REGIONAL CLIMATE CHANGE SCENARIOS FOR AUSTRALIA

Kevin J. Hennessy

1. INTRODUCTION

Small perturbations to the mean climate may produce relatively large changes in the probabilities of extreme events [1,2,3,4,5]. To determine the sensitivity of extreme temperature probabilities to greenhouse warming, a warming scenario was developed, based on the results of General Circulation Model (GCM) simulations. Although the reliability of climate model information on regional scales remains poor, the best possible advice on regional greenhouse impacts is in demand and must be provided through scenario development and sensitivity studies.

A detailed intercomparison of the results produced by 4 different GCMs has been performed by Grotch [6], for both control simulations (atmospheric CO_2 concentration of around 300ppm) and perturbation simulations (equivalent to doubled CO_2). The perturbation case represents the proposed situation expected by as early as the year 2030 due to the combined effect of increased levels of all greenhouse gases [7], though the thermal inertia of the oceans may delay the surface temperature response by a further 10-20 years. The models considered were developed by (i) the National Centre for Atmospheric Research (NCAR), (ii) the Geophysical Fluid Dynamics Laboratory (GFDL), (iii) the

Goddard Institute for Space Studies (GISS), and (iv) Oregon State University (OSU). MacCracken (personal communication) has provided results of the simulated increases in mean maximum and minimum surface temperatures due to a doubling of the current CO_2 concentration, for both summer and winter in Australia. The increase in maximum temperatures ranged from 0.9 to 4.8°C in summer and from 2.2 to 4.1°C in winter. The rise in minimum temperatures ranged from 3.0 to 3.8°C in summer and from 2.6 to 3.5°C in winter.

For the purposes of this sensitivity study, the temperature scenario for the year 2030 comprised a 3°C increase in the mean, maximum and minimum surface air temperatures in both summer and winter. It was also assumed for simplicity that the variance, autocorrelation and shape of the temperature frequency distribution at each station remained unchanged when the mean is increased. With these crude assumptions, the results cannot be taken as accurate predictions, but serve to highlight the order of magnitude of possible changes.

Going beyond such generalised climate scenarios, we can critically examine the results of particular GCM simulations to provide more detailed regional climate change scenarios. The confidence placed in scenarios based upon particular GCM simulations of the future climate under enhanced greenhouse conditions depends heavily on their ability to adequately simulate the present climate. Since models compute climate variables as area-averaged gridpoint values, validation of model results requires comparison with observed climatological values interpolated onto the same regular grid. Before irregularly-spaced climate station data are interpolated to grid values, the data quality should be tested and adjustments made where necessary.

2. EXTREME TEMPERATURES

The impact of a simulated 3°C greenhouse warming on the frequency of extreme temperatures has been analysed by considering the change in probability of hot summer (DJF) days and cold winter (JJA) days in the state of Victoria. 'Hot' days were defined as having a maximum temperature greater than or equal to 35°C and 'cold' days had a minimum temperature less than or equal to 0°C. Climate station records of daily maximum and minimum screen temperatures at 37 Victorian sites (Figure 1) were used to empirically calculate probability maps for each extreme event, under both the present climate and the warmer scenario. The perturbation scenario was simulated by simply adding 3°C to each daily temperature value at all stations. This is equivalent to calculating the frequency of summer maximum temperatures greater than or equal to 32°C and winter temperatures less than or equal to -3°C in order to represent the effect of a 3°C warming on the frequency of 'hot' and 'cold' days, respectively. Of course, greenhouse climatic changes may not be this simple in reality. Details of the calculations have been documented by Hennessy and Pittock [8].

Some probability values have been converted to an equivalent number of days per season by simply multiplying the calculated probabilities by the number of days per season. For example, a probability of 0.1 would be converted to 9 days per 90-day season.

Probability maps were plotted from surfaces fitted to data at the irregularly spaced climate stations. The surface-fitting procedure of Hutchinson and Bischof [9] uses Laplacian smoothing spline surfaces which are functions of two or more independent variables. In this case, a spline function of station latitude, longitude and elevation was fitted to the seasonal probability data sets. Mean elevation data were available on a regular 1/8° latitude x 1/8° longitude grid and were used in conjunction with fitted probability surfaces to evaluate probabilities on the elevation grid. Stations were weighted such that mean data values with longer periods of record tended to be fitted more closely than values with shorter periods of record.

