Urban heat island features of southeast Australian towns

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This study investigates the magnitude of the urban heat island (UHI) effect in four small towns, with populations of less than 10,000, and one large city, with a population of 3.02 million. All of the experiment sites are located in southeast Australia. Several climatic variables were measured along automobile transects from rural locations through the centres of each settlement. Some transects were repeated at different times of the day. A comparison of long-term temperature records is made from independent sites at one of the towns, and the influence of the UHI effect on the historical temperature record is discussed in a qualitative nature. The maximum UHI effect at the centre of a town over grass is related to population via a regression equation. The urban-rural temperature difference was found to increase with increasing population via the equation

$$\Delta T_{u\text{-}r(\max)} = 1.42 \log(\text{population})\text{-}2.09$$

The results are discussed in the context of investigations in Europe and North America, and it is suggested that Australian towns and cities are likely to have smaller maximum UHI effects than are observed on the other two continents, for settlements with the same population. The findings of this study have implications for the compilation of historical temperature records and the maintenance of observation networks, particularly for climate change studies.

Introduction

The purpose of this investigation was to examine the current urban heat island (UHI) effect in a number of southeast Australian towns and to provide discussion on its potential impact on the historical temperature record. High-quality long-term historical temperature data are fundamental in the examination of climate change. Observational datasets are essential for the monitoring of climate and the analysis of past trends, and the validation of climate models. It is therefore necessary to account for any possible bias in the record due to non-climatic influences. Changes affecting the record, such as site moves and instrument modifications, have been addressed on both regional (e.g. Easterling and Peterson 1994; Plummer et al. 1995) and global (Jones et al. 1986; Karl and Williams 1987) scales.

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Anthropogenically induced changes in the energy balance in urban centres have a significant effect on temperature, which has been termed the urban heat island (UHI) effect. This bias arises as a result of two different but associated processes. A direct warming of the air can result from various combustion processes such as those involved with vehicles, air conditioning and heating. The energy balance can also change as a result of land-surface changes that include variations in the albedo, thermal aerodynamic properties, hydrology and morphology of the surface. The UHI effect varies temporally and spatially depending on the prevailing meteorological conditions, location and land-surface characteristics (Oke 1987). Before long-term temperature trends can be examined with confidence, these biases must be adjusted for in the climate record.

UHIs are also related to the population of a town, and have been studied extensively via direct observation (e.g. Oke 1973). Observational results, using population as a surrogate for the degree of urban development, suggest a relationship between the maximum urban-rural temperature difference ($\Delta T_{u\text{-}r(\max)}$) and population (POP) of:

$$\Delta T_{u\text{-}r(\max)} = 2.96 \log_{10}(\text{POP}) - 6.41 \text{ (North America)} \quad \ldots 1$$

$$\Delta T_{u\text{-}r(\max)} = 2.01 \log_{10}(\text{POP}) - 4.06 \text{ (Europe)} \quad \ldots 2$$

Direct measurement of the UHI in Melbourne, a city in southeastern Australia (Fig. 1), was made in 1972 (van Meurs, personal communication). This involved making simultaneous transects along major Melbourne highways. A maximum urban-rural temperature difference of 6.8°C was measured between the city centre, which had a population of 2.5 million in 1972, and the western rural fringe. Another traverse of Melbourne soon afterwards (Bond 1974) measured an urban-rural difference of 5.7°C to the east, however this traverse of the inner west of the city was carried out in overcast and windy conditions and has not been used as a comparison in this present study. Lyons (1974) made observations of the UHI in Adelaide, a major urban centre 650 km northwest of Melbourne with a population of 870,000 in 1973, indicating a maximum urban-rural temperature difference of 4.4°C. As the transect commenced and concluded at the coast, the observed UHI effect may have been decreased by the moderating influence of St Vincent's Gulf. The maximum urban-rural temperature difference in Hobart in 1978 was measured as 5.7°C (Nunez 1979). At that time, the population of Hobart was 130,000. Both Lyons and Nunez sampled the temperature from sensors mounted on vehicles.

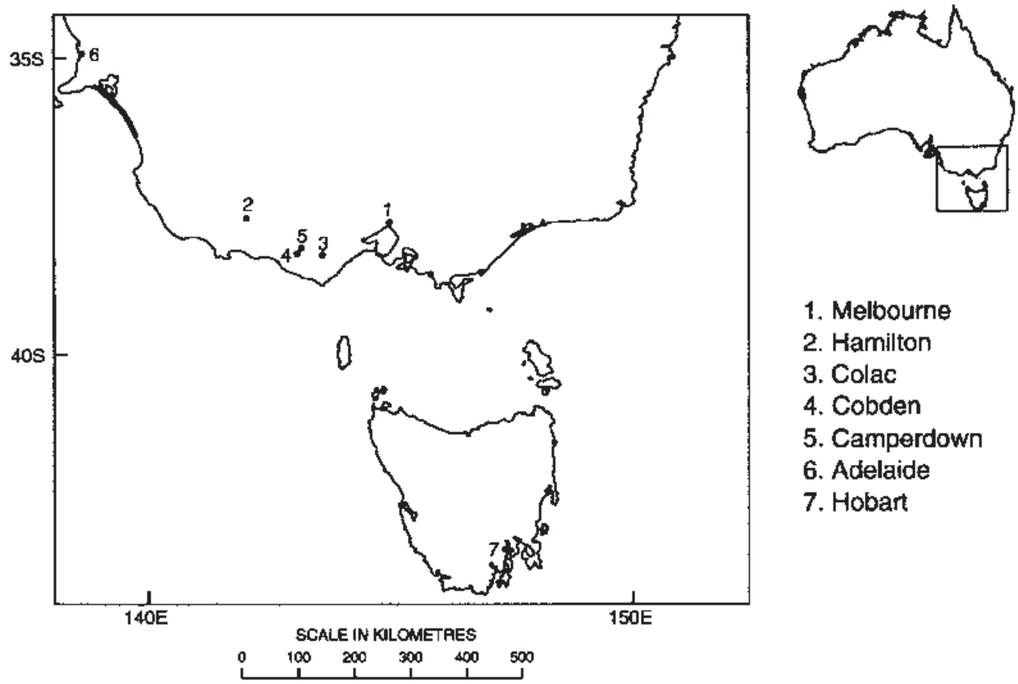
The UHI effect on the long-term record has been studied via the comparisons of records from urban centres with those from rural localities. Historical comparisons are essential for the quantification of the UHI effect on trends in the record. Results from Karl et al. (1988) suggest an exponential relationship between mean urban-rural annual temperature difference ($\bar{T}^*_{u\text{-}r}$) and urban population (POP) of:

