A NEW INDEX FOR MONITORING CHANGES IN HEATWAVES AND EXTENDED COLD SPELLS

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1. INTRODUCTION

As part of the analysis of changes in global temperature generally, changes in temperature extremes have attracted considerable attention in recent years. Much of the work which has been done has been focused on single-day extremes, with the most comprehensive global analysis produced by Alexander et al. (2006).

Extended episodes of heat and cold have their own specific impacts. As a particularly striking example, the 2003 European heatwave, which claimed many thousands of lives, took the form, over many of the most severely affected areas, of temperatures well above the mean annual 99th percentile for between 7 and 10 consecutive days. The specific impact of the prolonged nature of the heatwave is indicated by the fact that the observed mortality rate in Paris did not increase significantly above background levels until the fifth day of extremely high temperatures, peaking from the seventh day onwards (Bessemoulin et al., 2004).

Most studies of extreme temperature events have made use of indices, which may be based either on fixed thresholds (that is, relative to a specific temperature) or relative thresholds (that is, defined with respect to a station's climatology). In general analyses based on relative thresholds have been emphasized in regional or global studies (in local studies fixed thresholds that are of importance to that area often play a greater role), as such indices are relevant over a much broader range of climates than those based on fixed thresholds are. (As an example, the number of days with maximum temperatures above 30°C is a good indicator of extreme high temperatures in many temperature climates, but is not useful in tropical climates where maximum temperatures exceed 30°C on most days through much or all of the year).

Frich et al. (2002) analysed changes in a heat wave duration index over a region encompassing most of Europe, the United States, Canada, China, the former Soviet Union and Australia, finding a general increase in duration over the 1950-1996 period. This study defined a heat wave as a period of five or more consecutive days with maximum temperatures more than 5°C above the 1961-90 daily normal for the date in question. An alternative definition used in other studies (e.g. Alexander et al., 2006), defines heat waves in terms of consecutive days above the 90th percentile for the date.

A limitation of indices of both types is that they are not independent of the local climate, which can pose difficulties for global analyses. The difficulty for fixed-threshold (or fixed-anomaly) indices is similar to that for single-day extremes – in many climates with low temperature variability (especially in the tropics), even one day with an anomaly exceeding 5°C is rare. More subtly, the range of values taken by relative indices also varies from place to place. While the expected value of the percentage of individual days with temperatures above the 90th percentile is, by definition, 10% at all stations, the frequency of occurrences of (for example) five consecutive days above the 90th percentile will vary from station to station, as it depends on the day-to-day autocorrelation of daily temperatures as well as their absolute level.

This paper will propose a range of new indices which can be defined in any climate, and whose statistical properties are generally more amenable to meaningful analyses than previously-used indices have been.

2. WHAT ARE THE DESIRABLE PROPERTIES OF AN INDEX FOR MULTI-DAY HOT OR COLD PERIODS?

In the context of climate change, the principal purposes of an index for multi-day hot or cold periods is to maximize the ability to detect a secular change in their occurrence, and to identify the extent to which such changes are consistent (or inconsistent) with changes in other variables (such as mean temperature), or changes predicted by climate models.

A major motivation for this analysis is to develop an index which is applicable globally. As such, desirable properties of an index include:

- Can be validly defined in any climate.
- Produces time series with a high signal-to-noise ratio.
- Produces time series which are amenable to statistical analysis (preferably with few or no zero or undefined values, and a frequency distribution which is reasonably close to normal).
- Has units such that geographical comparisons can reasonably be made, which can be achieved either by using units which vary in a consistent manner (e.g. changes of temperature in degrees C) or units which have consistent climatological values (e.g. the use of the 90th percentile for single-day extremes, which should include 10% of days in any climate).
- Is intuitive and has a meaning which can be easily communicated.
- Is capable of effectively identifying the most extreme events.

The ability to define an index seasonally (as opposed to annually) is desirable in some applications, but not necessary in others.