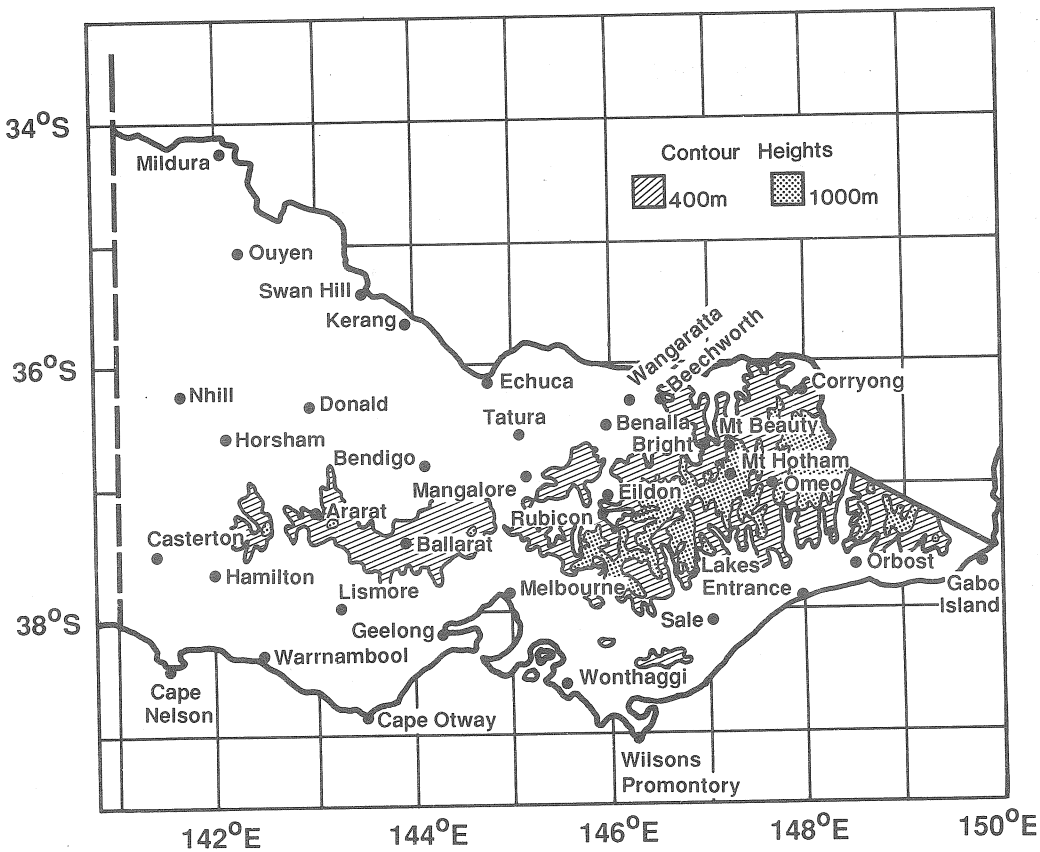

Figure 1. Map of Victoria, Australia, showing the geographical locations of 37 selected climate stations for which continuous records of daily maximum and minimum screen temperatures were available. Elevation contours at 400m and 1000m are shown to indicate the eastern highlands and western ranges.

Figure 2a shows that under present conditions, the contour for 10 summer days with maximum temperatures greater than or equal to 35°C covers the region north of the eastern highlands and most of the northwest of the state, while the 20-day contour is restricted to the far northwest. The southeast sector generally experiences fewer than 5 'hot' summer days, while the southwest lowlands have about 5-10 such days. With the proposed 3°C warming, Figure 2b shows that the 10-day contour would be shifted southward to the approximate position of the 5-day contour in Figure 2a, and the 20-day contour would cover most of the northern half of the state, except the eastern highlands. More than 10 'hot' summer days would also be found in a small region to the southeast of the highlands.