$$\bar{T}^*_{u\text{-}r} = a(\text{POP})^{0.45} \quad \ldots 3$$

The coefficient, a, was found to be -3.9 x 10^{-4} for maximum temperatures, and 3.61 x 10^{-3} for minimum temperatures. In towns with populations below 10,000, a was found to be -0.77 x 10^{-3} for maximum temperatures and 5.12 x 10^{-3} for minimum temperatures. Towns with a population of 10,000 were seen to average 0.1°C warmer for mean annual temperature than nearby rural sites with adjacent populations of less than 2000. The effect of urbanisation on the United States Historical Climatology Network of 1219 stations, over the period 1901-84, was seen to average 0.13°C for minimum and -0.01°C for maximum temperatures. Coughlan et al. (1990) examined the UHI effect in seven Australian cities. They concluded, consistent with the results in the United States, that an exponential expression best described the relationship between population and the average UHI effect, but with a smaller exponent value of 0.3. Contrasting with the US study, the coefficient a was seen to be positive for maximum temperatures with a value calculated to be 3.7 x 10^{-3}, and for minimum temperatures, a was calculated to be 1.89 x 10^{-2}. It is obvious from these studies that the UHI effect on trends in the historical record, primarily observed in the minimum temperature, is much less than the experimentally observed maximum UHI effect and this will be discussed further.

This paper differs from previous studies in that the UHI in small towns is examined. Overlapping historical data from urban and rural sites in small towns are generally not available, hence the UHI was physically measured. Morris (1998) concluded that in the absence of appropriate data the preferred method to estimate the UHI was to measure the difference along an urban-rural transect. In this study, the UHI was directly measured in the afternoons (at the approximate time of the maximum temperature observations), in the evenings (at the approximate time of maximum urban-rural temperature difference (Oke 1982)) and in the early mornings (at the approximate time of the minimum temperature observations). The selection of small towns was based on the assumption of a relatively small UHI bias in their records and, for this reason, they have frequently been used in long-

Fig. 1 Map of southeast Australia showing locations relevant to the study.



term climate change analyses (e.g. Karl et al. 1988; Jones et al. 1990; Torok and Nicholls 1996). In addition, climatic variables from Melbourne were measured for comparison with results from the smaller towns, and with studies from other continents. The urban-rural temperature difference was examined with respect to variations in town population at each settlement.

Procedure

The parameters considered in the selection of the four small towns were population, used as a surrogate for town size, morphology of the town and its ambient land use, and the availability of nearby official meteorological data. The towns selected, shown in Fig. 1, were: Hamilton, 250 km due west of Melbourne, in a mostly flat area with undulating hills to the immediate north and mountain ranges approximately 60 km to the northeast; Colac, 120 km southwest of Melbourne, in a mostly flat area with a lake to the north and hills located to the south; Camperdown and Cobden, 165 and 175 km southwest of Melbourne, respectively, in an undulating area, with Camperdown on a higher plateau. One large city was also selected: Melbourne, the capital city of the State of Victoria, located at the northern end of Port Phillip Bay and set on undulating country with mountains to the north and east. Details of each urban centre are given in Table 1.

Air temperature and wind were recorded following automobile traverses (Table 1), as performed previously both internationally (e.g. Oke 1973) and in Australia (e.g. Tapp 1977; Bond 1974). Wet and dry-bulb temperatures were measured at a height of approximately 1.3 metres, facing into the wind, using an Assmann psychrometer. The wind measurements were made at a height of approximately two metres with a hand-held anemometer.

For the four small towns the transects involved driving from a position in the rural area (in the cases of Hamilton and Colac from an official Bureau of Meteorology [BoM] site), through the town centre (past an official BoM site in all towns), to a rural area on the other side of the town. For consistency, all of the small town transects were made in a north-south orientation. For the Melbourne profile, due to the city size, the transect was divided into nine segments, with teams of three researchers traversing each segment

Table 1. Population within geographical boundary of town/city (Australian Bureau of Statistics 1993), latitude and longitude (in degrees and minutes), official BoM station numbers and years of temperature measurement and time taken for transect to be completed for the urban centres used in this study.

Town name	*Latitude*	*Longitude*	*Transect time (mins)*	*Population*	*BoM sites*	*Years open*
Camperdown	38 14 S	143 09 E	216	3315	090011 (P.O.)	1903 - 1975
Cobden	38 20 S	143 04 E	-	1477	-	-
Colac	38 21 S	143 35 E	125, 141, 158	9171	090022 (P.O.)	1899 - 1968
					090147 (Shire Office)	1969 - 1983
					090174 (Residential)	1983 - 1994
Hamilton	37 45 S	142 02 E	181, 206.5,155	9753	090044 (P.O.)	1886 - 1983
					090173 (Aerodrome)	1983 - 1994
					090103 (Research station)	1965 - 1994
Melbourne	37 49 S	144 58 E		3,022,157	086071 (City Centre)	1855 - 1994

simultaneously. Measurements were made in an east-west direction, from the western fringe, past the Shrine of Remembrance, approximately 2 km south of the city centre, through the Central Business District (CBD) to the northern fringe. It is possible that the measured Melbourne UHI is a slight underestimate, as measurements across the urban-rural boundary were not continued far into the rural area. Measurements at all settlements were taken at designated locations which were broadly representative of the immediate area. A single measurement was made at each location, at a sufficient distance from the motor vehicle, several minutes after stopping to allow equilibrium of the thermometers to be reached, and over grass where possible, in order to have comparable results between the transect measurements and the historical data from Stevenson screens (also located over grass). The site in the centre of Cobden and the site near the centre of Hamilton were the only surfaces where the temperature measurements were not taken over grass. The transect was then repeated in reverse order, with measurements taken at the same locations, and the average value calculated for each stopping point. This minimises the effect of nocturnal radiative cooling on the measurements, which arises due to the time taken for the transect to be completed. Radiative cooling was assumed to be a linear function of time over the period of the experiment. In order to estimate the maximum UHI effect, transects were completed during weekdays because anthropogenic activity is more prevalent (Lawrence 1971).

