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Australian Surface Temperature Corrections for Thermal Modelling

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ABSTRACT

For any temperature modelling it is important to have robust thermal gradient data upon which to build an interpretation. In many cases this data can be taken from a continuous temperature log, particularly when using data specifically collected for geothermal exploration. However, in Australia there are a large number of discrete downhole temperature measurements from other sources (eg Holgate and Gerner, 2010). To make the best use of this data it is necessary to have established surface temperatures from which to calculate an overall temperature gradient. On an even broader scale Beardsmore et al. (2010) identify creating a robust surface temperature map as one of the steps in estimating global Enhanced Geothermal System (EGS) potential. The ground surface temperature is also an important boundary condition when building a 3D thermal model whether on a continental or regional scale to characterise the broad thermal regime or at smaller scales for geothermal exploration.

Importantly, ground surface temperature refers to the temperature in the top layer of the rock or soil which in Australia is usually warmer than the average air temperature. Howard and Sass (1964) extrapolated surface temperature from 11 near surface gradient readings distributed across Australia (seven of which were in the Yilgarn province of Western Australia) to calculate a mean difference of +3° C relative to the air temperature across the whole of Australia. This value has been widely relied on since (eg. Beardsmore and Cull, 2001).

To provide the greatest spatial coverage of the continent, extrapolated surface temperature data from more than 100 wells logged by Geoscience Australia and soil temperature data at 1 m depth collected by the Bureau of Meteorology have been used to test the assumption that the +3° C correction is appropriate for the whole continent. Mean annual maximum temperature and the mean annual minimum temperature grids (Bureau of Meteorology) were used to calculate a mean annual average air temperature grid to which the soil temperatures and the extrapolated surface temperatures were compared.

The average of the differences between the air temperature and the ground surface temperatures is broadly consistent with the value determined by Howard and Sass (1964); however when examined in a spatial context it is apparent that there are a number of factors influencing the difference between the air temperature and the ground surface temperature that are unaccounted for if using an average value. A map of the variation in the difference between the air temperature and the ground surface temperature has been produced at Geoscience Australia. The new work can be used as a guide for corrections when working with subsurface temperature data.

1. INTRODUCTION

The temperature measured in the top layer of the rock or soil is generally higher than the average air temperature. Howard and Sass (1964) extrapolated surface temperature from 11 near surface gradient readings to calculate a mean difference of +3° C relative to the air temperature across the whole of Australia. This value has been relied on since and continues to be used at regional or greater scales (eg. Middleton, 1979; Cull and Conley, 1983; Somerville, et al 1994; Beardsmore and Cull, 2001; Beardsmore 2004). Smaller scale studies have noted different values for the difference between the average air temperature and the observed surface temperature taken for temperature logs, but this is documented only on a local scale (e.g. Beardsmore, 2005).

There have been several attempts to characterise the thermal regime of the Australian crust. Early attempts (e.g. Sass and Lachenbruch, 1979, Cull & Conley, 1983) using heat flow determinations were limited by data coverage with only around 100 heat flow determinations available for the whole continent and little likelihood at the time of that being improved by any meaningful amount. This led Somerville et al. (1994) to take a different approach and utilize discrete bottom-hole temperatures largely drawn from open-file petroleum industry well completion reports. While the method they employed had other limitations and the distribution of the data was less than ideal, the amount of data available for this was much larger than the number of available heat flow determinations with approximately 5000 wells between the onshore and offshore data. Somerville et al. (1994) utilized the bottom-hole temperatures with a surface temperature layer to calculate the average thermal gradient for each location. A 3 °C correction was applied to the air temperature based on Howard and Sass (1964). Subsequent efforts by Chopra and Holgate (2001) and Gerner and Holgate (2010) were both based on similar approaches and both treated the surface temperature in the same way by applying the 3 °C correction to the air temperature.

With greater amounts of data becoming available through programs such as Geoscience Australia's temperature logging operations it became apparent that there are more accurate ways to apply the surface temperature correction. When working at the lease and prospect scale, ideally a locally derived correction should be applied but this becomes unrealistic when considering larger regional and continental scales.

A new estimation of the difference between the air temperature and the ground surface temperature has been developed at Geoscience Australia by combining new borehole log temperature data with existing data measured in the top layer of the earth at meteorological stations from the Australian Bureau of Meteorology. This new temperature correction information can be applied at large scales or used as a guide or starting point prior to local data collection.