3. EXISTING AND NEW INDICES

Four indices based on existing analyses are assessed in this study, along with a family of new indices. For simplicity, the description in this section is with respect to extreme high temperatures, where 'temperatures' in this context could refer to any one of daily maximum, minimum or mean temperatures (although only maxima and minima are considered in this study). All indices may be defined equivalently for extreme low temperatures, with the 10th percentile replacing the 90th percentile and negative anomalies (where applicable) substituted for positive.

The 'old' indices are as follows:

Index name	Definition and comments
$I90_{seas}$	The largest number of consecutive days (with a minimum of 6 – otherwise the value is 0) in a year on which the temperature exceeds the 90th percentile, where this percentile is calculated for each day from 1961-90 data for a 5-day window centred on that date. This index is currently used in the RClimdex software distributed by the CCI/CLIVAR /JComm Expert Team on Climate Change Detection and Indices (ETCCDI)
$I5_{seas}$	As for $I90_{seas}$, except that instead of the 90th percentile, the bound used is an anomaly of 5°C from the daily mean temperature (also calculated from a 5-day window centred on the date). This index is similar to that used by Frich et al (2001) *(add ref to Klein Tank)*
$I90_{ann}$	As for $I90_{seas}$, except that the 90th percentile used is the annual 90th percentile, calculated using all days of the year for the 1961-90 period
$I5_{ann}$	As for $I5_{seas}$, except that the bound is a value 5°C above the 1961-90 mean temperature of the hottest month.

Table 1. 'Old' indices chosen for use in this study

$I90_{seas}$ and $I5_{seas}$ are chosen because of their use in previous analyses. As both indices are based on data from which the annual cycle of mean temperature has been removed, two additional indices $I90_{ann}$ and $I5_{ann}$ have been defined which are similar in nature, but are defined based on data which includes the annual cycle, to allow comparison with the new indices which are based on annual data.

The 'new' indices are defined as follows:

Index name	Definition and comments
Ilim(N)	The highest temperature T in a year such that there are at least N consecutive days in that year with a temperature equal to or greater than T. (For example, for N=5, if there is a sequence of 5 or more consecutive days in that year with temperatures of 32.1°C or above, but no sequence of 5 consecutive days of 32.2°C or above, the index value for that year will be 32.1°C).
Imean(N)	The mean temperature of the N-day period defined by the index value Ilim(N) above.
Irun(N)	The highest value of the N-day running mean of temperature in the year, whether or not all days in the period have temperatures at or above Ilim(N)

Table 2. 'New' indices chosen for use in this study

For all indices, a value is only defined in a year if there are no more than 20 days in that year with missing data. (This equates to a minimum probability of approximately 75% that the available data captures the hottest 5-day period of the year, assuming any missing data are randomly distributed through the year).

A 'year' is defined as running from 1 January to 31 December for warm indices at Northern Hemisphere stations and cold indices at Southern Hemisphere stations, and from 1 July to 30 June for warm indices at Southern Hemisphere stations and cold indices at Northern Hemisphere stations (such years are referred to using the year in which 1 July falls). Runs of consecutive days which extend through two or more years are not considered, although these would be expected to be virtually unknown except possibly at some equatorial stations.

In this study, for the 'new' indices, analyses were carried out for N = 5 days and N = 10 days. There is no specific reason for the choice of these values and any value of N could be chosen.

4. DATA SOURCES

A major objective of this study was to assess the performance of indices in a range of climates. Daily maximum and minimum temperature data of varying levels of quality are available from a range of sources. The data sources used in this study were as follows:

1. Data from the homogenized Australian long-term temperature data set (Trewin, 2001a). (103 stations)
2. Data from the European Climate Assessment and Dataset(ECA&D) data set (Klein Tank et al., 2002) which were available through the ECA website and were classified as 'homogeneous' for at least the period 1961-2004 (72 stations).

3. 10 stations from the homogenized Canadian temperature data set (Vincent et al., 2002). Only maximum temperatures were available in this data set.
4. GCOS Surface Network (GSN) stations which were available as part of the National Climatic Data Center (NCDC)'s daily Global Historical Climatology Network (GHCN-Daily) data set (http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/). A total of 144 stations were selected for initial analysis, chosen to cover a representative range of all continents (except Europe and Australia which are covered by the above-listed data sets).
5. Six stations from Australian-administered offshore island and Antarctic stations, obtained from the Australian Bureau of Meteorology database.