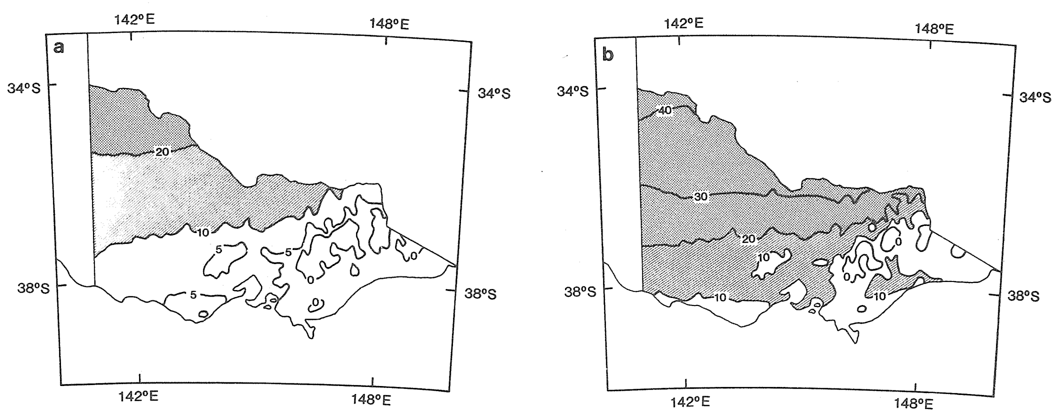

Figure 2. Contours of average number of days in summer (DJF) when daily maximum screen temperatures occur greater than or equal to 35°C (a) before and (b) after a 3°C uniform greenhouse warming.

Table 1 shows the change in frequency of 'hot' summer days for 1, 2 and 3°C warming scenarios at various Victorian stations. The non-linear response of the event frequencies to incremental warming is evident, and substantial changes occurred for only a 1°C increase at some stations.

Table 1: The effect of a 1, 2 or 3°C mean greenhouse warming on the average number of summer (DJF) days with maximum temperatures greater than or equal to 35°C at 37 sites in Victoria.

Station	Summer $T_{max} \geq 35$ with warming of			
	0	1	2	3 (°C)
Ararat	6	8	11	15
Ballarat	4	6	8	10
Beechworth	2	4	7	11
Benalla	13	18	24	32
Bendigo	9	12	17	21
Bright	7	11	15	23
Cape Nelson	2	3	4	4
Cape Otway	2	2	3	4
Casterton	9	12	15	18
Corryong	12	17	23	30
Donald	13	17	22	27
Echuca	17	21	26	32
Eildon	7	10	14	19
Gabo Island	0	0	0	0
Geelong	8	9	11	13
Hamilton	6	8	11	14
Horsham	15	19	23	28
Kerang	19	24	29	35
Lakes Entrance	3	4	5	6
Lismore	8	10	13	17
Mangalore	11	14	19	24
Melbourne	8	10	13	15
Mildura	23	27	33	38
Mt. Beauty	7	9	14	19
Mt. Hotham	0	0	0	0
Nhill	16	20	24	29
Omeo	2	3	5	9
Orbost	6	7	10	13
Ouyen	25	29	34	40
Rubicon	0	1	1	2
Sale	4	6	7	9
Swan Hill	20	24	30	37
Tatura	9	12	17	22
Wangaratta	15	20	26	33
Warrnambool	5	6	7	8
Wilsons Prom.	1	1	2	3
Wonthaggi	4	5	7	9

In terms of absolute increases, there were 12-19 more 'hot' summer days in the northern half of the state, except at highland stations above 500m [10]. At coastal sites, the increase was about 2-7 days.

Figure 3a shows that at present, the contour for 20 winter days with minimum temperatures less than or equal to 0°C is restricted to the northeastern sector of the state, with most of the eastern highlands having in excess of 40 days. Under a 3°C warming, Figure 3b shows that the region with more than 10 'cold' winter days would contract to higher elevations that formerly received at least 20 such days. Only the highest alpine areas would receive more than 20 'cold' days in the warmer conditions. Regions to experience greatest reduction in 'cold' winter days would generally be those in and adjacent to the highlands.

