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Climate and mortality in Australia: retrospective study, 1979–1990, and predicted impacts in five major cities in 2030

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ABSTRACT: Quantitative assessment of climatic and environmental health risks is necessary because changes in climate are expected. We therefore aimed to quantify the relationship between climatic extremes and mortality in the 5 largest Australian cities during the period 1979–1990. We then applied the relationship determined between recent climatic conditions and mortality to scenarios for climate and demographic change, to predict potential impacts on public health in the cities in the year 2030. Data on mortality, denominator population and climate were obtained. The expected numbers of deaths per day in each city were calculated. Observed daily deaths were compared with expected rates according to temperature thresholds. Mortality was also examined in association with temporal synoptic indices (TSI) of climate, developed by principal component and cluster analysis. According to observed-expected threshold analyses, for the 5 cities combined, the annual mean excess of deaths attributable to temperature over the period 1979–1990 was 175 for the 28°C threshold. This sum of statistically significant differences from the 5 cities was the greatest excess found in association with any threshold considered in the range of temperatures that occur. Excess mortality for the hottest days in summer was greater than for the coldest days in winter. Temperature-mortality relationships were little modified by socio-economic status. TSI analyses produced similar results: using this method, the climate-attributable mortality in the 5 cities was approximately 160 deaths yr^{-1}, although this number was evenly distributed across summer and winter. Persons in the group aged 65 yr and older were the most vulnerable. After allowing for increases in population, and combining all age groups, the synoptic method showed a 10% reduction in mortality in the year 2030. We conclude that the 5 largest Australian cities exhibit climate-attributable mortality in both summer and winter. Given the scenarios of regional warming during the next 3 decades, the expected changes in mortality due to direct climatic effects in these major coastal Australian cities are minor.

KEY WORDS: Climate · Mortality · Australia · General circulation models · Temporal synoptic indices

1. INTRODUCTION

The health problems associated with climate change may include increased morbidity and mortality from a higher frequency of extreme climatic events, including heatwaves (Houghton et al. 1996, McMichael et al. 1996). By the middle of next century, many major cities around the world could experience up to several thousand additional heat related deaths annually (Kalkstein 1995). While global warming may lead to lower mortality in winter, the annual balance is expected to be adverse overall, but this would probably vary by region.

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Australian climate-change scenarios indicate that the greatest warming effect is expected in the southern inland of the continent (Ewan et al. 1990, Commonwealth Scientific and Industrial Research Organization 1992). The major centres of population are all on the coast, including the 5 largest cities in Australia, chosen for the present study (Fig. 1). Brisbane has a subtropical climate with a mild winter and a sultry summer. Sydney, Melbourne, Adelaide and Perth have temperate climates, mostly rather comfortable. In extreme heat, however, all may be affected by winds from inland. Perth has the hottest summer (mean daily maximum of 29°C) and Melbourne the coldest winter (mean maximum of 14°C). As preliminary Australian assessments suggested that local impacts might be major (Ewan et al. 1990), the Commonwealth government established a Climate Change Program, through which this work was funded. A quantitative risk assessment in Australia of the climate-related health burden was a priority.

Exposure to abnormally high ambient temperatures may cause health effects that range from mild to very serious (Kilbourne 1991). The competing demands of blood pressure regulation and body temperature maintenance may result in an uncontrolled increase in core body temperature which can lead to collapse (heat stroke, with central nervous system disturbance), coagulative neuropathy, and death (Hales 1991). It is estimated that for every death attributed directly to heat, 10 occur due to aggravation of a pre-existing illness, particularly due to coronary and cerebral thrombosis (Ewan et al. 1990). Excessive heat is likely to be under-reported as a registered cause of death; time period and location, as well as acute weather events, may all influence assignment of this cause.

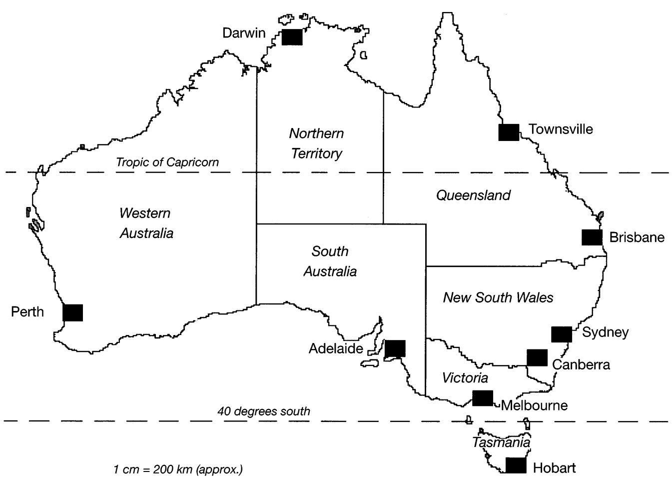

Fig. 1. Map of key Australian locations including the 5 cities of the study

This project examines exposure to thermal extremes and the altered frequency or intensity of various climatic phenomena that cause 'direct' health outcomes, including altered rates of heat- and cold-related illness and death (McMichael et al. 1996). 'Indirect' health outcomes, including those due to ecological disturbance that may influence vector-borne diseases, are the subject of other studies now underway in Australia and elsewhere.

In the retrospective part of this study, we aimed to describe the relationship between temperature and mortality (cause-specific and all causes) in the 5 largest Australian capital cities, during the period 1979–1990. Climate-associated mortality was also studied in this period by temporal synoptic indices (TSI), following the assumption that people respond to the entire umbrella of air that surrounds them, rather than to individual weather elements such as temperature (Kalkstein & Smoyer 1993). Non-linear regression methods were also applied to the data as a third and more theoretical approach.

The relationships determined between recent climatic conditions and mortality were then applied to possible scenarios for both climatic and demographic change in Australia, to predict potential impacts on public health. Estimates of regional climate change due to the accumulation of heat-trapping 'greenhouse' gases are derived from general circulation models (GCMs) (Houghton et al. 1996). These models are computer programs that solve mathematical equations describing the laws of physics that govern atmospheric, oceanic, and land-based processes. About 30 GCMs exist worldwide; an Australian model was used in this project (Commonwealth and Scientific Industrial Research Organisation 1992, Watterson et al. 1997).

2. METHODS

The present study required the linkage of daily meteorological and mortality data from existing national collections (methods are detailed below and summarised in Table 1). Population data were also obtained as denominators for the calculation of mortality rates. The 5 cities chosen for the project together account for 55% of the national population (17.7 million in 1998). The 12 yr period 1979–1990 was chosen for study as it extends over the period of use of the Ninth Revision of the International Classification of Diseases (ICD 9) (World Health Organization 1977).

2.1. Mortality data. Mortality data for the years 1979 to 1990 were obtained from the Australian Institute of Health and Welfare, Canberra. The data were classified into 5 yr age categories up to the age of 85 yr and subdivided by sex.