At Colac the experiment was performed at three times of the day; mid-afternoon, soon after sunset, and just before sunrise. Experiments were undertaken over the last two time periods at Hamilton, with the after-sunset experiment being repeated on two days with different temperature regimes. The Camperdown-Cobden experiment was performed after sunset only. The Melbourne transect was carried out once about three hours after sunset.

The local weather at the time of each town transect was generally clear skies with light winds. The first transect was made at Hamilton on the evening of 24 January 1994. A high pressure system was centred south of the area of interest (Fig. 2(a)), resulting in light winds and high daytime temperatures.

Fig. 2(a) Synoptic conditions over southeast Australia at 1200 LST, 24 January 1994.

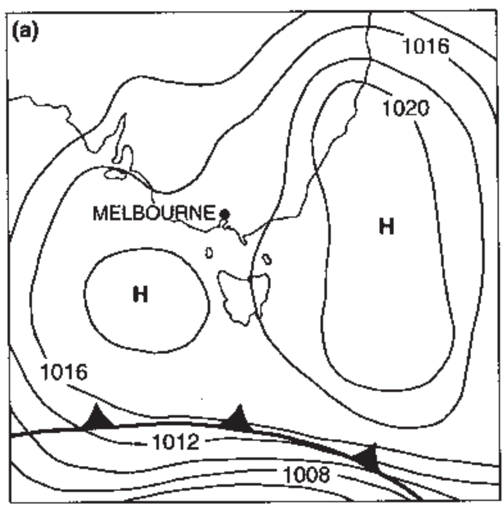


Fig. 2(b) Synoptic conditions over southeast Australia at 1200 LST, 28 January 1994.

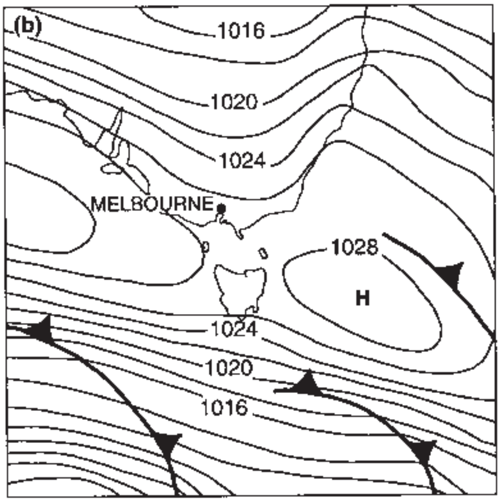
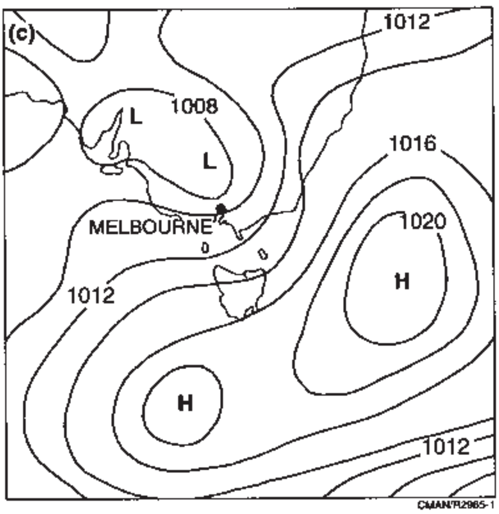


Fig. 2(c) Synoptic conditions over southeast Australia at 0600 LST, 4 February 1994.



Observations at the official BoM site are shown in Table 2, as they are for all stations. On the evening of 28 January the Camperdown-Cobden transect was performed in similar conditions. The mean sea-level pressure chart is shown in Fig. 2(b), however, no official BoM data were available for comparison. On 3 - 4 February the three transects of Colac were made. In the afternoon, conditions were clear, with increasing cloud to 3 oktas by the end of the experiment. In the evening it was cloudless with no fog. The following morning featured early dew, fog patches in some areas (but not at experiment sites), a thin cover of cirrus at dawn but generally clear skies. Synoptic conditions are displayed in Fig. 2(c). On 1 March the town of Hamilton was revisited on a clear evening for sunset and sunrise experiments. The morning produced clear skies above the transect area, stratocumulus on the horizon that drifted over the north of the town and then cleared. As dawn approached, scattered stratocumulus were observed in the vicinity, with thicker cloud on the horizon to the east. Synoptic conditions are displayed in Fig. 2(d). The Melbourne transect was completed on the evening of 25 August 1992. Light winds and clear conditions prevailed due to the

Fig. 2(d) Synoptic conditions over southeast Australia at 0600 LST, 2 March 1994.

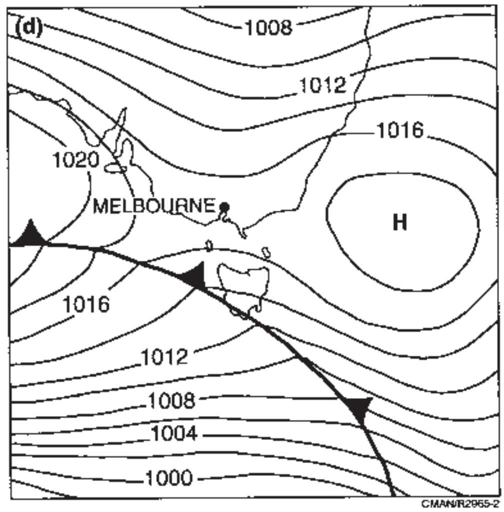


Fig. 2(e) Synoptic conditions over southeast Australia at 0600 LST, 25 August 1992.