2. DATA

To provide the greatest spatial coverage of the continent this study used extrapolated surface temperature data from more than 100 wells logged by Geoscience Australia and soil temperature data at 1 m depth collected by the Bureau of Meteorology (Figure 1). While very similar the two datasets are not perfectly comparable and they display some discrepancies that are likely due to the differences in the methods for measurement and the processing of the data. For example, uncertainties are introduced in the extrapolated surface temperatures when choosing which part of the temperature log to extrapolate back to the surface. Similarly, the extrapolation of the log is conducted with the assumption that there is no variation in thermal gradient in the top section of soil or rock whereas in reality variations in the thermal conductivity of the upper layers of soil will lead to minor variations in the thermal gradient that would therefore introduce uncertainties in the extrapolated surface temperature. This lack of direct comparability in the two datasets is less than ideal however neither dataset has the required spatial coverage to base an interpretation on alone. For example there are no logs available from boreholes any further north than about 19° 34' S and the temperature logs fill some of the gaps between the soil temperature measurements particularly in inland areas.

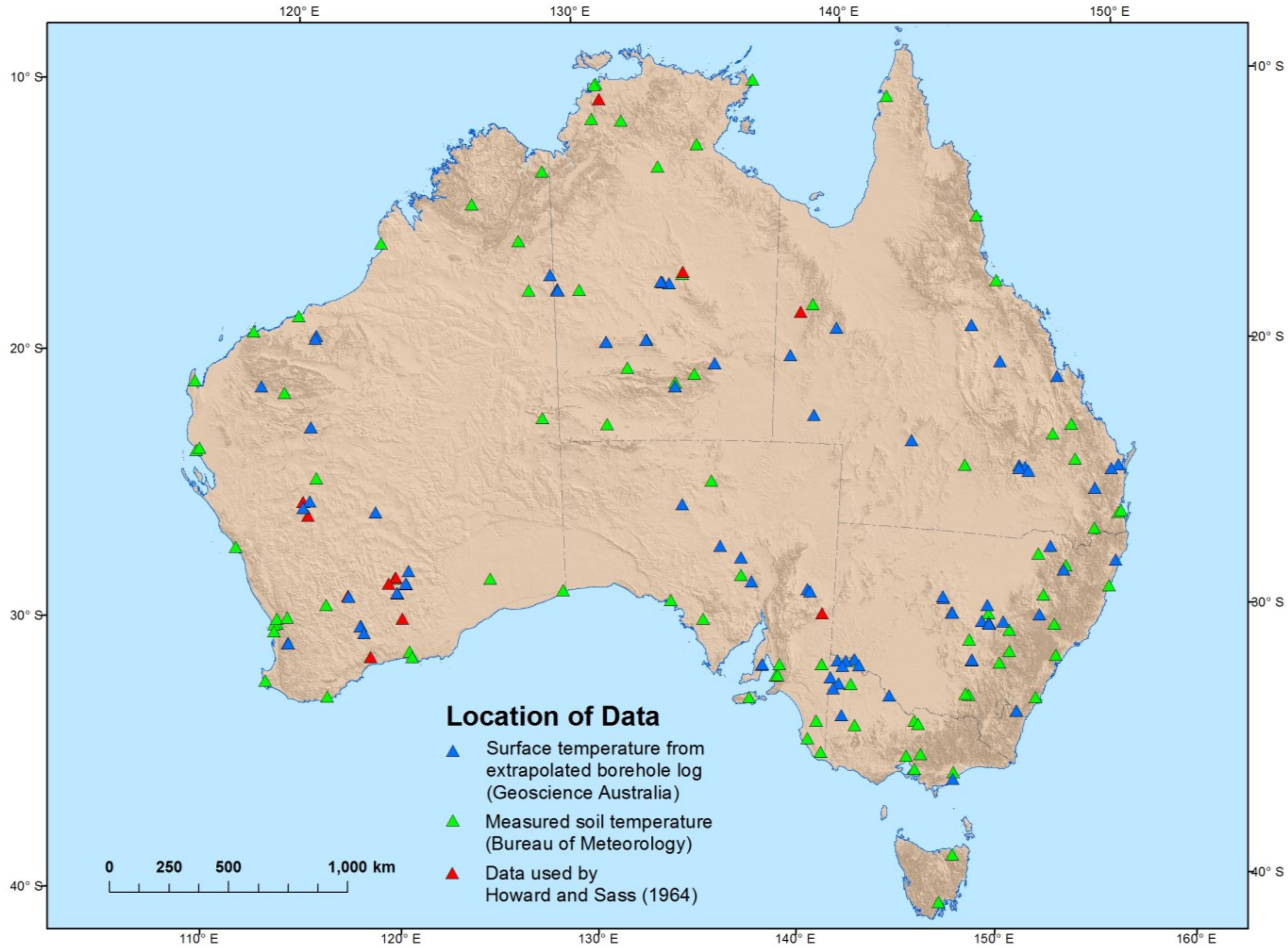

Figure 1: Map showing the distribution of the data used to create the surface temperature correction map. Data taken from temperature logs extrapolated to the surface shown in blue. Soil temperatures measured at 1m depth shown in green and the points used by Howard and Sass, 1964 shown in red. Displayed on a background terrain image.

2.1 Bureau of Meteorology Data

The soil temperature data was accessed through the Australian Bureau of Meteorology website. The data package contains a range of data for stations across Australia. While data for individual stations are downloadable directly from the website we contacted the Bureau directly in order to access the full record from all stations in one data package. Each station has varying combinations of data recorded at 5 cm, 10 cm, 20 cm, 50 cm and 1 m depths, recorded at various times of the day or night. Additionally due to the timing of commissioning/decommissioning and maintenance etc. of stations the availability of soil temperature records is inconsistent and all data are not available for all recording stations for all years, or even all months. Therefore, only years with complete monthly averages and with more than 5 complete years have been used to calculate an annual average. This has left 81 useable stations with average annual values calculated from records spanning between 5 and 37 years, with the earliest year being 1959 and the most recent 2008 (Figure 1) .

The Bureau of Meteorology also supplied the grids of mean annual maximum and minimum air temperature that were used to construct the grid of mean annual average temperature to determine an air temperature for each location. These grids are the average annual maximum and minimum temperatures over the period of 1961 to 1990. The averaged grid was the source of the air temperature for all locations, even where air temperature data were available from the same stations as the soil temperature measurements. This was done to provide a level of consistency to the calculations.

