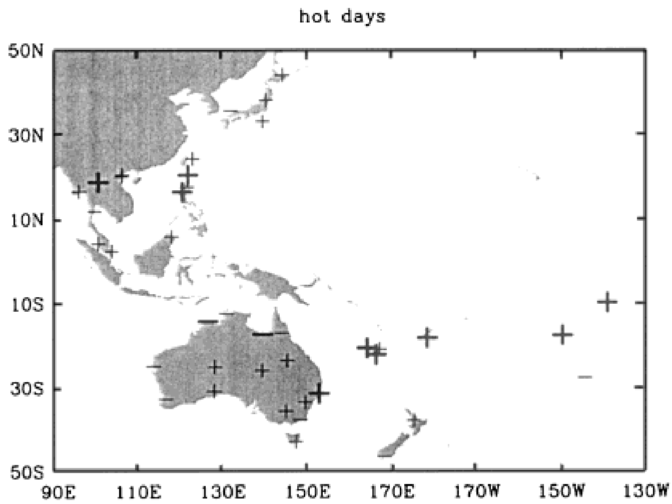

Figure 6. Trend in the frequency of days with maximum temperature above the 1961–1990 mean 99th percentile (*hot days*). The sign of the linear trend is indicated by +/− symbols at each site; bold indicates significant trends (95%). Data from 1961–1998

As there is considerable spatial coherence in the sign of the temperature trends (with the notable exceptions being Australia and New Zealand), country-average trends were calculated, to allow comparison of the magnitudes of the trends. Figure 10 shows a larger decrease in the number of cold nights than cool days, except in the Philippines. Fiji is the only country with an increase in the number of either cool days or cold nights. Figure 11 shows that there has been a stronger increase in the number of warm nights than hot days except in the Philippines, Fiji, New Zealand and French Polynesia. Neighbouring countries exhibit considerable consistency in the magnitude, as well as the sign, of the trends.

The spatial consistency of the trends exhibited in Figures 6–11 encouraged us to calculate simple regional averages of the trends in the numbers of hot/warm and cool/cold days and nights, by calculating arithmetic averages, for each year, of all stations. Area-weighting was considered inappropriate because much of the area is ocean and may not be well-represented by land-based stations. The time-series of these

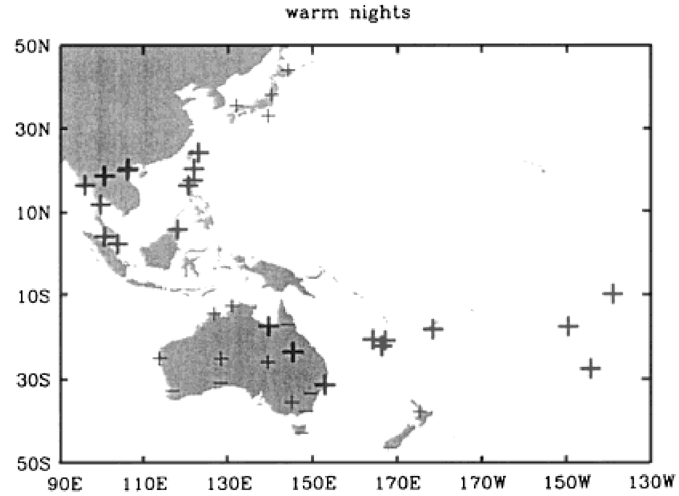

Figure 7. Trend in the frequency of days with minimum temperature above the 1961–1990 mean 99th percentile (*warm nights*). The sign of the linear trend is indicated by +/− symbols at each site; bold indicates significant trends (95%). Data from 1961–1998