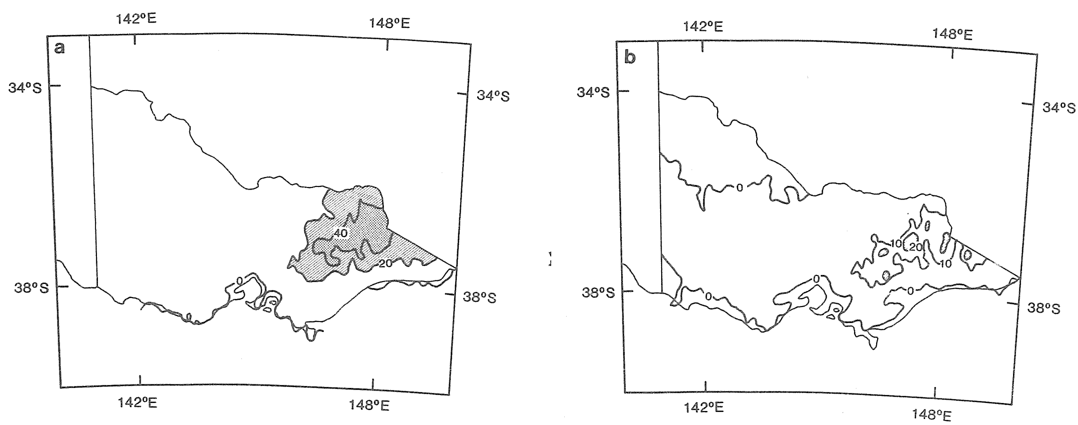

Figure 3. Contours of average number of days in winter (JJA) when daily minimum screen temperatures occur less than or equal to 0°C (a) before and (b) after a 3°C uniform greenhouse warming.

Table 2 shows the change in frequency of winter days with temperature minima less than or equal to 0°C at various Victorian stations. Even for a 1°C warming, the chance of sub-zero minimum

Table 2 : The effect of a 1, 2 or 3°C mean greenhouse warming on the average number of winter (JJA) days with temperature minima less than or equal to 0°C at 37 sites in Victoria.

Station	Winter $T_{min} \leq 0$ with warming of			
	0	1	2	3 (°C)
Arararat	14	9	6	4
Ballarat	9	5	2	1
Beechworth	18	9	3	1
Benalla	18	11	5	1
Bendigo	6	3	1	0
Bright	31	21	14	7
Cape Nelson	0	0	0	0
Cape Otway	0	0	0	0
Casterton	7	4	2	1
Corryong	27	17	9	4
Donald	8	4	2	1
Echuca	9	5	2	1
Eildon	11	6	2	1
Gabo Island	0	0	0	0
Geelong	2	1	0	0
Hamilton	9	5	3	1
Horsham	7	4	2	1
Kerang	6	2	1	0
Lakes Entrance	1	0	0	0
Lismore	4	1	1	0
Mangalore	13	6	2	1
Melbourne	1	0	0	0
Mildura	4	1	0	0
Mt. Beauty	21	11	4	1
Mt. Hotham	82	74	61	48
Nhill	10	6	3	1
Omeo	45	35	25	15
Orbost	3	1	0	0
Ouyen	6	2	1	0
Rubicon	9	2	0	0
Sale	12	6	3	1
Swan Hill	4	1	0	0
Tatura	17	9	4	2
Wangaratta	18	11	5	1
Warrnambool	1	0	0	0
Wilsons Prom.	0	0	0	0
Wonthaggi	2	1	0	0

temperatures is significantly reduced. A 1°C warming produced 10 fewer 'cold' winter days at Bright, Corryong, Mt. Beauty and Omeo, all in the northeast of the state. Warming in excess of 1°C appeared to have greater absolute effect at higher elevations. For a 3°C warming, the number of 'cold' days decreased from 82 to 48 at Mt. Hotham (elev. 1750m), and from 45 to 15 at Omeo (elev. 677m). At non-alpine stations in central and northeast Victoria, there were 15-24 fewer 'cold' days, with smaller changes in western and coastal areas. Assuming that frost occurrence is associated with sub-zero screen temperatures, the winter frost-free period would be extended by 15-24 days at many inland stations, with larger increases in the highlands. The frost-free season would lengthen further if the temperature variance declined.

The change in the frequency of runs of extreme temperatures, such as heat waves, is likely to occur more rapidly than for single daily extremes [8].

3. IMPACT OF CHANGED FREQUENCY OF EXTREME TEMPERATURES

Plants and animals, including humans, currently living in marginal conditions would be the first affected by the changed frequency of extreme temperatures. The increased frequency of 'hot' summer days, assuming no precipitation change, would raise the demand for irrigation in response to higher evapotranspiration, alter the seasonal discharge of rivers fed by snow-melt, boost tourism in the extended warm season, and lengthen the growing season and shorten the maturation time for some crops. The design of structures would need to incorporate higher heat tolerances in order to cope with conditions outside the range of past experience. Heat waves would become more likely, enhancing bushfire potential and increasing heat stress to sensitive stock and crops.