Table 1. Study of the climate-mortality association—summary of methods

Method	Description and application
Observed-expected	Temperature only Systematic examination of arbitary thresholds with 2°C interval Retrospective only
Correlation coefficients	10 climate variables (Table 2), considered separately Retrospective only
Temporal synoptic indices	Climate variables, considered simultaneously: ambient and dewpoint temperatures, wind speed components, cloud cover Retrospective and prospective City-specific[a] identification of mortality-associated oppressive air masses[b]
Non-linear regression	Temperature only Retrospective and prospective Thresholds with temperature-related mortality[b] emerged from analysis

[a]All analyses in the present study should be considered city-specific. Tentative comparisons of the observed-expected and other analyses are made between cities, however, after standardization to correct for potential confounding by demographic differences
[b]Defined in the text

Mortality data were classified according to ICD9 codes, selected on review of the literature in which causes of death and increased temperatures have been related (Guest 1997): (1) all causes; (2) 390–429, heart disease; (3) 430–439, cerebro-vascular disease; (4) 480–519, respiratory disease; (5) E810–E825, vehicle accidents; (6) E900–E901, excessive heat and cold; (7) E950–E989, suicide and intentional injury.

While all of these were examined separately, in this paper, except where noted, mortality refers to the all-cause category. (Generally, the populations of these cities were too small for statistically significant findings from the other mortality categories.)

Deaths were coded by place of usual residence. For intra-city analyses, the crude mortality rates (per 100 000) were used. To compare cities, we also calculated a standardized mortality rate by the direct method, with Segi's world population as the standard population (King & Rewers 1993) (see Table 1, footnote a).

2.2. Population data. Information on the denominator populations was obtained from the Australian Bureau of Statistics according to the Australian Standard Geographic Classification (ASGC) 2 digit codes (i.e. statistical divisions) which relate to the major metropolitan areas. Data for census years 1976, 1981, 1986 and 1991 were available. Intercensal populations were calculated for the remaining years of the period 1979–1990 by linear interpolation.

The data were also obtained according to 4 digit codes (statistical local areas, SLAs) which correspond to local government areas, to allow for analyses according to socio-economic status (SES), determined by a composite index from the Australian Bureau of Statistics (1990). This index of relative socio-economic advantage and disadvantage summarises variables related to the economic resources of households, education, occupation, family structure and ethnicity. For example, advantage is indicated by high income, tertiary education and skilled occupation, while disadvantage is indicated by low income, lower educational attainment and high unemployment.

Data on projected population for 2030 were obtained for the 5 cities (Australian Bureau of Statistics 1994). These data account for ageing as well as growth of the population. Assuming that the proportions of urban and rural populations will not change in the next 4 decades, the projected population for each age/sex group in each state was multiplied by the proportion of the state population in the capital city in 1990 to obtain the projected population. (This and other assumptions are discussed below.)

2.3. Meteorological data. Daily climate data were obtained from the Commonwealth Bureau of Meteorology National Climate Centre for the years 1979 to 1990. Variables included were maximum and minimum dry- and wet-bulb temperatures, maximum and minimum dew points, wind speed, atmospheric pressure and cloud cover, available for a number of sites in each capital city and consisting of 3-hourly measurements.

2.4. Climate change scenarios. Scenarios of regional changes in temperature, rainfall, and other climate variables have been developed by CSIRO Division of Atmospheric Research. The scenarios used draw on information from 2 sources (CSIRO 1992).

First, the range of the global-average warming is determined. This takes into account the range of possible future greenhouse gas emissions, the range of GCM sensitivities to changes in greenhouse gas concentrations, and the rate of heat absorption by the oceans (Wigley & Raper 1992). By the year 2030, the increase in global average air temperature is expected to be between 0.6 and 1.7°C relative to 1990. The lower limit represents the lowest greenhouse gas emission scenario combined with the lowest climate sensitivity, while the upper limit represents the highest greenhouse gas emission scenario combined with the highest climate sensitivity. (Note that the 2030 scenario is a scaled-down version of the $2 \times CO_2$ model expected for 2060. A $4 \times CO_2$ model is now considered irrelevant, but extrapolation of present relationships between mortality and climate variables may not hold in the future if more extreme conditions or new categories of oppressive air mass are experienced.)

The second source of information is the spatial pattern of changes simulated by GCMs in the Australian region. This provides information on regional departures from global averages. The regional climatic patterns of a given GCM under enhanced greenhouse conditions are only accepted if current climatic patterns are simulated sufficiently well. The CSIRO Mark 2 GCM was judged to perform acceptably well in its simulation of surface temperature and other variables in the Australian region (Whetton et al. 1996, Watterson et al. 1997). This model has been run for present carbon dioxide concentrations ($1 \times CO_2$) and doubled carbon dioxide concentrations ($2 \times CO_2$), and near-surface climate variables required for this study have been extracted. Monthly mean changes in the following variables were computed: minimum dry-bulb temperature (°C), maximum dry-bulb temperature (°C), dewpoint temperature (°C), wet-bulb temperature (°C), north-south wind speed (ms^{-1}), west-east wind speed (ms^{-1}), cloud cover (%), mean sea-level pressure (hPa). For each of the 5 capital cities, monthly mean changes in these variables were divided by the CSIRO GCM global mean warming of 4.3°C to give changes per degree of global warming. These values were then scaled to the year 2030 using the upper and lower global warming estimates of 0.6 to 1.7°C relative to 1990. For example, if the increase in north-south wind speed at Melbourne is 2.15 m s^{-1} for a doubling of CO_2, this is divided by 4.3°C to give 0.5 m s^{-1} per degree of global warming. For the year 2030, this is then (1) multiplied by 0.6°C to give a low scenario at 2030 of 0.3 m s^{-1}, and (2) multiplied by 1.7°C to give a high scenario at 2030 of 0.85 m s^{-1}.

Low and high climate change scenarios were computed separately for each city and month. Monthly mean changes in climate for the year 2030 were applied to the observed 3 hourly values at each of the 5 cities, for the period 1979–1990. The modified time series then effectively represented 12 yr of data centred on 2030 (i.e. 2024 to 2035). This method assumes that variability remains unchanged in future (see 'Discussion'). Changes in maximum and minimum temperature were around 0.5 to 1.5°C, changes in windspeed were mostly positive and ranged from 0 to 20%, and changes in cloud cover were mostly negative and ranged from 0 to –10%.

2.5. Observed-expected analyses. Initially for statistical divisions, for all-cause mortality, average numbers of daily deaths were calculated for each month, for each age group. This was done for each year in the study period to give expected daily death rates for each calendar month averaged over the 1979–1990 period. To allow for a secular decline in mortality over the study period, a linear regression of monthly mortality versus year provided mortality rates adjusted for year. This was subsequently used to calculate the expected number of deaths per day.

Temperature-related mortality in cities of higher latitude than those in the present study has been shown to increase above about 35°C (McMichael et al. 1996). Threshold phenomena in epidemiology are events or changes that occur only after a certain level of a characteristic has been reached (Last 1983), such as the latter temperature. In the present study, thresholds are defined as temperatures above or below which a calculation of excess mortality was made.