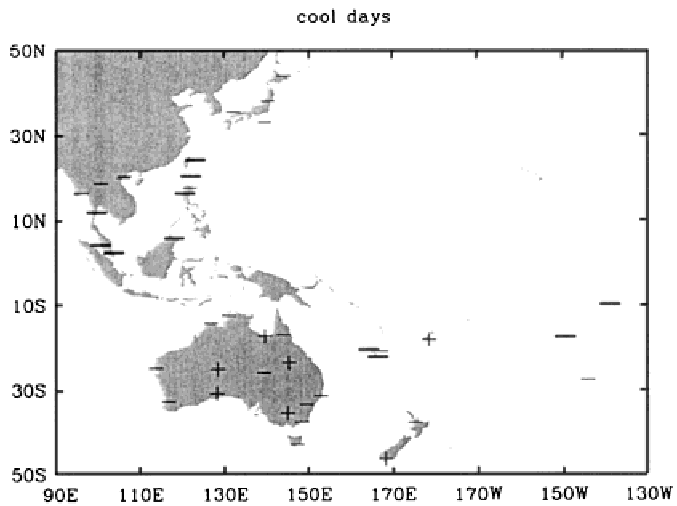

Figure 8. Trend in the frequency of days with maximum temperature below the 1961–1990 mean 1st percentile (*cool days*). The sign of the linear trend is indicated by +/− symbols at each site; bold indicates significant trends (95%). Data from 1961–1998

regional average indices are shown in Figure 12. This figure indicates that the decline in the numbers of cold days and cool nights, and the increase in the number of hot days and warm nights, has been reasonably linear (although with considerable year-to-year variability) through the 1961–1998 period. There was a dramatic increase in hot days and warm nights across the region in the last year examined (1998), coinciding with the globe's warmest year in the period of instrumental records. The linear trends in all four time-series are statistically significant. The number of cold nights and cool days have been reduced by about half, while the numbers of hot days and warm nights have increased by a factor of about 2–3.

3.2. Trends for each country

The maps and charts presented above summarize some interesting trends across the region. In this section, we briefly discuss the changes that have occurred in each country.

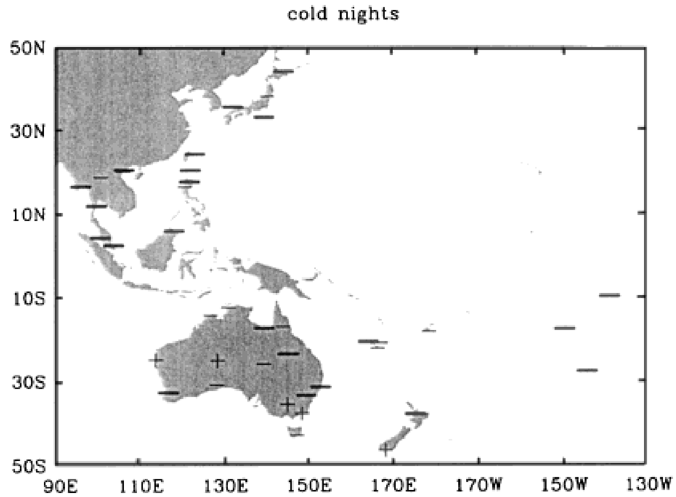

Figure 9. Trend in the frequency of days with minimum temperature below the 1961–1990 mean 1st percentile (*cold nights*). The sign of the linear trend is indicated by +/− symbols at each site; bold indicates significant trends (95%). Data from 1961–1998

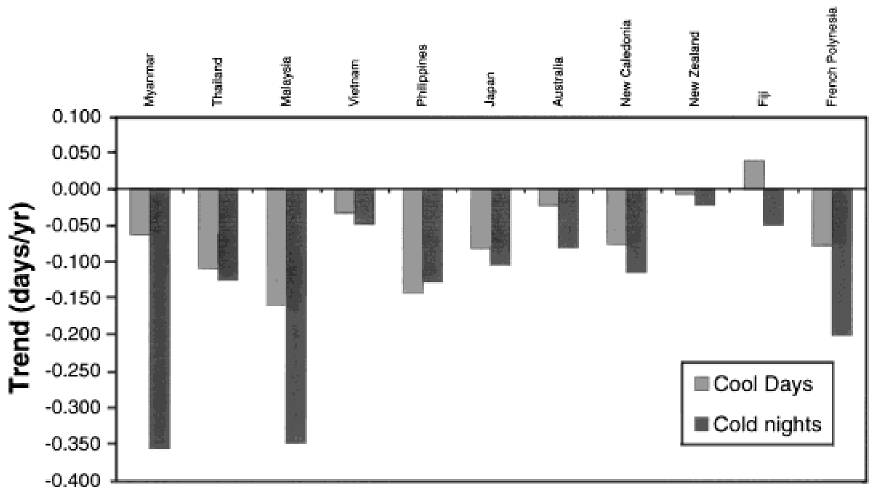

Figure 10. Bar chart showing the trends in the number of cool days and cold nights, for each country. The countries are exhibited in a general west–east orientation, so the results can be compared with neighbouring countries