The reduced frequency of sub-zero minimum temperatures would imply an extension of the frost-free season, which would benefit most crops except those with high winter chilling requirements [10], and allow the introduction of new subtropical varieties, provided sufficient water is available. Threshold altitudes for pasture production would increase as snow risk was reduced, but the ski industry would suffer. Disease, pests and weeds may extend further south and to higher elevations with the reduced occurrence of cold days [11]. Seasonal energy consumption would be altered by increased summer cooling requirements and reduced winter heating demands.

The change in ecological elevation and latitude bands will favour some species at the expense of others. Major dislocation of species and communities may lead to extinctions due to elimination of habitats, competitive exclusion, predation, parasites or disease [11].

It was assumed, due to the uncertainty of regional scale predictions, that precipitation, cloudiness, soil moisture, humidity, ocean currents and atmospheric circulation patterns remained unchanged, but it is acknowledged that agricultural impacts will be in part determined by these factors. The timing of the proposed scenario will depend on the rate at which CO_2 and other greenhouse gas concentrations increase (which largely depends on human intervention), and on the thermal lag of the oceans relative to the land.

Since this study has been limited to analysis of temperature alone, and many simplifying assumptions have been made about the characteristics of the temperature change, these results should be used with caution and interpreted as estimates of the order of magnitude of possible changes rather than as accurate predictions. Changes in the shape of the frequency distribution of daily temperatures and autocorrelation have not been considered in this study, but can theoretically enhance or suppress the response of extreme event probabilities to a change in the mean [1].

4. THE SHAPE OF THE TEMPERATURE FREQUENCY DISTRIBUTION

The shape of the temperature frequency distribution is characterised by its mean, variance and skewness. At a given site, the shape of the distribution for a single season may be strongly influenced by local climatic factors, such as rainfall, soil moisture, wind direction and cloudiness.

Pittock et al [12] used a GCM to simulate the climatic effects of an elevated smoke layer, and found bimodal distributions of January maximum temperature at two model gridpoints in Australia. At these points, analysis of 100-day time-series of temperature and soil moisture showed that the warmer temperature peak corresponded to relatively dry soil, with lower evaporative heat-loss, while the cooler peak corresponded to relatively moist soil, with a higher evaporative heat-loss. It was concluded that extended periods of moist soil followed by relatively long spells of almost dry soil accounted for the bimodal temperature distribution. This soil moisture behaviour may have been an artifact of the crude 1-layer "bucket" surface hydrology scheme used in the model, which is considered to produce a surface temperature response less realistic than that derived using a 2-layer scheme, with a thin surface layer [13]. However, the model of Pittock et al [12] served to highlight the link between changes in surface temperature and changes in rainfall, via soil moisture and evaporation.

At a grid-point in Northern Australia with a strongly bimodal temperature distribution, the reduction in insolation due to the smoke layer caused a marked change in the shape of the histogram, with both peaks occurring at lower temperatures. However, the average temperature did not change because the warmer of the two temperature peaks, corresponding to drier soil, increased in frequency. There was a 2°C decline in the upper quartile temperature in response to reduced insolation when the soil was relatively dry, but the average temperature hid this effect due to the reduced frequency of wetter soil conditions. This example illustrates that the shape of temperature frequency distributions may not be well reflected by changes in the average temperature.

Observational data support the existence of bimodal distributions in nature [14]. Time-series of daily maximum temperature and precipitation at Mildura, Victoria, show that warmer temperatures occurred during dry spells and cooler conditions corresponded to periods of rainfall (Figure 4). The rainfall spike for a given day represents total rainfall in the 24 hours to 9am that day, ie. rainfall for last 15 hours of the previous day plus the first 9 hours of the current day. The rainfall events in Figure 4 appear to lag the fall in maximum temperature by a day, but since the net rainfall refers more to rainfall on the previous day than on the current day, the coolings are actually synchronous with rainfall events. Of course, increased cloud cover would be associated with rainfall, and a change in wind direction would occur with the passage of a rain-bearing cold front, so rainfall alone cannot distinguish the dominant mechanism for surface cooling. Coolings on days 12 and 15 do not appear to be related to rainfall events, so changes in cloud cover or wind direction may have been responsible.