Data from the first three sources listed have either been found to be homogeneous, or have been adjusted to make them homogeneous. The GSN and Australian island/Antarctic data are not homogenized and have been excluded from those parts of this study dealing with analysis of trends. In some cases GSN stations which were known to be inhomogeneous – e.g. Phoenix (United States), which has a well-documented urban heat island (e.g. Hawkins et al., 2004) – were selected in order to obtain an indication of what impact an inhomogeneity would have on various indices of extended hot and cold spells.

To be considered for further analysis, stations were required to have sufficient data for index calculation (see section 3) in at least 25 of the 30 years of the standard normal period 1961-90. For the calculation of trends stations were further required to have sufficient data for index calculation in at least 40 of the 47 years 1961-2007. The extent to which GSN stations, in particular, met these requirements was very geographically uneven. Only one of the 20 candidate stations from South America, and only three of the 20 from Africa (two of them on offshore islands), met the basic requirement for inclusion. Depending on which type of extreme was being considered (hot and cold extremes, and maxima and minima, were assessed separately), 49-55 Australian stations and 52-64 ECA and Canadian stations were available for trend analysis, while 59-63 Australian stations and 154-163 international stations were available for other parts of the analysis.

6. EVALUATION OF STATISTICAL PROPERTIES OF INDICES

The following indicators were used to assess the performance of indices against the desirable properties outlined in section 2:

- The range between stations of mean annual value of the index, for those indices defined in terms of a number of days per year.
- The percentage of stations at which the indices have zero values in 20% or more of years, and in 50% or more of years, , for those indices defined in terms of a number of days per year.
- The percentage of stations at which the frequency distribution of index values in the 1961-90 period is positively skewed.
- The percentage of stations at which the skewness of the 1961-90 frequency distribution indicates a departure from the normal distribution significant at the 95% and 99% levels.

Indicators based on skewness were not calculated at stations with a mean index value of 0 (that is, stations at which the event defined by the index did not occur once in the 1961-90 period).

Index	Low max	Low min	High max	High min
$I90_{seas}$	0 (3%) – 5.45	0 (5%) – 4.83	0 (1%) – 5.93	0 (1%) – 5.33
$I5_{seas}$	0 (18%) -14.6	0 (20%) – 14.6	0 (18%) – 14.37	0 (19%) – 14.27
$I90_{ann}$	0.73 – 20.66	0.6 – 16.5	0.2 – 14.63	0.6 – 19.87
$I5_{ann}$	0 (37%) – 11.33	0 (30%) – 12.27	0 (39%) – 4.23	0 (78%) – 1.83

Table 3. Range of mean annual values of indices. (Where a percentage is shown it indicates the percentage of all stations considered with a zero mean value)

Index	Low max	Low min	High max	High min
$I90_{seas}$	100.0 92.0	100.0 97.7	100.0 87.6	100.0 96.2
$I5_{seas}$	79.6 53.3	80.8 58.7	81.9 52.7	79.7 66.0
$I90_{ann}$	51.1 11.6	56.3 14.6	70.4 22.6	71.2 17.0
$I5_{ann}$	96.9 82.7	96.7 80.3	100.0 99.6	100.0 100.0

Table 4. Percentage of stations at which the index has a zero value in at least 20% of years (upper value) and 50% of years (lower value)

Index	Low max	Low min	High max	High min
$I90_{seas}$	71.1 57.3	86.2 65.5	58.9 45.1	80.4 67.5
$I5_{seas}$	48.1 38.9	54.7 40.0	41.9 30.1	61.0 48.3
$I90_{ann}$	33.3 19.6	30.5 14.6	36.3 20.4	25.0 12.7
$I5_{ann}$	69.2 51.0	66.7 52.0	98.6 94.9	100.0 100.0
Ilim(5)	13.8 2.7	12.2 3.8	12.4 5.8	9.4 4.2
Imean(5)	11.1 3.6	9.9 3.3	8.0 3.5	9.4 1.9
Irun(5)	10.7 3.1	10.8 4.2	10.2 4.0	11.3 3.8
Ilim(10)	15.1 3.6	13.6 4.2	15.5 6.6	8.5 2.4
Imean(10)	10.7 1.3	11.3 1.9	8.4 2.2	7.5 2.4
Irun(10)	14.7 2.2	11.3 2.3	12.4 3.1	11.3 2.8