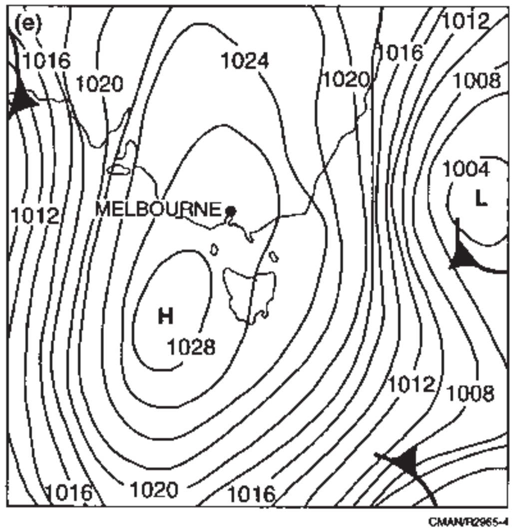


Table 2. Official Bureau of Meteorology observations. Time is local summer time (UTC + 11 hours). All measurements were taken in 1994 except for Melbourne where they were recorded in 1992.

Date, Time, Location	*Dry-bulb temp. (Deg. C)*	*Wet-bulb temp. (Deg. C)*	*Wind (nearest 5 knots, Dir)*	*Cloud (oktas)*
24/1, 1400 LST, Hamilton	33.0	18.5	5 W	0
24/1, 1700 LST, Hamilton	29.2	19.2	10 S	0
24/1, 2000 LST, Hamilton	17.1	12.7	VARIABLE	0
25/1, 0200 LST, Hamilton	14.5	11.5	10 SW	0
3/2, 1400 LST, Colac	28.1	20.8	5 SW	3
3/2, 2000 LST, Colac	20.0	17.6	5 NE	1
4/2, 0800 LST, Colac	19.0	17.4	5 NE	2
1/3, 1400 LST, Hamilton	21.5	13.9	VARIABLE	1
1/3, 1700 LST, Hamilton	21.3	14.6	10 S	1
1/3, 2000 LST, Hamilton	11.9	10.1	5 S	1
2/3, 0200 LST, Hamilton	9.0	8.9	VARIABLE	1
2/3, 0500 LST, Hamilton	8.0	7.9	5 SE	1
2/3, 0800 LST, Hamilton	12.4	11.4	5 SE	1
2/3, 1100 LST, Hamilton	17.0	12.8	5 NE	1
25/8, 1800 LST, Melb.	10.8	7.6	5 S	2
25/8, 2100 LST, Melb.	8.9	6.5	VARIABLE	1
26/8, 1200 LST, Melb.	12.6	8.1	VARIABLE	1

dominant influence of an anticyclone. Synoptic conditions are displayed in Fig. 2(e). Tapp (1977) observed that Melbourne's maximum average heat island intensity occurred in October, hence the measurement of the maximum UHI in this experiment may be a slight underestimate.

Results

The transects through Hamilton on the evenings of 24 January and 1 March 1994 and the morning of 2 March, with the land height profile along the transects, are shown in Fig. 3(a). On the first evening, in the centre of town over concrete the air averaged 5.4°C warmer than the lowest rural temperature at the airport. Over grass, close to the post office BoM site, this value was 3.9°C. On the second, milder evening, the difference between the temperature over grass in town and the temperature at the airport was 2.6°C. By morning the temperature had shown a greater decrease in the rural area so that the urban-rural temperature difference had increased to 3.0°C. Wet-bulb temperatures were slightly higher in town, and winds slightly lighter (not shown in figure).

The transect through Camperdown-Cobden on the evening of 28 January 1994 and the land height profile along the transect are shown in Fig. 3(b). One site in Camperdown was measured near an industrial complex over concrete, exhibiting temperatures 1.0°C higher than in the centre of town. The urban-rural

Fig. 3(a) Transects of the temperature through Hamilton on 24 January and 1 - 2 March 1994. Elevations of the measurement sites are also shown.

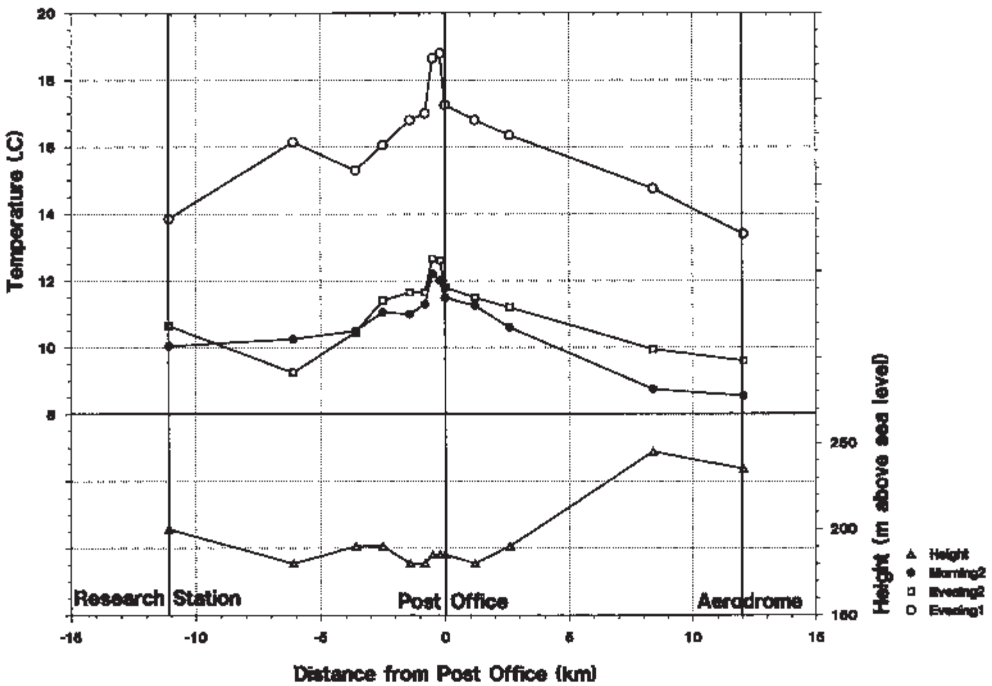


Fig. 3(b) Transects of the temperature through Camperdown-Cobden on 28 January 1994. Elevations of the measurement sites are also shown.