In the observed-expected mortality analyses below, arbitrary thresholds at intervals of 2°C were examined. Frost & Auliciems (1993) recently demonstrated that the mortality-temperature relationship was linear in Brisbane. Consistent with that finding, no obvious threshold appeared in this study in any of the 5 largest Australian cities. Because of this, we examined the temperature-excess mortality relation for a wide range of maximum temperatures, above 20°C in summer. Excess mortality was also examined for thresholds of minimum temperature in winter. For each age-sex group, observed daily death rates were compared with the expected rates, during summer and winter. The mean excess numbers of deaths per day were calculated in order to identify the temperatures associated with greatest mortality.

In conventional risk assessment, a threshold refers to a sudden change in the slope of the dose-response curve (Patz & Balbus 1996). For example, the differences in regional sensitivity to heat-related mortality necessitate separate analyses for each city in the present study. Alternatively, for ecological risk assessment, thresholds are better considered as points of non-linear behaviour in the ecosystem relations under study, either temporal or geographical (Patz & Balbus 1996). In the case of the non-linear regression analyses, described below, the thresholds emerged from the analysis.

Mortality and climate data were correlated after stratification according to SES. Pearson correlation coefficients between the mortality and climate data were calculated at the city level and also for selected SLAs within the cities. The SLAs were selected in order to perform separate analyses for areas of low and high SES. The correlation coefficients were also calculated for the 50 d of highest maximum temperature and the 50 d of lowest minimum temperature in summer and winter respectively.

2.6. Temporal synoptic indices. TSI were prepared at the Centre for Climatic Research, University of Delaware from the daily climate data (Kalkstein & Smoyer 1993, Greene & Kalkstein 1996). These indices are specific to each city, and provide a summary of the meteorological characteristics of dominant air masses, as determined by principal component and cluster analysis. In the creation of these indices, the variables used are listed (Table 1).

A baseline measure of mortality was needed. If there was a significant ($p < 0.05$) linear relationship in the regression of mortality against days, then the predicted values from the regression were used as the baseline mortality. Otherwise, the overall seasonal average was used as the baseline mortality. TSI clusters (categories of air mass) were defined as 'oppressive' if the mean mortality above baseline on the days within the cluster was significantly greater than on all other days and if the cluster type occurred on at least 10 d of the 12 yr study period. The latter condition was specified to make it less likely that events unrelated to climate might explain the high mortality associated with a TSI cluster.

Increased mortality may occur on days following a particular weather pattern, so analyses were undertaken with lags of up to 2 d. The lag with the largest mean mortality above baseline in association with a cluster was chosen for report.

The excess mortality associated with a cluster multiplied by the duration and frequency of this category of air mass, summed for all oppressive clusters, determines the total seasonal climate-related mortality in a given city. TSI models were developed for each of the 5 capital cities in summer and winter. The total number of 'excess' deaths for each season was obtained by averaging over the 12 yr of the retrospective study period and summing over all oppressive clusters.

With climate change, it is projected that the frequency of the cluster types will also change. The assignment of projected weather days to TSI clusters was done in a similar manner to the initial calculation of the TSI clusters. Firstly, the projected weather under the climate-change scenarios was calculated. From these projected data, principal component scores were then calculated. The third step was to calculate the average Euclidean distance between each projected day and all of the initial TSI clusters. The projected day was assigned to the TSI cluster with which it had the smallest average Euclidean distance (Davis & Kalkstein 1990, Kalkstein & Smoyer 1993).

The predicted mortality rate above baseline for each projected oppressive cluster day was ascertained from the within-cluster regressions using the projected weather data. The rate was then multiplied by the projected population for 2030 to give the number of deaths.

2.7. Non-linear regression threshold models. Independent of the thresholds set for the observed-expected analyses, threshold models as given below were fitted to the data using non-linear regression (Ratkowsky 1983). The range of starting values for the constant, slope and threshold was determined from city/season specific averages.

Threshold model—summer:

$$(1)\ y = a1 \qquad x < t$$
$$(2)\ y = a1 + b2 \times (x - t) \qquad x \geq t$$

where y = crude daily mortality rate, x = maximum dry-bulb temperature, t = threshold, $a1$ = constant, $b2$ = slope.

Threshold model—winter:

$$(1)\ y = a2 + b1 \times (x - t) \qquad x \leq t$$
$$(2)\ y = a2 \qquad x > t$$

where y, x, and t are as above, $a2$ = constant, $b1$ = slope.

If a given model did not converge at a threshold, then linear regression over all the data in the season was used to determine if there was a linear relationship between mortality rate and temperature. If the slope from neither the threshold model nor the linear regression was significantly different from zero, we assumed that there was no relationship between mortality rate and temperature, and therefore no temperature-related (TR) deaths.

We defined the TR mortality rate to be the average of the predicted mortality rate above/below (depending on season) the threshold, minus the constant mortality rate below/above the threshold (the 'background' mortality rate).

If there was no threshold, we assumed that the 'background' mortality rate was as predicted by the regression model from below the minimum temperature in summer or above the maximum temperature in winter. This is likely to be an underestimate of the 'background' mortality rate, so we are probably overestimating the TR mortality rate. TR deaths were calculated by multiplying the TR mortality rate by the average population over the period. These daily deaths were then summed for all days above/below the threshold (or all days if no threshold) to given current season total TR deaths. Season total TR deaths in 2030,

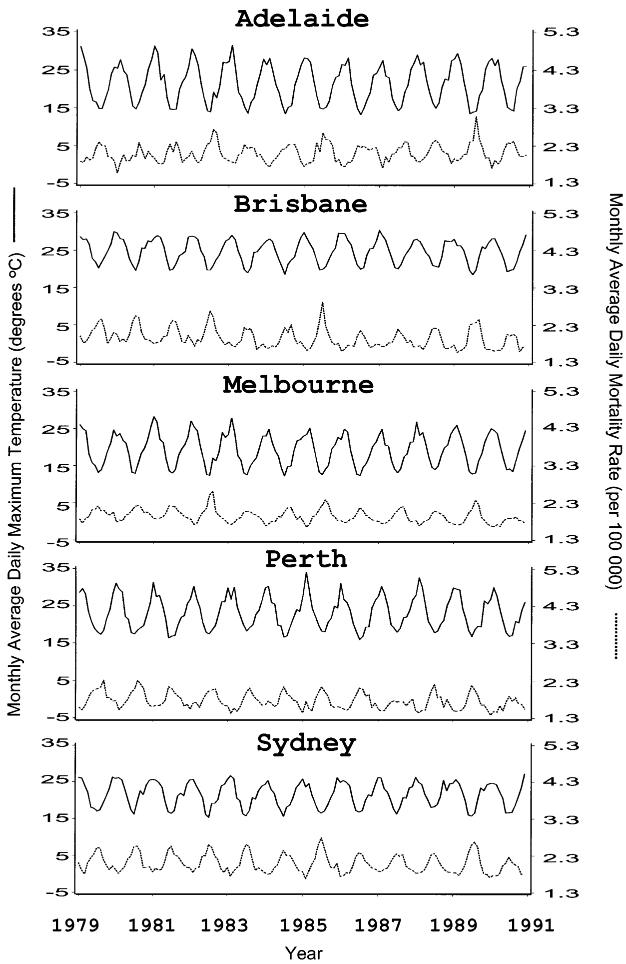

Fig. 2. Monthly average of daily maximum temperature (—) and mortality rate (------) by year

assuming no change in climate, were obtained in a similar fashion, this time multiplying by the 2030 population. Season total TR deaths in 2030 under the low/high climate change scenarios were calculated by adding the forecasted change in temperatures to current temperatures, then predicting the TR mortality rate from the threshold (or linear regression) model as above, multiplying by the 2030 population, and finally summing over all days above/below the threshold. Note that a change in temperature will alter the frequency of days above/below the threshold as well as the TR mortality rate per day.