Table 5. Percentage of stations at which the skewness of the frequency distribution of index values indicates a departure from normality significant at the 95% (upper value) and 99% (lower value) level

Index	Low max	Low min	High max	High min
$I90_{seas}$	98.2	100.0	96.9	99.0
$I5_{seas}$	87.0	87.1	68.8	84.9
$I90_{ann}$	80.9	82.6	74.3	78.3
$I5_{ann}$	96.5	96.0	100.0	100.0
Ilim(5)	34.7	35.7	66.4	66.0
Imean(5)	38.2	37.1	59.7	67.0
Irun(5)	31.1	34.7	64.2	70.8
Ilim(10)	30.2	30.0	69.9	59.9
Imean(10)	37.8	39.4	59.7	58.5
Irun(10)	32.4	33.8	67.7	71.7

Table 6. Percentage of stations at which the frequency distribution of index values is positively skewed

The results in Tables 3 and 4 show that all four ‘old’ indices have a very wide range of climatological mean values, with the events defined by the indices rarely or never occurring in some climates (especially in the tropics), whilst being regular occurrences in other climates (especially cold indices at high latitudes). $I90_{ann}$ is the only one of the four indices for which zero values do not occur in at least 20% of years at 79% or more of stations. Such a wide range of climatological mean values limits the capability of these indices to assess changes in the occurrence of extended hot or cold periods – a change of, for example, 1 day/year in the index over the 1961-2007 period is a very large change at a station where the climatological mean value of that index is 0.5, but a small one at one where the climatological mean value is 10.

The ‘old’ indices also all have a strong tendency to be positively skewed, which limits the ability to use standard statistical tests to assess their properties (for example, the significance of trends in their values). The ‘new’ indices show a weaker tendency to be negatively skewed (for cold extremes) or positively skewed (for warm extremes), but in few cases is the skewness significant. This indicates that, at least to a first level of approximation, these indices can be used in statistical analyses which require variables to be normally distributed.

The ‘new’ indices also have the advantage of being expressed in degrees C, making them directly comparable to observed or predicted changes in mean temperature. Some single-day indices of this type (for example, the highest temperature observed in a given year) have a very high level of interannual variability and hence a low signal-to-noise ratio, but calculating indices over multiple days would be expected to reduce this volatility.

Whilst a comprehensive assessment of the ability of the indices to identify the most extreme events has not been carried out, it is interesting to note the response of the indices to the extremely damaging 2003 European heatwave (Bessemoulin et al., 2004). Figure 1 shows time series of selected indices for extreme high maximum temperatures at Deols-Chateauroux, France (46°52’ N, 1°43’ E). The ‘new’ indices shown clearly identify the 2003 event as the most extreme in the historic record, whereas the ‘old’ indices identify it as being only one of several significant years.

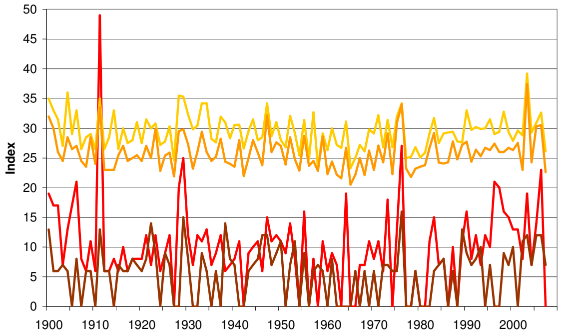

Figure 1. Time series of indices of extreme high maximum temperature at Deols-Chateauroux, France – ‘old’ indices $I90_{seas}$ (brown) and I90ann (red), and ‘new’ indices Ilim(5) (yellow) and Ilim(10) (gold).