3.2.1. Australia. No spatially-consistent pattern of trends in the rainfall extremes indices emerged from the Australian stations. The only statistically-significant trends were a decrease in the proportion of rainfall from the wettest four events (extreme proportion) at Deniliquin in the southeast, and an increase at Mardie in the northwest. These results contrast somewhat with those reported by Hennessy *et al.* (1999) for a longer period starting in 1910. They found significant increases in the 99th percentile daily rainfall in parts of southeast Australia. This emphasizes that the trend results are influenced by the sampling period.

The all-Australian average of trends in hot days was close to zero, owing to a mixture of positive and negative trends throughout the country. The largest positive trends for this index were at Bathurst and Port Macquarie in the southeast, with the trend at Port Macquarie significant at the 5% level. Significant negative trends were found at Kalumburu and Burketown, both in northern Australia.

Trends in warm nights were generally positive throughout Australia and, consequently, the average for the whole country showed an increasing trend. Burketown, Barcaldine and Port Macquarie showed significant positive trends for this index.

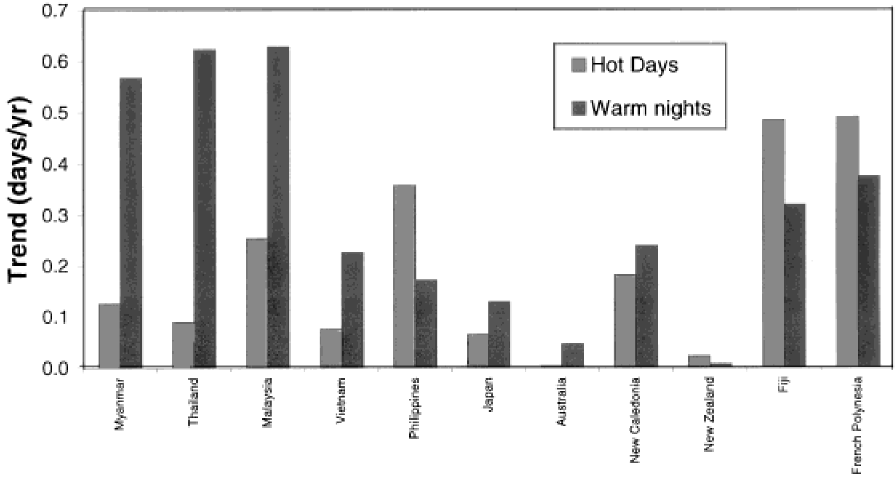

Figure 11. As in Figure 9, but for hot days and warm nights

The frequency of cool days showed predominantly decreasing trends, but all trends were non-significant. Consequently the all-Australian average showed a decreasing trend for this index.

The strongest and most consistent trends were in the frequency of cold nights with a decrease in the overall Australian average. Five stations (Wandering, Burketown, Barcaldine, Port Macquarie and Bathurst) recorded significant negative trends.

3.2.2. Fiji. Rotuma and Ono-I-Lau exhibited significant increases in the proportion of annual rainfall falling in the extreme events ('extreme proportion'). Labasa Mill had a significant decrease in the number of rain days. There was a significant upward trend in warm nights and hot days for Laucala Bay, with a distinct rise in the trend from 1971. The frequency of hot days and warm nights rose sharply from the late 1980s.

3.2.3. French Polynesia. In Atuona, in the Marquesas Islands, there has been a significant increase in total rainfall, in the frequency of extreme rainfall, and in the number of rain days. Annual total rainfall increased by more than 50% after 1976. This climate shift, which at first sight appears to reflect an inhomogeneity, is confirmed at neighbouring stations. Elsewhere in French Polynesia, no extreme rainfall trends were significant.

Significant increase in warm nights and decreases in cold nights were found at all stations. Significant increases in the number of hot days and decreases in the number of cool days were also detected at all stations except Rapa, where the trends were not significant.