3. RESULTS

3.1. Standardized mortality rates

The yearly standardized mortality rate declined over the 12 yr period for all 5 cities. Generally, Sydney had the highest mortality rates and Perth had the lowest. The standardized mortality rates for summer and winter also showed a decline for all 5 cities. Generally, Perth had the lowest mortality rates in summer, and Brisbane had the highest mortality rates in winter. Heart disease contributed the greatest numbers of deaths; only 86 deaths in the entire study period were classified as due to excessive heat or cold.

3.2. Temperature-mortality relationships

Monthly maximum daily maximum dry-bulb temperatures show that Brisbane and Sydney have narrower ranges of variation between summer and winter than the other 3 cities (Fig. 2). The seasonal nature of all-cause mortality, higher in winter than in summer, is apparent.

There was no apparent correspondence between mortality and temperature at the daily levels in any of

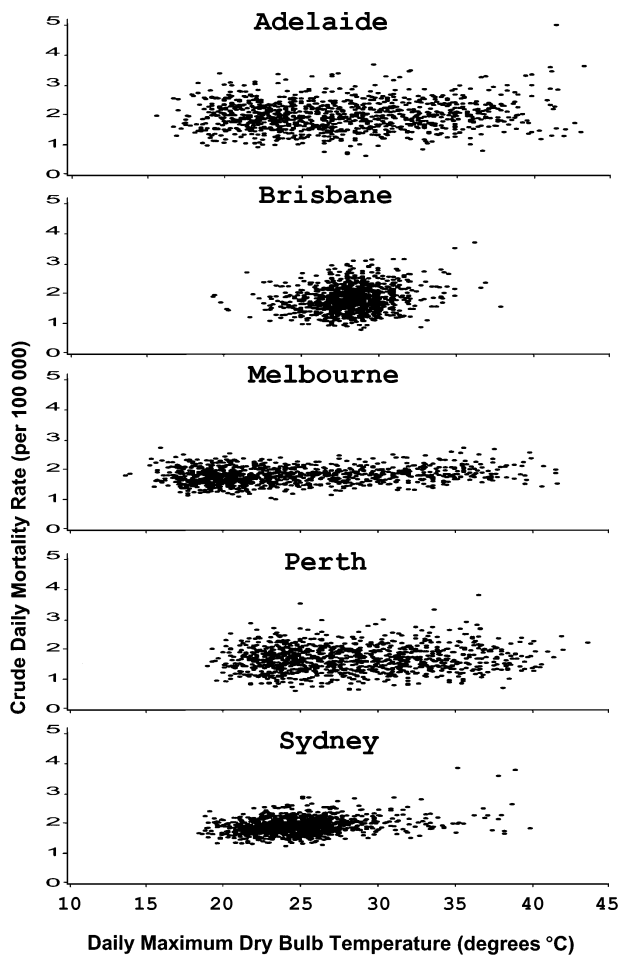

Fig. 3. Monthly rate, by maximum daily dry bulb temperature, by city

the 5 cities (Fig. 3). The same held for the other climate variables when all-cause mortality was considered for the whole population in each city. Nor did plots of restricted age groups or particular causes of death against different climate variables show any other obvious relationships.

A few outliers in Fig. 3 suggested relationships that required further investigation. Daily newspapers (local and national) were searched for reasons other than the weather that may have explained the high mortality of the outlier days. News reports noting heatwave conditions associated with health effects appeared in Sydney (6 to 11 January 1979, 9 to 10 January 1983) and Adelaide (24 January 1982), while news reports of heat or other explanations of the other outliers (Brisbane, 17 December 1979 and 7 December 1981; Perth, 24 February 1984) were not obvious from the sources available.

3.3. Comparison of observed and expected deaths

The excess mortality was calculated by summing the differences of observed and expected numbers of daily deaths for different thresholds of temperature over the summer months in each of the 5 cities separately, over the 12 yr of the study period (Fig. 4). The greater number of excess deaths with successively lower thresholds reflects the higher number of days exceeding the lower temperatures, together with the inclusion of the deaths that occurred at the higher thresholds. For example, the temperature-attributable deaths above the 40°C threshold are also counted in association with the 38°C and 36°C thresholds.

For the 5 cities combined, the excess number of deaths observed over the study period (compared with the expected number and attributable to temperature) was 699 for the 36°C threshold, an annual burden for the 5 cities of approximately 58 deaths. The burden was not shared equally (Fig. 4), although the differences were partly explained by the differences in population among the cities (mid-study period, approximate populations were Sydney 4 million; Melbourne 3 million; Adelaide, Brisbane and Perth, 1 million each). The greatest annual mean excess of deaths attributable to temperature over the period was 175, for the 28°C threshold, the sum of statistically significant differences from all cities. Comparison of mean differences showed that, in general, hotter days were associated with greater mortality risk (Fig. 5).

Compared with the summer extremes, there was less excess mortality associated with the coldest days in winter (Fig. 6). Statistically significant excesses were only found for Sydney, Melbourne and Brisbane where, in general, colder days were associated with greater mortality (Fig. 7).

3.4. Climatic extremes and socio-economic status

Correlation coefficients between the climatic variables and daily mortality rates were calculated, considering all days in the summer and winter seasons for the 5 cities. The correlations were weak (all < 0.3) when data from all days were included (data not shown). When the calculations were made with restriction to the 50 days with highest maximum temperatures in summer, and the 50 days with lowest minimum temperatures in winter, some of the coefficients were increased (Table 2). Thus, mortality effects were somewhat more apparent when the analyses considered only the climatic extremes. The coefficients were generally greater, and more often positive, during the summer months.

Comparisons of the correlation coefficients between mortality rates and the climatic variables between areas of high and low SES in summer and winter did not show that the response of mortality to climatic variables was modified by SES.