A negative of the ‘new’ indices is that their definition is relatively complicated, making them difficult to use in communication with the general public. In their present form they also cannot be defined seasonally, which makes them more limited than $I90_{seas}$ and $I5_{seas}$. Nevertheless, their other desirable properties make them suitable for use in applications such as trend analyses and relationships with other broadscale climate variables, as discussed in sections 6 and 7.

7. TRENDS IN THE OCCURRENCE OF EXTENDED HOT AND COLD SPELLS

Three of the four data sets described in section 4 can be considered as homogeneous: the Australian, Canadian and ECA sets. (The first two have been adjusted to correct for inhomogeneities, whilst the stations chosen from the much larger overall ECA set are those which have been found to be homogeneous over at least the 1961-2004 period).

The index Ilim(N) was chosen for further analysis for values N=5 days and N=10 days. Trends in this index were calculated over the 1961-2007 period at each station which met the minimum data requirements (a valid index value in at least 40 of the 47 years 1961-2007), for each of the four extreme categories (high maxima, high minima, low maxima, low minima). It was also calculated whether this trend differed significantly from zero using a standard t-test.

Index	Region	% of stations with +ve trends		% of stations with –ve trends	
		Total	Sig.	Total	Sig.
Low maxima N=5	Aust	96.3	38.2	3.7	0.0
	ECA/Can	89.7	29.3	10.3	0.0
Low maxima N=10	Aust	90.9	29.1	9.1	0.0
	ECA/Can	94.8	10.3	5.2	0.0
Low minima N=5	Aust	95.9	42.9	4.1	0.0
	ECA/Can	100.0	25.0	0.0	0.0
Low minima N=10	Aust	91.8	24.5	8.2	0.0
	ECA/Can	96.2	26.9	3.8	0.0
High maxima N=5	Aust	56.4	20.0	43.6	7.3
	ECA/Can	92.1	44.4	7.9	0.0
High maxima N=10	Aust	76.4	25.5	23.6	1.8
	ECA/Can	95.3	32.8	4.7	0.0
High minima N=5	Aust	85.7	14.3	14.3	0.0
	ECA/Can	92.9	60.7	7.1	0.0
High minima N=10	Aust	85.7	36.7	14.3	0.0
	ECA/Can	92.9	58.9	7.1	0.0

Table 7. Percentage of stations with positive and negative trends in the value of Ilim(N)

Index	Time period	Australia	ECA/Can
Low maxima	N=5	0.17	0.46
	N=10	0.15	0.40
Low minima	N=5	0.25	0.60
	N=10	0.21	0.62
High maxima	N=5	0.05	0.38
	N=10	0.18	0.39
High minima	N=5	0.12	0.33
	N=10	0.19	0.34

Table 8. Mean trends (°C/decade) in the value of Ilim(N) over the period 1961-2007.

Table 7 shows the percentage of stations with positive trends in the index Ilim(N) (indicating an increased incidence of extended hot spells, and a decreased incidence of extended cold spells), while Table 8 shows the mean trends across the regions considered. These means are calculated for simplicity as an arithmetic mean of the values at all available stations without any area-weighting being applied.

The results show a strong tendency for positive trends in Ilim(N) for most variables and regions, particularly for the two Northern Hemisphere data sets. The main exception is for high maxima in Australia, where the tendency towards positive trends in Ilim(N) is much weaker, especially for 5-day periods. This is also the only region and variable for which any stations show significant negative trends, with four stations (all exposed coastal locations, three of them in the southwest) showing significant negative trends for N=5, and one also showing them for N=10.