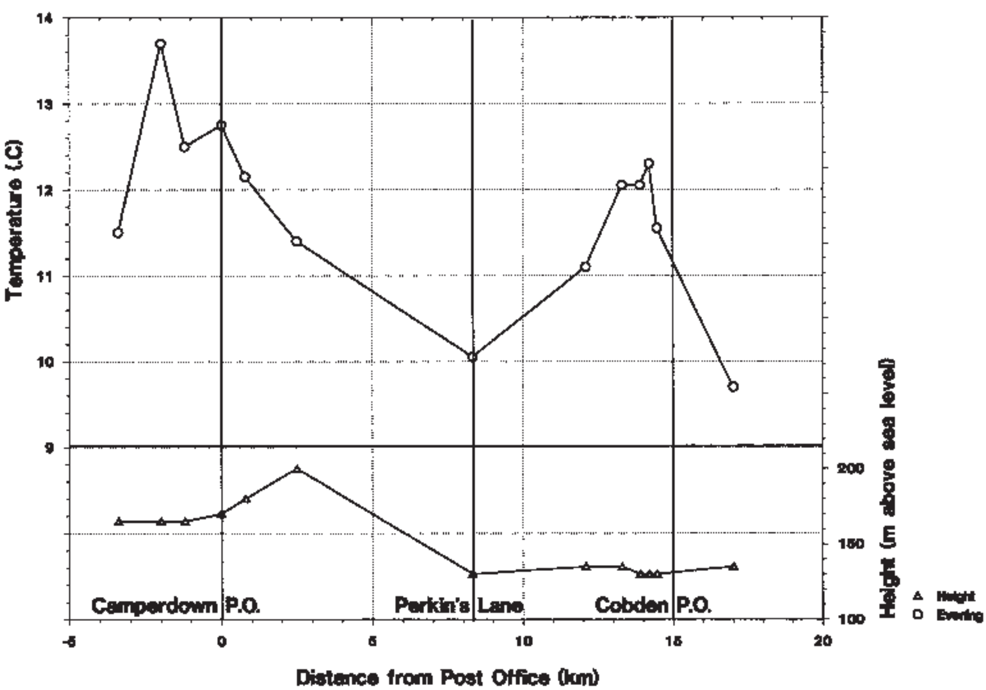


Fig. 3(c) Transects of the temperature through Colac on 3 - 4 February 1994. Elevations of the measurement sites are also shown.

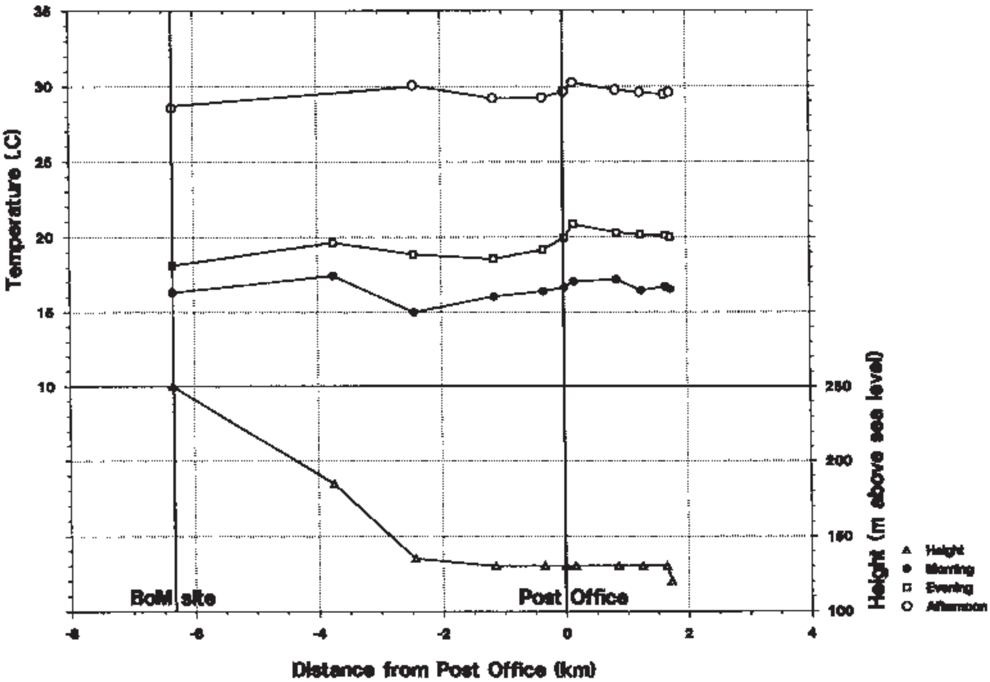
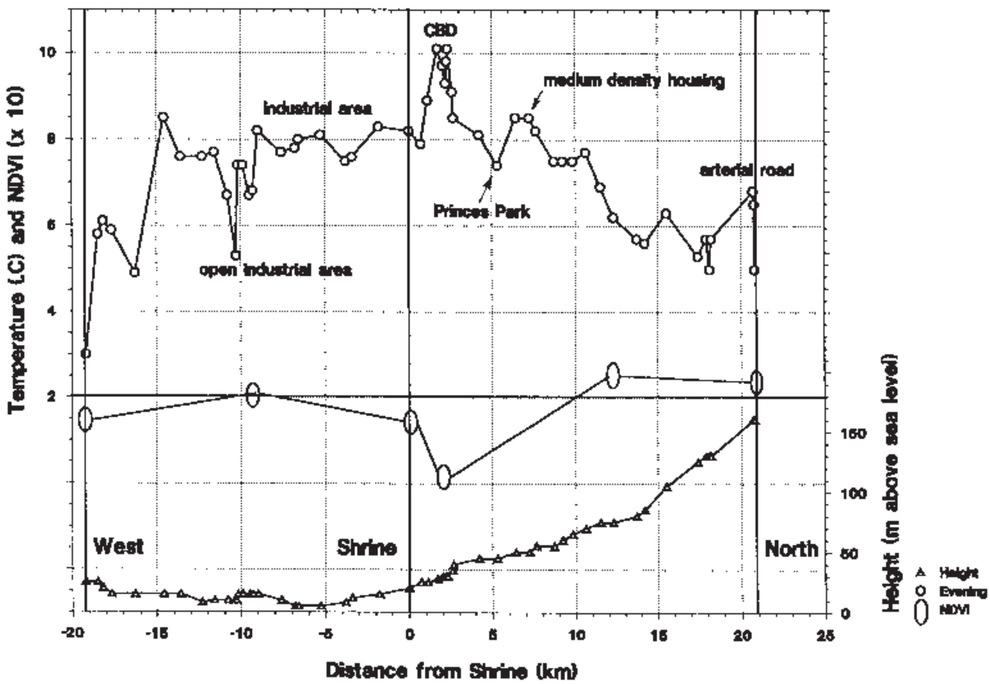