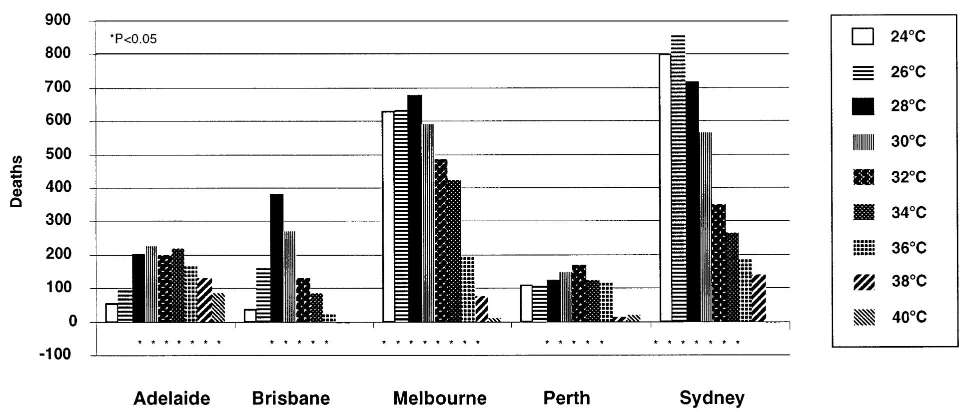

Fig. 4. Difference between observed and expected number of deaths, according to temperature thresholds 24 to 40°C in summer, by city, 1979–1990

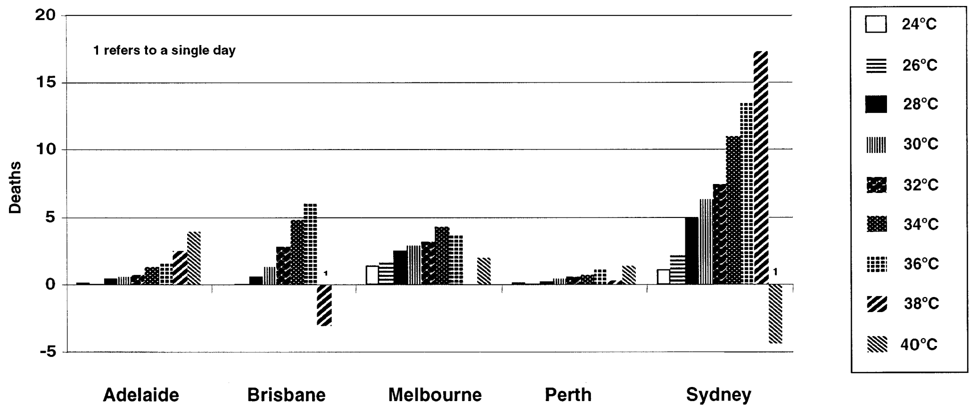

Fig. 5. Mean daily difference between observed and expected numbers of deaths according to temperature thresholds 24 to 40°C in summer, by city, 1979–1990

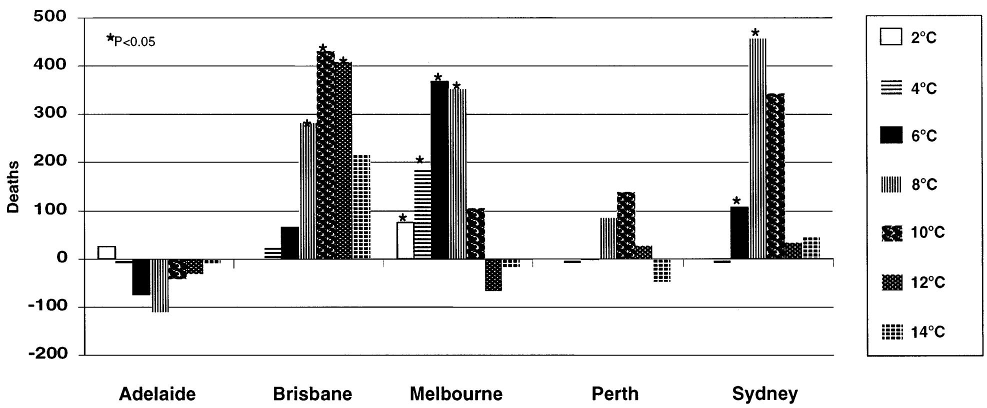

Fig. 6. Difference between observed and expected numbers of deaths, according to minimum temperatures 2 to 14°C in winter, by city, 1979–1990

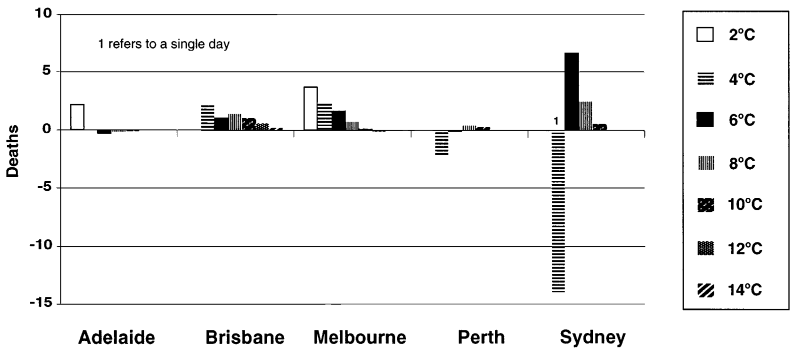

Fig. 7. Mean difference between observed and expected numbers of deaths according to minimum temperatures 2 to 14°C in winter, by city, 1979–1990

3.5. Temporal synoptic indices

In summer, all cities except Perth exhibited oppressive air mass types with climate-related deaths under current conditions. The average number of deaths each summer in the study period was 9 in Adelaide, 18 in Brisbane, 21 in Melbourne and 35 in Sydney, giving a total of 83. Most of these deaths occurred in persons aged 65 yr or older (Fig. 8, current deaths). The associated air masses had high dry-bulb and dewpoint temperatures, northwest winds and, except in Melbourne, below-average pressure.

In winter, all cities exhibited climate-related deaths under current conditions. For Adelaide, Brisbane, Melbourne, Perth and Sydney, 7, 11, 12, 10 and 37 deaths respectively were found on average each winter, giv-

Table 2. Correlations between daily mortality rate and climatic variables on the 50 days of extreme temperatures in summer and winter, 1979–1990. MAXTEMPD, maximum dry-bulb temperature (°C); MAXDEWPT, maximum dew point (°C); MAXTEMPW, maximum wet-bulb temperature (°C); MINTEMPD, minimum dry-bulb temperature (°C); MINDEWPT, minimum dew point (°C); MINTEMPW, minimum wet-bulb temperature (°C); AVGWNS, average north-south wind speed component (m s^{-1}); (N +ve, S –ve); AVGWEW, average east-west wind speed component (m s^{-1}); (E +ve, W –ve); AVGPRES, average pressure (hPa); AVGDCC, average daytime cloud cover (oktas), *$p < 0.05$