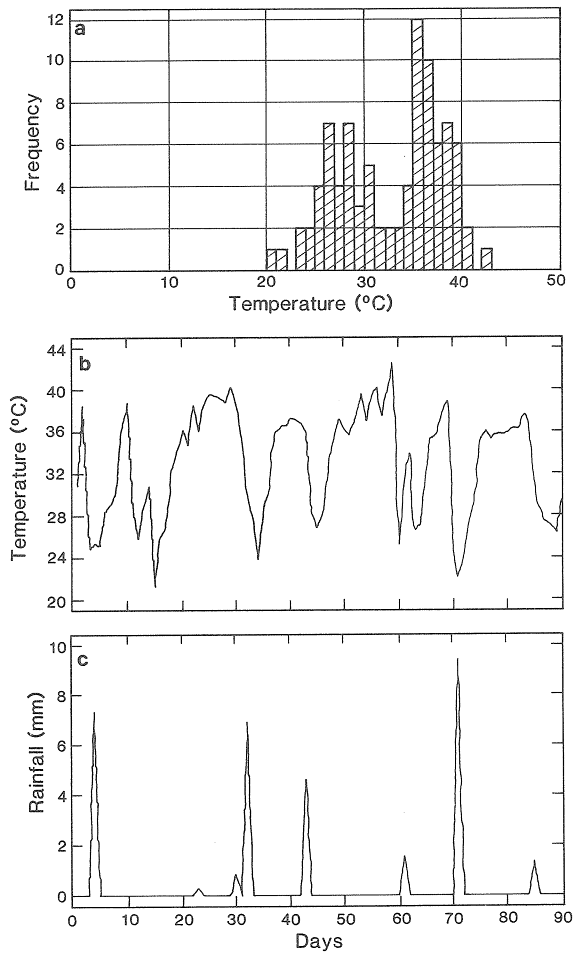

Figure 4. (a) Frequency distribution of daily maximum screen temperatures at Mildura (Vic.) from December 1960 to February 1961, and the corresponding time series of (b) maximum screen temperature and (c) daily rainfall.

Figure 5 shows that for Halls Creek in W.A., a period (Jan-Mar, 1965) of low rainfall (217mm), during which soils tended to be drier and cloud cover was reduced, tended to have higher average daily maximum temperatures than a wetter period (Jan-Mar, 1967, with 520mm) when soil moisture was higher and evaporative cooling was greater. Note that the skewness of the histogram is positive in the wetter period and negative in the drier period. The resulting change in the frequency of extremes is therefore very different to what would be expected from a simple translation of the histogram to the left or right, without any change in shape.

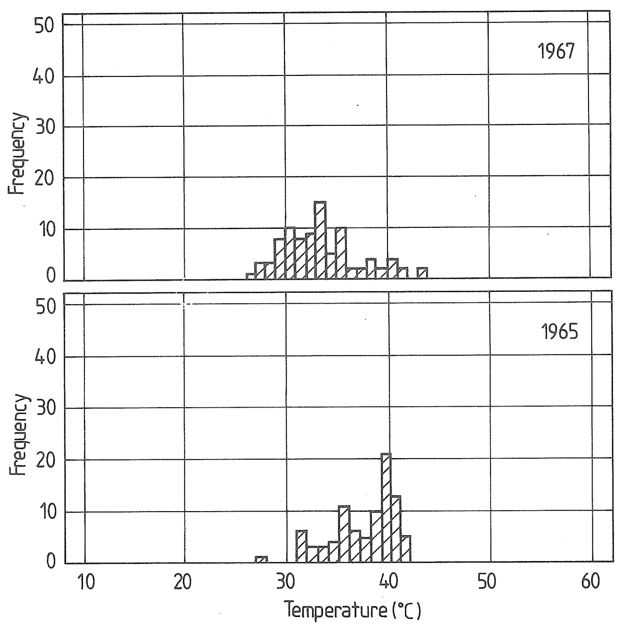

Figure 5. Frequency distribution of daily maximum screen temperatures at Halls Creek (W.A.) during (top) Jan-Mar of 1967, when the total rainfall was 520mm and the average maximum temperature was 33.7°C, and (bottom) Jan-Mar of 1965, when the total rainfall was 217mm and the average maximum temperature was 37.5°C.

Intuitively, we might think that rainfall, via the influence of soil moisture on evaporative cooling, may largely determine the skewness of histograms of daily maximum temperature. It is planned to correlate skewness with parameters such as net rainfall, number of raindays, average temperature, soil moisture and cloudiness where data are available, for a variety of stations, years and seasons.