Fig. 3(d) Transects of the temperature through Melbourne on 25 August 1992. Elevations of the measurement sites are also shown.



temperature difference between Camperdown post office and the rural area at Perkin's Lane was 2.7°C. The temperature in Cobden at the centre of town over concrete was 2.6°C higher than at the outskirts of town, but this value was reduced to 2.4°C over a grass site. Wet-bulb temperatures were slightly higher in both towns, and winds slightly lighter (not shown in figure).

The transects through Colac on the evening of 3 February and the morning of 4 February 1994, and the land height profile along the transects, are shown in Fig. 3(c). The nearby lake at Colac was likely to have had a significant moderating effect on the temperatures, but some useful information can still be gleaned from the results. In the afternoon, temperatures were higher in the town centre than the rural surroundings by 1.7°C over concrete and 1.1°C over grass. By evening, the rural temperatures had decreased more than the urban temperatures and the UHI effect had increased to 2.8°C over concrete and 1.9°C over grass. The next morning temperatures had further decreased, however the urban temperatures had decreased more than the rural temperatures and hence the UHI effect had decreased to 2.2°C over concrete and 1.7°C over grass. As in Hamilton and Camperdown-Cobden, wet-bulb temperatures were slightly higher and winds slightly lighter in the town centre (not shown in figure).

The transect through Melbourne on the evening of 25 August 1992 and the land height profile along the transect are shown in Fig. 3(d). Features of interest are the peak warming effect of 7.1°C in the CBD, and the secondary peaks in the industrial area to the west and the medium density terrace housing in the inner northern suburbs. A peak near the northern city fringe was measured next to an arterial road. Cool spots are evident over parks and open areas (cf. Princes Park, 5.3 km north of the Shrine, and an open industrial area, 16.3 km west of the Shrine). Sharp drops in temperature occur across the urban-rural boundary, particularly on the western fringe.

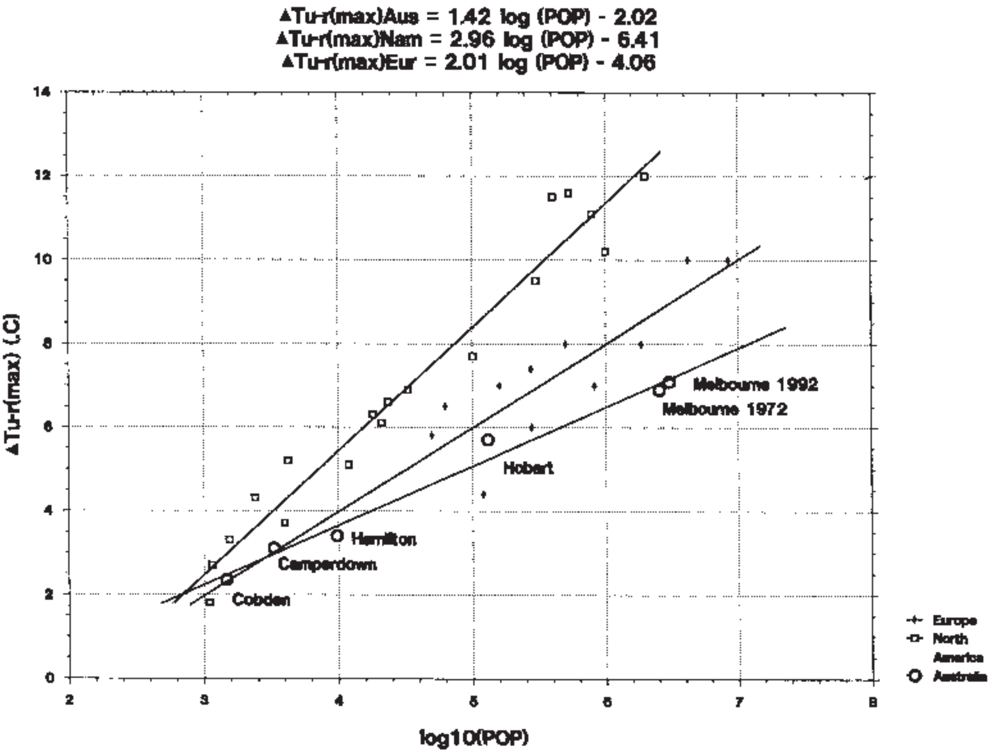
Discussion

As would be expected, all towns exhibited a relative peak in overnight temperature at the town centres. Although two measurements at sites over artificial surfaces may have influenced the air temperature for that site, the surrounding measurements at the sites over grass indicate increased air temperatures compared with the measurements in the surrounding non-urban area, i.e. the urban-rural temperature differences were still seen to be positive over grass sites within the town. Hamilton has an ideal topography and city morphology for UHI experiments, and its results were closest to those expected from previous studies (Oke 1979). Temperatures at Colac were moderated by the large lake to the north of the town but nonetheless showed a UHI effect of similar sign to the results in the other towns. Although varying in magnitude, the UHI effect was apparent in the afternoons, evenings and mornings, in Colac and Hamilton. The UHI effect was larger in magnitude on a warm day than on a milder day at Hamilton. From the simultaneous measurements of the wet-bulb temperature it was found that on the milder day the air was more moist. Hence limited overnight cooling in the rural areas relative to the urban sites may have resulted as the surface approached saturation temperature. Anomalous warm and cool areas were evident throughout the long traverse of Melbourne, with the maximum UHI effect at the centre of town.