The geographic distribution of the trends within Australia for high maxima and low minima are shown in Figure 2. This indicates that negative trends for high maxima are principally found in most of Western Australia, and in the mainland southeast (mostly in Victoria). The Western Australian trends are consistent with a decreasing trend in mean summer maximum temperatures over most of the state (as shown on the maps available at http://www.bom.gov.au/cgi-bin/silo/reg/cli_chg/trendmaps.cgi for the very similar period, 1960-2008), which in turn is associated with a marked increase in summer rainfall in much of the state, especially in the north. However, the same analyses indicate an increase in mean summer maximum temperatures in the southeast, and mostly weak positive trends in the occurrence of individual days with extreme high temperatures. This suggests a decrease in the persistence of synoptic systems favourable to extreme high temperatures, possibly associated with an increased proportion of El Niño years since the early 1980s, as discussed further in section 7.

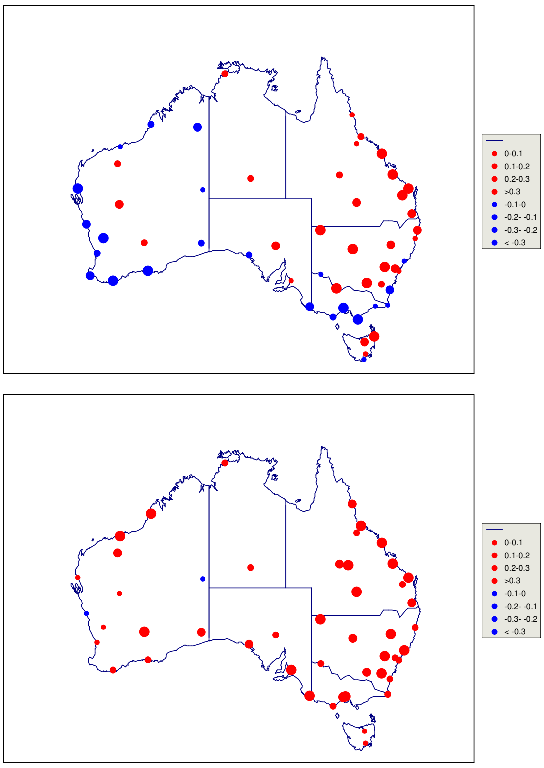

Figure 2. Trends (°C/decade) in Ilim(5) for extreme high maxima (top) and low minima (bottom) at Australian stations

The index values for low minima increased almost throughout Australia, with no clear geographic patterns in the strongest and weakest trends, except for a tendency towards weaker trends in the southwest (where winter rainfall has been declining in recent decades). This indicates a decline in the frequency of extended cold spells in most parts of the continent. The extent of positive trends is broadly consistent with the observed increasing trend in mean winter minimum temperatures over most of Australia, bearing in mind that in the major regions which shows a decreasing trend in mean winter minima, the north-east of Western Australia, adjacent parts of the Northern Territory, and Cape York Peninsula, there are no stations which met the data requirements for inclusion in this study.

The mean trends for Australia in the index values for low maxima and high maxima and minima are broadly consistent with the trends over the same period in Australian area-averaged mean temperatures for the relevant season (+0.16°C/decade for winter maxima, +0.08°C/decade for summer maxima, +0.15°C/decade for summer minima). The index trends for extended periods with low minima, however, are somewhat stronger than the national trend in mean winter minima temperatures (+0.09°C/decade). This may reflect, at least in part, the uneven spatial distribution of stations and the lack of stations in the northern tropics, which have shown a weaker warming trend in winter than the southern half of the continent.

8. RELATIONSHIPS BETWEEN EXTENDED HEATWAVES AND THE EL NIÑO-SOUTHERN OSCILLATION

The El Niño-Southern Oscillation (ENSO) is well-established as having a strong influence on mean temperatures over large parts of Australia (Jones and Trewin, 2000), with much of the continent tending to experience above-normal summer maximum temperatures during El Niño years. There is also a tendency to a greater number of individual extreme high temperatures in summer over most of Australia, particularly eastern Australia from northern Victoria northwards (Trewin, 2001b).

To determine whether similar relationships held for extended hot spells as those which exist for individual hot days, the annual values of Ilim(5) were correlated with the mean value of the Nino 3.4 index (the sea surface temperature (SST) anomaly averaged over the region 5°N-5°S, 17-120°W) for spring (September-November) over the period 1951-2007. Stations showing significant correlations are shown in Figure 3.