	Adelaide	Brisbane	Melbourne	Perth	Sydney
50 days of highest maximum dry bulb temperature in summer					
MAXTEMPD	0.11	0.25	–0.04	0.26	0.27*
MAXDEWPT	0.23	0.18	0.12	0.04	–0.17
MAXTEMPW	0.31*	0.29*	0.10	0.07	0.16
MINTEMPD	0.18	0.13	0.21	0.27*	0.36*
MINDEWPT	0.21	0.25	0.14	0.07	–0.02
MINTEMPW	0.24	0.26	0.07	0.19	0.07
AVGWNS	0.06	0.09	0.04	0.17	0.15
AVGWEW	–0.02	0.17	–0.08	–0.08	–0.19
AVGPRES	–0.55*	–0.10	0.11	0.13	–0.40*
AVGDCC	0.03	0.03	–0.02	0.10	0.18
50 days of lowest minimum dry bulb temperature in winter					
MAXTEMPD	0.05	–0.10	0.05	0.10	–0.23*
MAXDEWPT	–0.10	–0.03	0.03	0.00	–0.00
MAXTEMPW	–0.06	–0.14	0.04	0.03	–0.19
MINTEMPD	0.02	–0.13	–0.03	0.10	–0.09
MINDEWPT	–0.04	–0.08	–0.08	0.14	0.28*
MINTEMPW	–0.01	–0.16	–0.04	0.14	0.33*
AVGWNS	–0.02	0.03	–0.09	–0.00	0.02
AVGWEW	–0.10	0.02	–0.41*	–0.03	0.15
AVGPRES	–0.01	0.09	0.17	–0.17	0.07
AVGDCC	0.08	0.08	0.09	0.11	0.18

ing a total of 77. Again, most deaths were in the oldest age group (Fig. 9). The associated oppressive air mass varied between cities.

Considering the analyses for all causes of death directly associated with climate, with aggregation of summer and winter mortality, climate change in the year 2030 is projected to reduce total mortality by 41 to 62 deaths of a total mortality of 518, a decrease of 7.9 to 12.0 %, depending on the climate-change scenario considered (Table 3). Most of this change is found in the

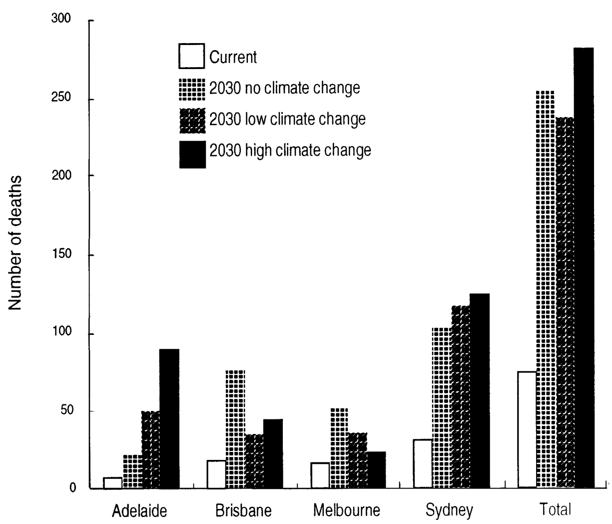

Fig. 8. Climate-related deaths in summer in persons aged ≥65 yr, current and projected to the year 2030, allowing for increased population and scenarios of climate change

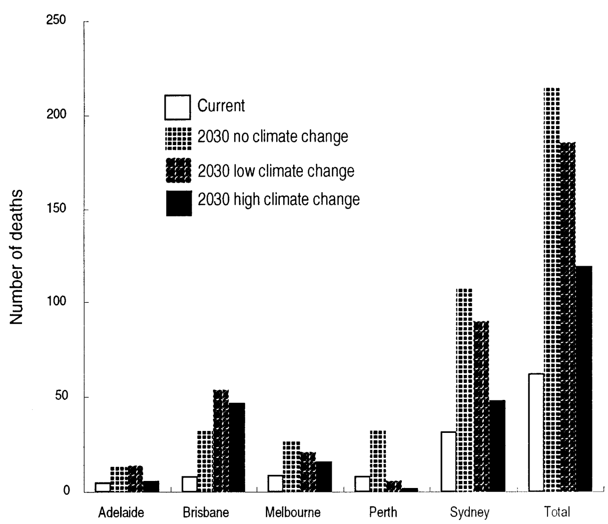

Fig. 9. Climate-related deaths in winter in persons aged ≥65 yr, current and projected to the year 2030, allowing for increased population and scenarios of climate change

Table 3. Mortality associated with climate (summer + winter): summary of analyses by temporal synoptic indices, with current total mortality and projected changes in mortality

Age-group (yr)	1979–1990: Annual mean	2030: Projected total[a]	Change[b] Low	High
0–4	11	11	3	4
5–19	4	5	4	3
20–49	3	16	1	1
50–64	6	17	–2	– 1
≥65	136	469	–47	–69
Total	160	518	–41	–62

[a]With allowance for aging and population growth
[b]Increase or decrease to projected total, according to low or high climate change scenarios

oldest age group (Table 3, Figs. 8 & 9). (The baseline in 2030 of 518 deaths is greater than at present because population increase and ageing are accounted for.)

In summer, Adelaide and Sydney showed an increase in climate-related deaths in persons aged 65 yr or older under projected 2030 conditions, while Brisbane and Melbourne showed a decrease (Fig. 8). All of the oppressive clusters for the oldest age group had above-average temperatures; in general, they also had below-average pressures and north-west winds. The Adelaide, Brisbane and Melbourne oppressive TSI clusters showed significant increases in mortality with increasing dry- or wet-bulb temperature. The apparently anomalous reductions in summer mortality in Melbourne and Brisbane (comparing high and low scenarios of climate change with the no climate-change scenario for 2030) are due to the reduction in northerly winds.

In winter, Adelaide, Melbourne, Perth and Sydney showed a decrease in climate-related deaths in those aged 65 yr or older in 2030, whereas Brisbane showed an increase (Fig. 9). The total decrease under the high climate-change scenario was 96 deaths. In general, the oppressive clusters for the oldest age group had below-average dew points; some clusters also exhibited below-average temperatures, below-average cloud cover or south-easterly winds. The apparently anomalous increase in mortality in Brisbane is explained by the increase in oppressive air masses due to the reduction in pressure and cloud cover, and the increase in south-easterly winds.