Relationship between UHI and population

Population was positively correlated with the urban-rural temperature difference, given similar synoptic conditions. The results are shown in Fig. 4 with the original observations of Oke (1973) for North America and Europe, of van Meurs (personal communication) for Melbourne in 1972, and of Nunez (1979) for Hobart in 1978. A regression line can be fitted through the values to give a model for the urban-rural temperature difference in a small number of Australian urban centres. The results in towns amplified by artificial surfaces directly beneath the site, and the results moderated by the lake at Colac and the Gulf at Adelaide (Lyons 1974), are not included in this model. This ensures that the value of the urban-rural temperature difference is based on comparisons between two observations over standard surfaces. Additionally, we are also concerned with the influence of the UHI effect on the historical temperature records of sites that have generally adhered to international standards of temperature measurement as described by the World Meteorological Organization (WMO 1983). This regression model could therefore be a slight underestimation of the influence that the measured UHI effect has on the temperature record, as station history documentation shows that a minority of stations in the Australian observation network have had screens exposed over non-standard, artificial surfaces for short periods of time. It should also be noted that the linear regression is based on only six stations, and although exhibiting a high correlation between population and urban-rural temperature difference, an analysis of more stations would be required to obtain a more rigorous relationship. The regression equation suggests that the maximum heat island development will, on average, be

Fig. 4 Maximum urban-rural temperature difference ($\Delta T_{u\text{-}r(\max)}$) versus the logarithm of population (POP) for Australian, European and North American towns and cities. Additional data has been obtained from Oke (1973) and Tapp (1977). Correlations and significance levels for Australia, Europe and North America, respectively, are: 0.997 at 97%, 0.861 at 99% and 0.980 at 99%.



less in Australian towns than in towns with the same population in North America and Europe, and increases at a slower rate with population growth. Tapper (1982) performed a similar analysis for New Zealand towns and cities and also found a reduced maximum UHI effect compared to that found over the two northern continents. Oke (1981) showed that the 'sky view factor', related to the geometry of the inner city, is a basic physical control on urban heat islands. Australian towns have a strong European influence in their morphology, having an open geometry, and would therefore be expected to exhibit a less intense maximum heat island than North American cities, which have deeper canyons. The stronger association between the population and the UHI in American and European towns is probably due to the greater population density (people per unit area), and hence building density, or height/width (H/W) ratio, of the northern hemisphere urban centres. The towns in our study have very wide streets and predominately single story buildings. Thus we estimate from 'ground truth methods' and from the aerial photos that the towns in this study have lower H/W ratios, and therefore the morphology component of the Australian UHI is weaker than that found in the northern hemisphere urban areas. Morris (1995, 1998) has considered the relationship between UHI effect and urban morphology in several small Australian towns.

Historical perspective

Comparing long-term absolute temperature records from neighbouring sites can provide us with some information about the UHI. Although such records are rare for southeast Australia for periods greater than one year, the National Climate Centre at the BoM has temperature data for Hamilton research station overlapping the records at both the post office and the aerodrome. Before comparisons were made, adjustments were applied to the relevant period of record using comparisons with an average of neighbouring stations highly correlated with respect to temperature, as described in Torok and Nicholls (1993) and Torok (1996). A discontinuity detected in the Hamilton post office maximum and minimum record was due to a move to a more open site at the school in 1968. Discontinuities were detected in the maximum temperature record at

Fig. 5(a) Comparisons of annual maximum temperatures at Hamilton between the post office and the research station, and between the research station and the aerodrome.

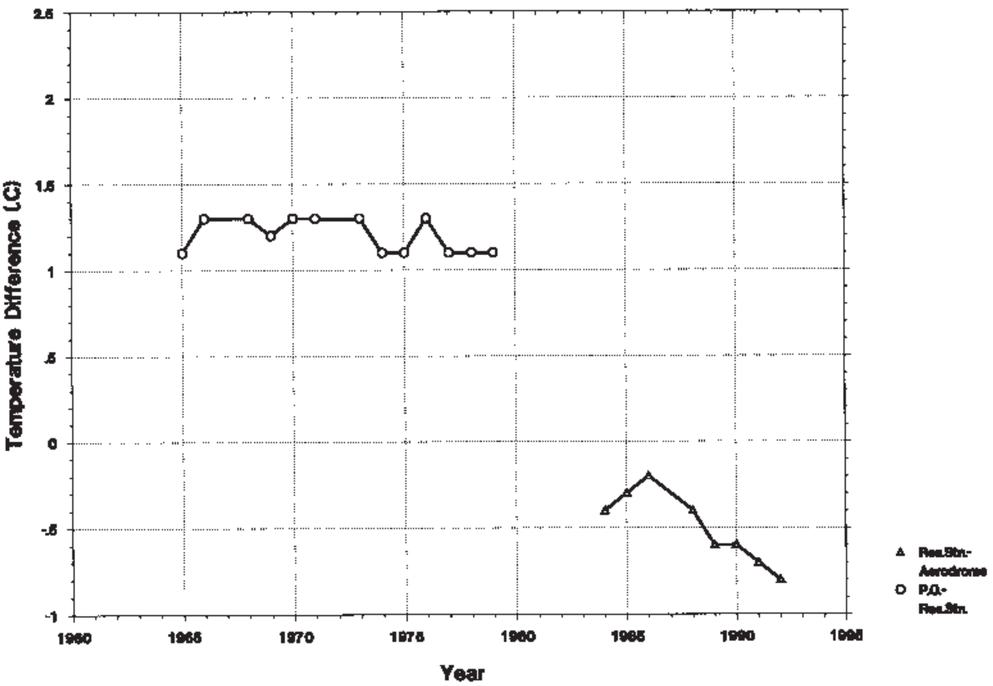
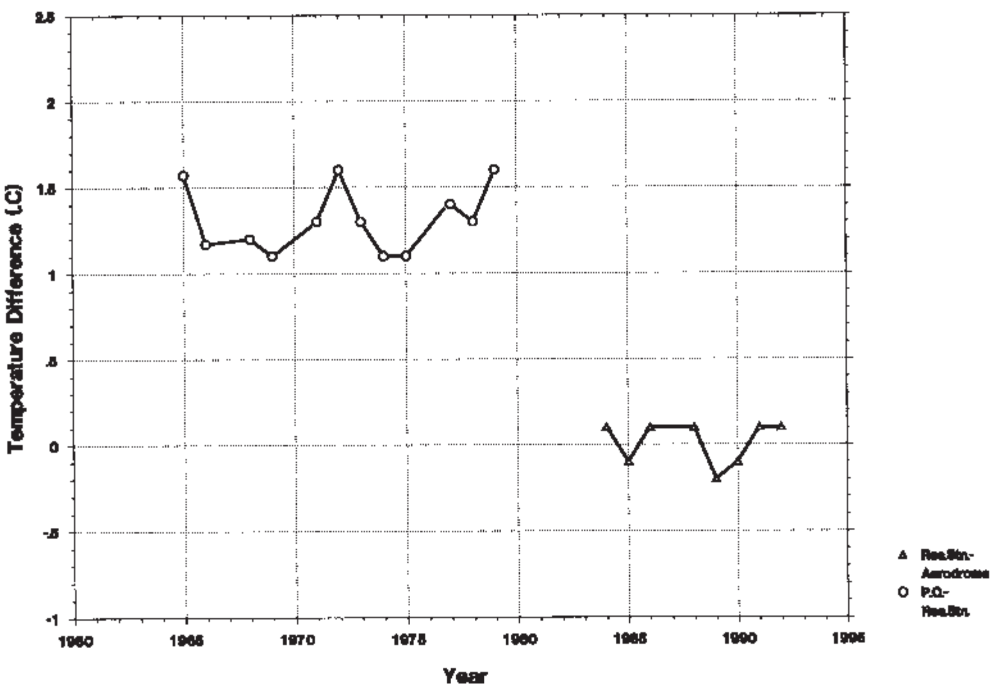