3.2.4. Indonesia. There were no significant trends in any of the extreme rainfall indices in Indonesia, and homogenous temperature data were not available.

3.2.5. Japan. In general, rain days have decreased and the extreme rainfall indices have increased. Positive trends in the 'extreme intensity' and 'extreme proportion' indices were significant at one station in northern Japan.

The frequency of cool days and cold nights has decreased. Negative trends in the frequency of cold nights were significant at most stations. The frequency of hot days and warm nights has increased. Significant positive trends have occurred in the frequency of warm nights at stations in southern Japan.

3.2.6. Malaysia. There has been a significant decrease in rain days at all stations, except Kuching. There were no other significant trends in extreme rainfall indices.

There was a significant positive trend in the number of warm nights, with a large peak in 1998. Likewise, there exists a significant decrease in the frequency of cool days and cold nights.

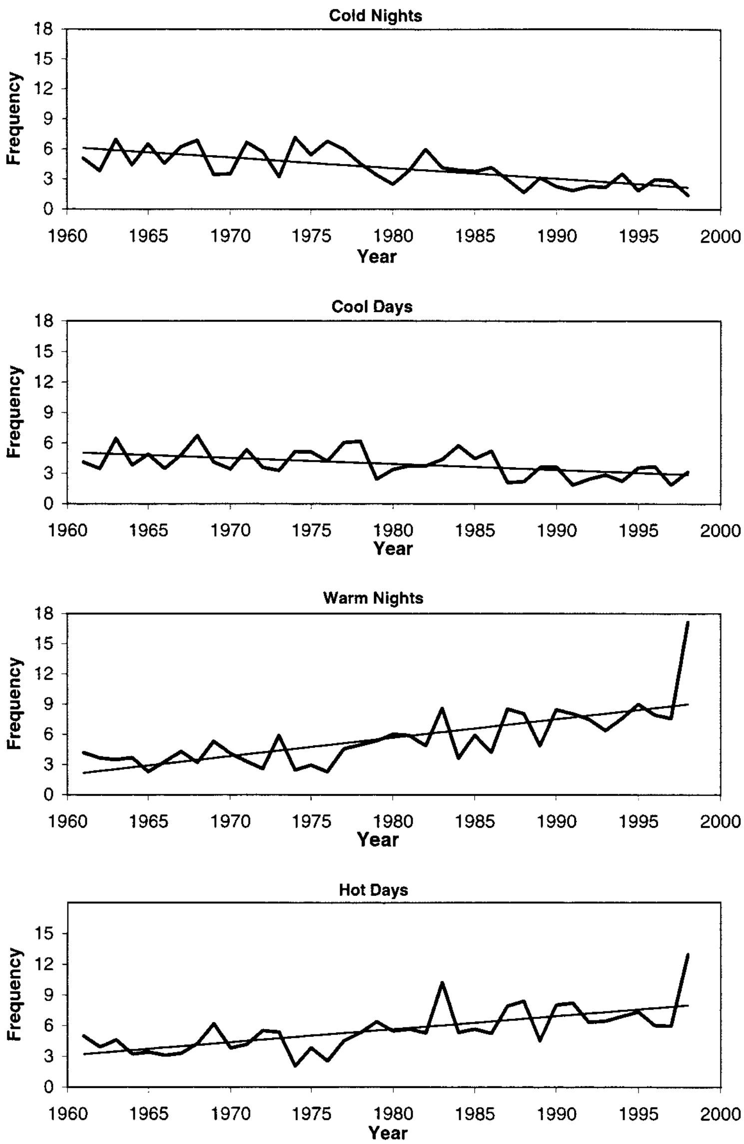

Figure 12. Time-series of the regional averages of the frequency of hot and cold days and nights. The thin line is a trend-line computed by linear regression

3.2.7. Myanmar. There were no significant trends in extreme rainfall indices. At the single temperature station, warm nights have significantly increased in frequency. Cold nights have decreased in frequency. There are no significant trends in maximum temperature (hot days or cool days).

3.2.8. New Caledonia. For the eight stations analysed, there were no significant trends in extreme rainfall indices. Of the eight stations, seven exhibited (non-significant) increases in the 'extreme proportion' index and a (non-significant) decrease in the 'extreme frequency' index. There has been a (non-significant) decrease in the number of rain days on the west coast, and a (non-significant) increase on the east coast.