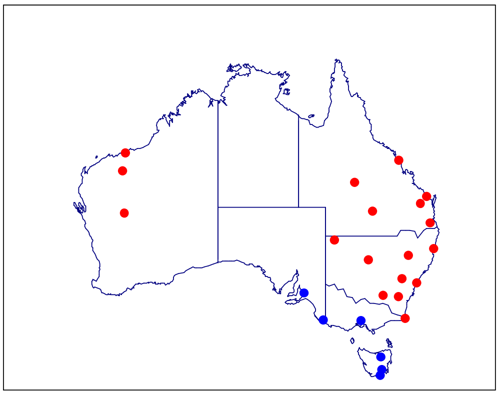

Figure 3. Stations with significant correlations between Ilim(5) for high maxima and spring Nino 3.4 – positive (red) and negative (blue)

Over most of Australia the results for extended hot spells are consistent with those for individual high temperatures, with positive correlations particularly widespread in Queensland and New South Wales, where the relationship for individual extremes is strongest.

However, an interesting outcome is that significant negative correlations between Ilim(5) and Nino 3.4 are found at a number of coastal or near-coastal stations in southeastern Australia, including Melbourne and Adelaide. At most of these stations the correlation between the frequency of individual extreme hot days and ENSO indices is near zero. A common feature to all of these stations is that high temperatures require a gradient northerly flow to override marine influences, but they are not so exposed to the ocean (as, for example, Cape Otway and Wilsons Promontory are) as to ensure that continuous 5-day periods without marine influence are essentially unknown.

The nature of the relationship between extended heatwaves and ENSO is illustrated further in Figure 4. This indicates that at Melbourne, extended heatwaves are essentially unknown during El Niño years – there has never been an episode of five or more consecutive days above 32.5°C in a year in which the spring Nino 3.4 was positive, whereas this has occurred in eleven different years with negative spring Nino 3.4. This indicates that episodes with five or more consecutive days of northerly flow are extremely rare during El Niño years, possibly suggesting a greater mobility of synoptic systems, although no analysis of this has been carried out. The relationship is much weaker for 10-day heatwaves (no station shows a significant negative correlation), which is a time period beyond the usual timescale of synoptic-scale weather systems in southeastern Australia.

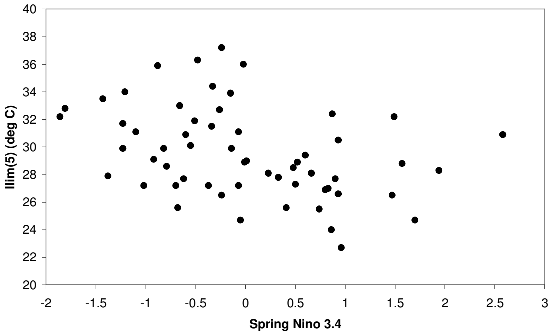

Figure 4. Spring Nino 3.4 and values of Ilim(5) for extreme high maxima at Melbourne, 1951-2007.

9. CONCLUSIONS

The indices discussed in this paper show considerable potential for use in the monitoring of extended hot and cold spells. They are more adaptable to a wide range of climates than indices used in previous studies for this purpose, and also, in general, have properties which make them more amenable to statistical analyses. Against this, the complex definition of the indices makes them potentially difficult to interpret, especially for casual users of the information.

In the areas analysed, the indices showed trends which were mostly broadly consistent with a warming trend in mean temperatures, although with some local exceptions. In Australia, local relationships between the frequency of extended heatwaves and ENSO were sufficiently strong to indicate some prospects of useful predictability of the risk of such heatwaves on the seasonal timescale.

10. ACKNOWLEDGEMENTS

Data from the European Climate Assessment and Dataset (Klein Tank et al., 2002) were obtained from the ECA&D website (http://eca.knmi.nl).

Data from the homogenized Canadian temperature data set were supplied by Lucie Vincent from Environment Canada.

Data from other GSN stations were obtained from the (U.S) National Climatic Data Center (ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/daily).

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