3.6. Non-linear regression models

The non-linear regression analyses showed that additional mortality is expected in summer, while some deaths may be avoided in winter. In the 5 cities, deaths (from all causes) were found to occur in summer in association with temperatures above city-specific thresholds (Fig. 10). In total, 401 TR deaths were calculated to occur each summer during the period 1979–1990, associated with the day of high temperature (in the case of Sydney), or on the day following (in Adelaide, Brisbane and Melbourne), or with a 2 d lag (for Perth). (This hypothetical result is simply achieved

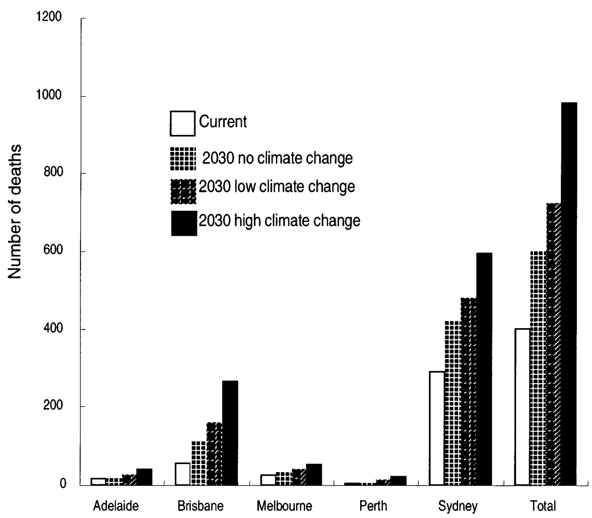

Fig. 10. Deaths associated with exceedances of city-specific temperature thresholds in summer, current and projected to the year 2030, allowing for increased population and scenarios of climate change

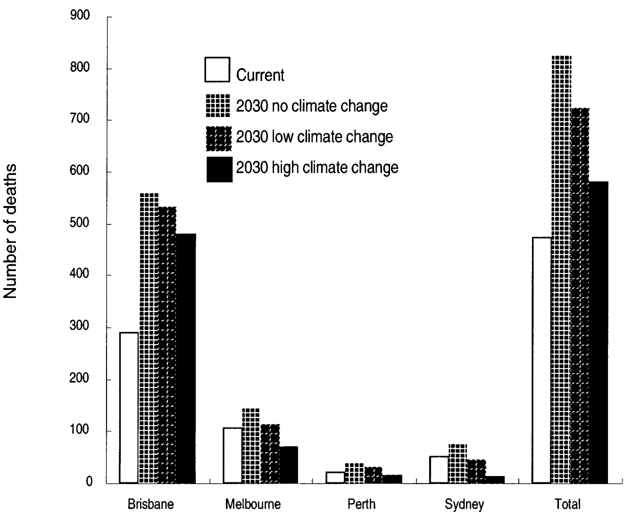

Fig. 11. Deaths associated with exceedances of city-specific temperature thresholds in winter, current and projected to the year 2030, allowing for increased population and scenarios of climate change

Table 4. Mortality (summer + winter): summary of threshold analyses by non-linear regression, with current total mortality and projected changes in mortality

Age-group (yr)	1979–1990: Annual mean	2030: Projected total[a]	Change[b] Low	Change[b] High
0–4	57	74	−3	−6
5–19	42	46	−2	−5
20–49	63	77	−3	−2
50–64	290	570	3	19
≥65	436	1317	17	203
Total	888	2084	12	209

[a]With allowance for aging and population growth
[b]Increase or decrease to projected total, according to low or high climate change scenarios

by addition of the numbers of deaths from the city-specific models, which are independent.) With climate change and population growth by the year 2030, the additional number of TR deaths is expected to be 122 (low climate-change scenario) or 390 (high scenario).

In winter (Fig. 11), 475 deaths now occur in association with temperatures below the thresholds identified, but by 2030, from 103 (low climate-change scenario) to 235 (high scenario) fewer deaths are expected to occur. Adelaide was the only city without any TR deaths in winter.

TR deaths, aggregates for summer and winter, total population and specific to age-groups, are summarised (Table 4). The most striking contribution was the occurrence of TR deaths in persons aged 65 yr and older in Sydney. The model suggests that above a threshold of 24°C between 76 (low climate-change scenario) and 239 (high scenario) additional deaths may be expected in the year 2030 due to climate change in Sydney in this age group while the number saved in winter (below a threshold of 8°C) is expected to be between 54 and 102.

4. DISCUSSION

4.1. Comparison of results, in a geographical and historical perspective

This project shows that in the 5 Australian cities, during the period 1979–1990, 160 deaths yr^{-1} occurred that were attributable to climate according to the TSIs, which we consider the most comprehensive method. According to the observed-expected method, 175 additional deaths occur annually, in association with days exceeding the 28°C threshold. After allowing for increases in population (but not for changes in the urban-rural distribution) that might occur, the TSI method showed an 8 to 12% decrease in mortality expected in the year 2030.

The non-linear regression analyses found a greater current mortality burden attributable to temperature, and small increases in mortality with climate change in the year 2030. As noted previously, the possibility that this method would overestimate the temperature-related mortality rate was considered before these analyses were undertaken. In view of the negative findings in the present study, we aimed to find a maximum mortality in the most theoretical analysis, the non-linear regression. We do not argue that there is a biologically plausible reason for the difference in lag-times among cities associated with the greatest mortality: those lags simply emerged from the analyses. The choice of standard lag-times of zero or 1 d produced less mortality.

By each analysis, based on the scenarios of regional warming during the next 3 decades, the expected changes in mortality are minor. Thus it appears that these independent approaches to climate-associated mortality give consistent results, although this study has not considered the less direct effects of climate change on health such as changes in vector-borne disease, which clearly also require investigation in Australia.

Air temperature alone is not a satisfactory indicator of heat stress, a fact that has stimulated the development of synoptic climatological procedures, as used here. This method can account for simultaneous changes in many meteorological variables, but studies also need to account for the human response of acclimatisation, which also determines the sensitivity of a particular location.

While relationships between temperature and mortality have been shown in these Australian cities, they are less obvious than in cities of low latitudes in developing countries, or cities of high latitudes in the USA (Kalkstein 1993). Acclimatisation, both physiological and artificial (by air conditioning), and relatively high socio-economic status, may explain the weak relationships in Australia compared with other countries. Thresholds for temperature-mortality effects vary regionally: they appear to be higher—or less evident—in warmer climates, and lower in cooler ones. Thresholds in this context are, however, simplifications in an ecological study design. An unknown proportion of deaths associated with temperatures above the threshold would be unrelated to climate, while many deaths associated with temperatures below the threshold may actually have a causal relationship with climate.

Since records of natural hazards began in the early nineteenth century in Australia, the number of deaths attributed to heatwaves—some 4000—has far exceeded that due to floods, lightning, cyclones, bushfires or earthquakes (Andrews 1994). In 1959 in Melbourne, 145 heat-related deaths were recorded, mainly amongst the elderly, during the heatwave when temperatures reached 42°C on 3 consecutive days (Rankin 1959). Between 1939 and 1968, extreme heat caused an estimated 44 deaths annually in Australia — more than the figure due to cyclones, bushfires and floods combined (Ewan et al. 1990). Faunt et al. (1995) reported on a 10 d period of exceptional heat in February 1993 from 4 major teaching hospitals in Adelaide. Among 94 patients with a heat-related illness, 78% experienced heat exhaustion, while 12% died. The current findings are consistent with reports based on shorter and more extreme periods.

4.2. Varying sensitivity of the cities

Differences in the climate-sensitivity between the cities were found. For Sydney, there were 6 significantly correlated variables (Table 2), compared with 1 or 2 for the other cities. This may be partly explained by the greater population of Sydney, with the greater likelihood of the number of deaths reaching significance, but the magnitude of some coefficients was also greater than in other cities. Air pollution, socio-economic differences, or local climatic (heat island) effects may account for the sensitivity in Australia's largest city, while Perth's lack of oppressive air masses in summer could possibly be explained by a greater availability of air conditioning or swimming pools, but data were not available to test these hypotheses. We caution against overinterpretation of these findings, however, which could arise from the problem of weak associations, multiple comparisons or chance.