Significant changes in the extreme temperature indices were found at all three stations. The clearest trend is for the number of warm nights with significant increases at all stations. Two stations had significant increases in the number of hot days, and significant decreases in the number of cool days. Only

Koumac, in the north of the country, had a significant decrease in the number of cold nights, although the other stations also exhibited decreases (but not significant).

3.2.9. New Zealand. Annual rainfall has decreased (non-significantly) in the two North Island stations (Ruakura and Gisborne), and increased in Invercargill (significantly) and Hokitika (non-significantly). A significant increase in the extreme frequency has occurred at Holitika in the west of the South Island. This rainfall pattern for the period 1961–1998 is consistent with an observed circulation change over New Zealand since 1976, to more westerly winds over southern New Zealand, and higher pressures over the North Island (Salinger and Mullan, 1999).

Somewhat consistent with these circulation changes has been an increase in the North Island hot days at Gisborne, a location sheltered from the west. The frequency of hot days has significantly increased, and there has been a significant decrease in the frequency of cool days there. In contrast, there has been a significant decrease in hot days at Hokitika in the west. No significant signal is observed for cold nights there, however. Invercargill in the south shows no trends in extreme temperatures at all. However, Ruakura in the north shows a significant decrease in the frequency of cold nights.

3.2.10. Philippines. There has been a significant decrease in the number of rain days at three of the five stations: Baguio, in the north of the archipelago, Daet, which is situated along the east coast, and Dumaguete, in the middle islands.

At Basco, there were significant increases in the frequency of warm nights and hot days (particularly high in 1998) and a decrease in the number of cool days and cold nights. At Baguio, the frequency of warm nights and hot days also exhibited significant increases (with large values in 1983 and 1998), but a significant decrease in the number of cool days. At Tuguegarao (located in a valley), the frequency of cold nights has shown a significant decrease.

3.2.11. Solomon Islands. The number of rain days has decreased at all stations, with Honiara, Kira Kira and Munda having significant decreases. At Honiara, the proportion of annual rainfall from extreme rainfall has increased significantly.

3.2.12. Thailand. At Nan, the number of rain days has decreased significantly, and the proportion of total rainfall from extreme rainfall has increased significantly. Prachuap Khiri Khan shows a significant decrease in rain days.

There was a significant increase in extreme minimum temperature at both stations, partly owing to a peak in 1998. The number of warm nights increased, and the number of cold nights and cool days decreased. Maximum temperature increased significantly at Nan, while the increases at Prachuap Khiri Khan were not significant.

3.2.13. Vietnam. Phulien showed no significant trends in any of the rainfall indices, although there were decreases in all indices except the percent of total rainfall from extreme events (which showed no trend).

4. DISCUSSION

The patterns of trends presented in the previous section show, for some of the indices, considerable spatial consistency within countries and across regions. For instance, almost all stations exhibit increases in the frequency of hot extremes, and decreases in cold extremes, with many of these trends being statistically significant. The country-by-country analyses show considerable consistency, even in the magnitude of the extreme temperature trends (as well as the sign), with their neighbours. This consistency extended to the relative magnitudes between, for instance, the trends in the frequency of hot days and warm nights: in the west of the region, the frequency of warm nights was increasing faster, whereas the frequency of hot days was increasing faster in the east. Even the dramatic peak in the frequency of hot days and warm nights in 1998 was reported at many stations, in various countries. The extreme rainfall indices showed less spatial consistency, except for the tropics-wide decrease in the number of rain days. Few of the rainfall indices, apart from the number of rain days, showed statistically significant trends. The general consistency, and the similarity of trends in neighbouring countries, lends credibility to the overall trends. This, in turn, suggests that the homogeneity testing and other approaches used in selecting and testing of station data prior to analysis has resulted in a data set useful for analysing trends and variations in extremes across the region.

Further improvements of the homogeneity testing would, nevertheless, be worthwhile. For instance, a concerted effort to adjust the daily data for inhomogeneities, similar to the approach used by Trewin (2000) for Australia, would lead to an improved data set for analysis. However, such an approach demands considerable resources (computing and human). In the short term, the necessary resources seem unlikely to become available for such an analysis to be applied to all countries in the region.