Fig. 5(b) As for Fig. 5(a), but for minimum temperatures.



the research station in 1973 due to a site move and at the aerodrome in 1986 due to an instrument relocation away from trees. An adjustment of -0.33°C was applied to the minimum temperatures and +0.40°C to the maximum temperatures prior to 1968 at the post office. An adjustment of -0.4°C was applied to the maximum temperatures prior to 1973 at the research station and prior to 1986 at the aerodrome. Comparisons show that minimum temperatures are on average 1.3°C warmer in town than at the research station (Fig. 5(b)), and maximum temperatures are on average 1.2°C warmer, although maximum temperatures at the research station are 0.5°C cooler than at the aerodrome (Fig. 5(a)). These observations are less than, but still consistent with, the results measured directly via the transects. As these average differences include all meteorological conditions, including those that are not ideal for maximum UHI formation, the reduced magnitude is expected. Note that the average value is the instantaneous difference measured with overlapping data from nearby sites, and cannot be interpreted as an overall trend on the record.

From these data it is not possible to obtain an estimate of the influence of the UHI effect on the historical temperature record. Assuming that the Australian relationship between the maximum UHI and population (Fig. 4) approximately holds for changes at a single location then, considering Hamilton and population changes alone (from 4900 in 1911 to 9753 in 1991), we may estimate that the rise in the maximum UHI has been around 0.4°C over the eighty-year period. However, this would be the trend due to the maximum UHI effect and does not represent changes in the annual mean UHI, which is the variable of most interest in climate change studies. There are several reasons why the annual mean UHI would be expected to be considerably less than this maximum value. Firstly, measurements of the maximum UHI are (by definition) performed during ideal conditions, i.e. generally clear skies with little or no wind, but the majority of days are not ideal for maximum UHI development at a location. Oke (1973) shows an inverse square root relationship between urban-rural temperature difference and wind speed for Canadian stations with a similar population size to Hamilton. Differences were between 4°C and 6°C under calm conditions and around 1°C or less when the wind speed had increased to 5 m s^{-1}. Secondly, the long-term temperature records used for climate change analysis generally use observations of maximum and minimum temperature and these are often observed at times when the maximum UHI effect is not observed. In summary, it is not yet possible to estimate the urban influence on the temperature records of these small Australian towns. While the relationship between a maximum UHI and annual mean UHI is likely to be far from linear we note that the maximum UHI for Australia appears to be less than that for North America and Europe for locations with the same population.

Conclusions

Temperatures across five urban centres in southeast Australia were measured directly two to three hours after sunset at the time when the maximum UHI effect generally occurs, as well as around the typical times of the maximum and minimum temperatures at four towns. It was further confirmed that a large UHI effect can be measured in the major urban centre of Melbourne, and that a smaller but significant UHI effect can be detected even in small towns. The UHI effect was seen to decrease in Hamilton on milder and more humid days, and in Colac due to the influence of a lake. The maximum UHI is very high in the large cities of North America, Europe and Australia, and increases approximately proportional to the logarithm of population. The maximum UHI effect appears to be less in Australia compared to those observed over the two northern regions.

The UHI effect can be identified in smaller Australian towns, where a significant proportion of climatological stations are located. In the towns studied with populations below 10,000 the effect was found to be of similar magnitude in the late evening and around sunrise. At the time of maximum temperature, the air is well mixed and, in agreement with North American observations of annual mean urbanisation effects in summer, appears to show a warming at the town centre. However, these experimental results were sampled during atypical conditions which were suitable for maximum UHI genesis. As a consequence they cannot be used to adjust long-term annual mean temperature records for urban influences. Nonetheless, these results imply that climatological stations in large cities should preferably be excluded from studies into long-term climate change, and those in small towns should be located away from the town centres. Data records exhibiting discontinuities, particularly those associated with moves from the centre of town to outskirts such as to the airport, must be treated with caution. With an improvement of satellite resolution, the use of boundary-layer models and further study into the land use of towns and their surrounding area, more general relationships could be evolved to determine UHI characteristics. A larger network of homogeneous temperature data records should be investigated to quantify the effect of towns and the UHI effect on the climate record.

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