Mearns et al [1] found that the effect of a change in the variance may be as important as a change in the mean temperature in determining the change in the frequency of extreme temperatures. Therefore it is also of interest to seek relationships between temperature variance and the parameters mentioned above.

The shape of temperature histograms can also be approximated as a binormal distribution, defined by three parameters. Toth and Szentimrey [15] describe this distribution as being similar to a normal distribution both above and below its mode (most frequent value), but the standard deviations on either side of the mode are different. The three parameters are the mode, and both standard deviations, and since the binormal distribution has a density function, the probability for a given interval can be calculated. So, changes in other climate variables could be related to changes in the shape of temperature histograms, via analysis of changes in the three parameters which characterise the binormal distribution.

If significant relationships can be found between the shape of temperature histograms and certain climatic variables, these may be useful in further sensitivity studies, in testing the performance of GCMs which incorporate a diurnal radiation cycle, and indeed in inferring changes in the frequency of extremes from simulations which do not include a diurnal cycle.

5. INHOMOGENEITIES AND URBAN BIAS IN OBSERVATIONS

Greater interest is focussing on regional climate change, so it is important that observed climate data be adjusted for the effects of urbanisation and any discontinuous inhomogeneities due to non-climate factors, such as site relocations or new instrumentation. Mitchell et al [16] and Karl and Williams [17] have described methods for various meteorological variables which isolate and adjust for station inhomogeneities using station history information and comparison with neighbouring homogeneous stations. The methods require accurate and complete station history information and comparison with neighbouring stations unaffected by urban bias.

The detection of urban bias in temperature records has been discussed in detail by Karl et al [18]. Urbanisation, as measured by population growth, was related to an increase in the diurnal range, and daily minima and mean temperature in all seasons. It is recognised that the use of population as a surrogate for urbanisation is not ideal, but parameterisation of the microclimate of each station is a major obstacle.

Karl et al [18] arbitrarily defined non-urbanised rural stations as those U.S. sites with a 1980 population below 2000, and urban-rural station pairs were chosen if spaced 30-100km apart. Correction was made for the additional non-urban sources of variability between pairs introduced by differences in latitude and elevation. Regression equations were then determined for each of the seasonal temperature variables, as an exponential function of population.

Tapp (personal communication) has performed a similar analysis for just six urban-rural pairs in Australia. The urban stations were all capital cities and "rural" stations were defined as their associated airports. The regression equation relating population to annual average daily minimum and mean temperature had a different exponent (.30) to that derived in the U.S. study (.45). An analysis of the rate of change of heat island intensity (urban-rural temperature difference) and associated trends in both population and meteorological variables suggested that the latter were more influential than population. However the limited sample size and the use of airports as non-urban "rural" sites introduces considerable uncertainty. Meaningful results can only be obtained from a study of similar complexity to that by Karl et al [18].

Examination and correction of the historical climate record will provide a firmer basis for detecting future climate changes and for validation of model simulations of the present climate.

6. VALIDATION OF GCM SIMULATIONS

An important test of the performance of a GCM is its ability to simulate the present climate. Indeed, an ability to give an acceptable representation of the present climate must be regarded as a necessary, but not sufficient, condition for using the results of a GCM simulation of enhanced greenhouse conditions as a basis for predictions.

The horizontal resolution of the four models considered in Section 2 varies from 4°x5° lat/long (OSU) to 8°x10° lat/long (GISS). With gridpoints spaced 500-1000km apart (Figure 6), the representation of topography, coastlines, vegetation and soil types is greatly simplified. In order to develop more-detailed regional greenhouse scenarios for Australia, it is proposed to drive a mesoscale model, with a grid-resolution of 50-200km, nested within an Australian GCM. Validation of simulations of the current climate in the Australian region will require comparison with a climatology that has been interpolated from climate station data onto a regular grid, with appropriate smoothing compatible with the GCM spatial resolution.

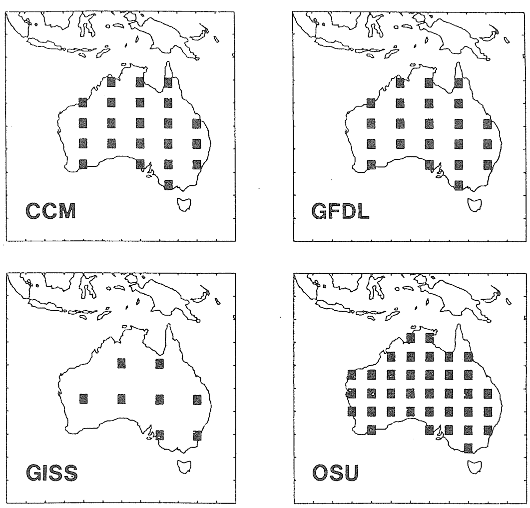

Figure 6. Gridpoint locations over Australia in each of four different global climate models (see text for details).