We cannot predict with any certainty that Perth will not have climate-related deaths in the future because it appears free of them now. The changes predicted in the other 4 cities are due to changed characteristics in the oppressive air masses. Although population increase has been allowed for, additional factors may contribute to changes in mortality in due course.

The correlation coefficients revealed some paradoxes. While Brisbane has the highest mortality rates in winter, no correlation coefficients were statistically significant in winter. Rather than interpreting this effect as climatic, however, we again suggest the need for cautious interpretation.

Correlation coefficients are often found to be low in epidemiological studies; they suggest relationships but do not provide the contrasts of a single population under 2 different conditions, as properly required to measure effects of particular exposures (Greenland & Rothman 1998). In the present study, there were not many climate-related deaths. Correlation coefficients have not provided a sensitive index of climate-related mortality here.

4.3. Uncertainties and limitations

There are many sources of uncertainty in the present study. Quantification of the error from the TSI is allowed for by isolation of all days within the oppressive category, with subsequent investigation of how mortality varies within that category. Thus, any variation within the TSI category which contributes to variation in mortality is determined statistically. The TSI account for approximately 80% of the variance in the original dataset, a consistent proportion in the data from a variety of cities for which TSI have been calculated (Kalkstein et al. 1987).

The synoptic approach has shown how the day-to-day mortality is sensitive to air mass types (Greene & Kalkstein 1996), but it remains possible that mortality associated with climatic conditions summarised by the TSI may partly arise from confounding factors. Further validation of these methods through studies of the capacity of TSI for 'prediction' of mortality data already collected would be valuable.

TSI were used in this project as site-specific air-mass-based indices. Our objective was to study the 5 cities without inter-site comparison of the air mass types, rather than to undertake studies of mortality associated with continental-scale air mass types, in which case, spatial synoptic classifications may have been more appropriate (Kalkstein et al. 1996). Given the possibility of evolution of new oppressive clusters as the climate changes, the TSI method based on present climate-mortality relationships has limitations.

The climate-change scenarios used were revised after completion of this study, so the predictions of mortality in the year 2030 presented here must be considered provisional. Revised 'high climate change' scenarios were scaled down by up to 30% (CSIRO 1996) to allow for cooling due to sulphate aerosols and carbon dioxide fertilisation given by IPCC (Houghton et al. 1996). Scenarios beyond $2 \times CO_2$ have been considered, but have doubtful relevance to policy, given the generally short-term outlook of such activity (as noted in the methods above).

In our present study, we have looked for the possibility of changes in the daily frequency distributions of climate variables. One of us (K.H.) has examined the simulated changes in the frequency distribution of temperature. The change in standard deviation was negligible relative to the change in the average, so it is reasonable to assume no change in the shape of the frequency distribution of daily temperature. Since we applied GCM-based changes in average values to observed daily climate variables, the observed frequency distributions have only been shifted laterally, while the shape of the distribution (variance and skewness) remains intact.

Changes in rainfall variance are potentially critical because there is an increase in the frequency of extreme rainfall, and in some regions there is a decline in light rainfall. This stretches and flattens the rainfall frequency distribution. However, as far as our mortality analysis is concerned, there is little sensitivity to rainfall in 'oppressive airmasses'. This study shows that changes in rainfall frequency distributions are not likely to have a major effect on mortality in Australia. Other significant consequences for health, however, such as higher rates of water-borne infections resulting from contamination of drinking water supplies, were not accounted for here.

The possible influence of sea level rise in Australia on rural/urban migration has not been modelled in the present study. While rising sea-levels have been emphasised as a major effect of climatic warming, their impacts may be considerably less important than those generated by increased flooding of inland rivers and other extreme events (Bryant 1990). Given the continued economic decline of the rural sector in Australia, it is probable that a steadily increasing proportion of the Australian population will live in coastal cities, the opposite trend to that which might follow the rise of sea levels. In aggregate, we assumed that the proportions of urban and rural populations will not change in the next 4 decades.

What actually causes the additional mortality during the hot weather? Some of the excess mortality during a heatwave is probably attributable to coexistent increases in air pollution (Rooney et al. 1998). The proportion of air-pollution-attributable mortality would vary according to local conditions (Kalkstein & Smoyer 1993). The magnitude of this problem in Australian cities is probably less than in more densely populated areas.

Analysis of the health impact of the 1995 heatwave in Chicago showed the need to identify isolated, vulnerable people living in apartment buildings if heat-related mortality is to be abated (Semenza et al. 1996). Mortality increases more in cities than in surrounding rural areas. This reflects not only the urban 'heat island' effect (due to the concentration of heat-absorbing construction materials) but also the poverty and isolation of some neglected people who live in the city. However, we found little evidence for modification of the effect according to SES. This may be partly explained by greater social homogeneity in Australia, with less extremes of wealth and poverty in this country (Jain 1994) than in the USA, where the influence of SES on human vulnerability to climatic extremes has been identified (Semenza et al. 1996). It is possible that the most vulnerable groups may live in rural and remote areas of Australia. Studies are needed to assess climate-health hazards in settings where population density is lower, including research on the climatic and other environmental vulnerability of Aboriginal communities in Australia.

The role of acclimatisation in mitigating human response to extreme weather is not well understood. In particular, research is needed to show how acclimatisation affects human sensitivity to uncomfortable conditions (de Dear et al. 1998). In the longer term, minimum temperatures, rising in the latter half of this century faster than maximum temperatures, may be critical (Epstein 1997). Under extreme conditions, vulnerable sub-populations may lose the capacity to obtain relief from heatwaves because night-time temperatures fall insufficiently, but this was not apparent in the present study.

Climate-related mortality in Australian cities is currently most marked amongst the elderly, a pattern which our results suggest is likely to persist. This study has not identified, however, the extent to which these deaths are 'borrowed from the future' by only a short period of days or weeks. Potentially important moderating effects that have not been accounted for in the present study include social and behavioural changes that may change the vulnerability of populations to the direct effects of heat. Increased use of air conditioning and modification of housing design could also reduce the influence of climate on mortality in coming decades.

5. CONCLUSION

In the 5 largest Australian cities, during the period 1979–1990, 160 deaths yr^{-1} occurred that were attributable to climate according to the TSI. Neither this mortality nor the variation expected with long-term climate change is major, despite the various methods used in this project to identify the maximum expected mortality. Australia may be less prone to heat-related increases in mortality under current models of climate change than countries at higher latitude. The interaction between climatic factors, air pollution and human health and the development of early warning systems for climate-related health problems need further investigation. Education of the public with regard to the reduction of health hazards associated with heat and other climatic exposure remains important, as does the broader agenda for research and development in public health appropriate to the changing climate in this region (Hales et al. 1995). The applicability of TSI methods for the development of early warning systems in order to reduce the adverse effects of oppressive climatic conditions should also be considered.

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