However, it would be feasible to apply our techniques of homogeneity testing and extremes analysis to larger numbers of stations, in each country. This would provide a more detailed analysis for each country, and allow increased confidence in the reality of the trends reported here. It is anticipated that individual countries, as the necessary resources become available, will undertake this task.

The relatively short time frame of 38 years used in this study is likely to produce trends that are sensitive to the sampling period. For example, trends in total rainfall, dry days and extreme events in Australia from 1910–1995 tend to be in the opposite direction to those for 1961–1998. For some countries in the region, appropriate data do not exist from before the late 1950s. So extending the analysis (across the entire region) backwards is not possible. Nevertheless, it would be worthwhile, in the countries for which this is possible, to extend the analysis backwards, to provide a better understanding of the decadal fluctuations in extremes prior to the period considered here.

This study has demonstrated that a concerted, regional, cooperative effort can produce a regional data-base of high quality that is useful for estimating recent trends in extremes. Extension of this approach to other parts of the world, where little is currently known regarding trends in extremes, would be worthwhile. A limitation, however, of such studies is the low spatial density of stations with homogenous data. This limitation is largely a consequence of departures from standards in instrumentation and/or observational practice that, while often unavoidable, significantly reduce the number of stations with homogeneous data. Even if an inhomogeneity in a station's data series, the collection (and proper management) of associated metadata can provide sufficient information to obtain the real climatic signal. The United Nations Framework Convention on Climate Change urges countries to address the deficiencies in climate observing networks and, as Karl *et al.* (1995) stress, adhere to the requirements for long-term climate monitoring.

No attempt has been made here to consider possible causes of the observed trends in extremes. We do note, however, that the observed increase in hot days and warm nights, and the decrease in cool days and cold nights is consistent with a number of simulations with global climate models, driven by increasing greenhouse gas levels (e.g. Hennessy *et al.*, 1998).

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APPENDIX A

List of high-quality stations, their location and period of record. Absence of a period of record for a specific variable indicates that the station was not used to analyse that variable.

Country	Station	Latitude	Longitude	Rainfall	Temperature
Australia	Birdsville	25.90°S	139.33°E	1910–1998	1957–1998
	Palmerville	16.98°S	144.07°E	1910–1998	1957–1998
	Burketown	17.73°S	139.53°E	1910–1998	1957–1998
	Barcaldine	23.55°S	145.28°E	1910–1998	1957–1998
	Port Macquarie	31.43°S	152.92°E	1910–1998	1921–1998
	Bathurst	33.43°S	149.57°E	1910–1998	1921–1998
	Deniliquin	35.55°S	144.93°E	1910–1998	1957–1998
	Orbost	37.68°S	148.45°E	1910–1998	1957–1998
	Mardie	21.19°S	115.98°E	1910–1998	
	Gunbalunya	12.33°S	133.06°E	1910–1998	
	Menzies	29.69°S	121.03°E	1910–1998	
	Fingal Forestry	41.64°S	147.97°E	1910–1998	
	Boyup Brook	34.15°S	116.20°E	1910–1998	
	Hobart	42.88°S	147.32°E		1944–1998
	Carnarvon	24.88°S	113.67°E		1945–1998
	Wandering	32.67°S	116.67°E		1957–1998
	Forrest	30.83°S	128.12°E		1947–1998
	Giles	25.03°S	128.28°E		1957–1998
	Darwin	12.42°S	130.88°E		1941–1998
	Kalumburu	14.28°S	126.63°E		1957–1998
Fiji	Rotuma	12.50°S	177.05°E	1961–1998	
	Suva	18.15°S	178.45°E	1942–1998	1942–1998
	Rarawai Mill	17.55°S	177.73°E	1925–1998	
	Ono-I-Lau	20.67°S	178.72°E	1961–1998	
	Labasa Mill	16.45°S	179.35°E	1931–1998	
French Polynesia	Rapa	27.62°S	144.33cW	1953–1998	1953–1998
	Faaa	17.55°S	149.60°W	1957–1998	1957–1998
	Atuona	9.80°S	139.03°W	1960–1998	1961–1998
Indonesia	Pangkal Pinang	2.17°S	106.13°E	1961–1998	
	Jakarta	6.17°S	106.82°E	1961–1998	
	Balikpapan	1.28°S	116.83°E	1960–1998	
	Menado	1.53°S	124.92°E	1961–1998	
	Ambon	3.70°S	128.08°E	1961–1998	
	Palu	0.70°S	119.73°E	1961–1998	
Japan	Hamada	34.90°N	132.07°E	1961–1998	1961–1998
	Kushiro	43.33°N	145.58°E	1961–1998	1961–1998
	Hachijo Island	33.10°N	139.78°E	1961–1998	1961–1998
	Yamagata	38.03°N	140.04°E	1961–1998	1961–1998
	Yonaguni Island	24.47°N	123.02°E	1961–1998	1961–1998
Malaysia	Bayan Lepas	5.30°N	100.27°E	1951–1998	
	Kuching	1.48°N	110.33°E	1953–1998	
	Sitiawan	4.22°N	100.70°E		1968–1998
	Miri	4.33°N	113.98°E	1953–1998	
	Kota Kinabalu	5.93°N	116.05°E	1953–1998	
	Sandakan	5.90°N	118.08°E	1954–1998	1954–1998
	Mersing	2.45°N	103.83°E		1968–1998