Interpolation of irregularly spaced data to a regular grid can be performed by three general types of analysis: empirical interpolation, statistical interpolation, and surface fitting [19]. In both empirical and statistical methods, the grid values are calculated from a distance-weighted sum of the data. However, the weighting function is usually predetermined for empirical interpolation, while statistical methods use weights that are based on statistics of spatial covariance of the data. Bussieres and Hogg [19] found that for the interpolation of daily rainfall data, the statistical technique was more suitable than three other empirical methods, which displayed larger errors away from the observing stations.

The surface fitting method of Hutchinson and Bischof [9] represents a substantial improvement over previously available subjective, least squares polynomial and weighted interpolation methods. Estimation of a spatial covariance function is not required, although a smoothing parameter must be estimated [20]. It works well regardless of how irregularly the data points are distributed and is not subject to erratic behaviour away from the data points. Fitted surfaces may be a function of two or more independent variables (eg. latitude and longitude), and data sets can contain up to a few thousand points. For the interpolation of meteorological data, especially temperature, it is critical to incorporate elevation as a third independent variable. In this regard, the surface fitting method of Hutchinson and Bischof [9] is clearly superior to two-dimensional interpolation methods.

The National Climate Centre archives meteorological data from climate stations with specified latitude, longitude and elevation. Given that Australian elevation data is also available on a regular grid of 1/16°x1/16° lat/long resolution, it would be possible to derive a climatology of various meteorological variables on the same grid, using the surface fitting method of Hutchinson and Bischof [9]. This would provide a useful tool for validation of both course-resolution GCM climatologies and finer-resolution climatologies from mesoscale models nested within GCMs.

However, the GCM representation of surface topography is highly smoothed, and the gridpoint values generated by the GCMs relate in some sense to the surrounding grid-box sized areal average. It is not clear that this relationship is the same for temperature as it is for rainfall, and furthermore the realism of the topography differs greatly between gridpoint-based GCMs and those which use spectral representation. These considerations pose serious problems as to how observed climatological data should be interpolated to GCM gridpoints.

7. FUTURE RESEARCH

Sensitivity analyses of daily maximum and minimum screen temperatures show that warmings of the order envisaged over the next several decades will have substantial effects on the frequency of extreme temperatures, with serious implications for agriculture, human health, fire regimes and ecology. This highlights the need for better regional predictions, not only of changes in the mean temperature but of changes in minimum and maximum temperatures.

Changes in the frequency of extremes of other less well-behaved or more complex variables such as rainfall, coastal flood levels, wave heights and fire danger indices will also be of great practical importance. These involve complex statistical considerations which will require much effort to satisfactorily deal with.

The Exceedance Probability Method of Middleton and Thompson [21] may be useful in estimating return periods of any partly deterministic process from data records spanning as few as 5 years. A simple extension of this method has been applied to a 5-year record of Sydney tide gauge data (Middleton, personal communication). An assumed sea-level rise of 30cm over the next 50 years reduced the return period of a 105cm surge from 100 years to 20 years. This was further reduced to 10 years with a superimposed increase in storm activity (increase in surge variance by 40%).

However, Klemes [22] warns of the dangers of making a statement about high extremes based on a statistical model fitted to a short record, especially in view of the increasingly apparent non-stationarity of the climate signal. It is suggested that more would be gained by the study of physical mechanisms responsible rather than extrapolating the tails of "best-fit" distributions. This highlights the real need for a rigourous theory on extrapolation of extreme event probabilities when frequency distributions change.

It is hoped that significant progress will be made in the next few years in climate modelling, including the generation of long time-series of diurnally varying climatic variables for analysis. However, a major uncertainty arises from the possibility of changes in ocean circulation, which are only now beginning to be studied and modelled. The first of such studies with coupled atmosphere-deep ocean models already suggests the possibility of multiple quasi-stationary states [23], which introduces a whole new level of complexity.

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CSIRO Division of Atmospheric Research
Private Bag No. 1,
Mordialloc, Victoria, 3195
Australia