Myanmar	Dawei	14.07°N	98.18°E	1960–1990	
	Taunggyi	20.78°N	97.05°E	1967–1990	
	Sittwe	20.15°N	92.90°E	1961–1990	
	Myitkina	25.36°N	97.35°E	1960–1990	
	Kaba Aye	16.87°N	96.18°E	1961–1990	1961–1990
	Mandalay	21.98°N	96.10°E	1960–1990	
New Caledonia	Koumac	20.56°S	164.29°E	1951–1998	1954–1998
	Nouméa	22.24°S	166.45°E	1951–1998	1951–1998
	Ouanaham	20.78°S	167.26°E	1961–1998	1960–1998
	Touho	20.78°S	165.23°E	1952–1998	
	Ponérihouen	21.08°S	165.40°E	1952–1998	
	Yaté	22.15°S	166.91°E	1951–1998	
	Toutouta	22.01°S	166.22°E	1951–1998	
	Païta	22.14°S	166.37°E	1951–1998	
New Zealand	Ruakura	37.78°S	175.31°E	1907–1996	1940–1998
	Gisborne	38.68°S	178.01°E	1938–1998	1940–1998
	Lincoln	43.63°S	172.47°E	1900–1998	1900–1998
	Hokitika	42.72°S	170.99°E	1900–1998	1900–1998
	Invercargill	46.42°S	168.33°E	1939–1998	1938–1998
Philippines	Basco	20.45°N	121.97°E	1961–1998	1961–1998
	Tuguegarao	17.62°N	121.73°E	1961–1998	1961–1998
	Baguio	16.42°N	120.60°E	1961–1998	1961–1998
	Daet	14.12°N	120.98°E	1961–1998	1961–1998
	Dumaguete	9.37°N	123.28°E	1961–1998	1961–1998
Solomon Islands	Taro Island	6.70°S	156.40°E	1975–1998	1975–1998
	Munda	8.33°S	157.26°E	1962–1998	1962–1998
	Honiara	9.41°S	159.97°E	1951–1998	1951–1998
	Henderson	9.42°S	160.05°E	1974–1998	1974–1998
	Auki	8.14°S	160.73°E	1962–1998	1962–1998
	Kira Kira	10.42°S	161.92°E	1965–1998	1965–1998
	Lata	10.70°S	165.80°E	1970–1998	1970–1998
Thailand	Nan	18.77°N	100.77°E	1951–1998	1951–1998
	Udon Thani	17.38°N	102.80°E	1951–1998	1951–1998
	Suphan Buri	14.47°N	100.13°E	1951–1998	1951–1998
	Chanthaburi	12.60°N	102.12°E	1951–1998	1951–1998
	Prachuap Khiri Khan	11.83°N	99.83°E	1951–1998	1951–1998
Vietnam	Phu Lien	20.80°N	106.63°E	1957–1998	1957–1998
	Playcu	15.20°N	106.50°E	1959–1998	
	Van Ly	20.12°N	106.30°E	1957–1998	1959–1998

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