2.2 Geoscience Australia Data

In addition to the soil temperature data, ground surface temperatures have been extrapolated from 108 borehole temperature logs recorded by Geoscience Australia. These data were collected during the heat flow mapping program conducted during the Onshore Energy Security Program between 2007 and 2012.

The holes that were available to Geoscience Australia for logging were largely drilled by the minerals exploration industry. In many cases there were access restrictions to the holes due to rehabilitation requirements, meaning that some of the holes logged were not fully thermally equilibrated. For this study, where possible only holes that had lengthy equilibration times were chosen for analysis as it was noted early in the work that un-equilibrated holes produced inaccurate extrapolated surface temperatures.

The value of surface temperature for each log was extracted by selecting the shallowest linear section of the log (below the level of water in measured in the borehole) in the top part of the hole and extrapolating that back to the surface. Like many interpretive processes, this method has an element of subjectivity in that the choices of which section of the log chosen to extrapolate from affect the final surface temperature. While this is limited as much as possible through consistency of technique, it does add an element of uncertainty that is not present in the directly-measured soil temperature data. The necessity to select the best part of the log to extrapolate from, rather than use the same depth for all logs, is in part due to the influence of the seasonal temperature variations propagating through the upper portion of the ground. Other influences on the choice of which section of log to extrapolate from are the standing water level in the hole and the degree of variation in the thermal conductivity of the surficial materials (which cause changes in thermal gradient and the rate and attenuation of the propagation of the seasonal thermal signal).

Each temperature log yielded a single ground surface temperature. This is distinct from the measured soil temperatures that were averaged over a period of years. However, due to the nature of the propagation of seasonal temperature changes through the ground and the way in which the ground surface temperature is extracted from the log, the extrapolated value is in effect averaged from a period of several years.

2.3 Historical Data

The 11 wells on which the first estimation of surface temperature correction by Howard and Sass (1964) was based on have also been included. The distribution of these wells is irregular and spatial coverage of the continent incomplete with seven of the wells located in the Yilgarn province in the southern half of Western Australia, two in the Northern Territory (Rum Jungle, southwest of Darwin and Tennant Creek) and one each in Mt Isa, Queensland and Radium Hill, South Australia. The difference between the ground surface temperature and the air temperature in these 11 wells ranges from 1.2 °C to 4.7 °C (Howard and Sass, 1964).

3. METHOD

The point data (soil, extrapolated borehole log and historical data) were intersected with the mean annual air temperature grid to ascribe an air temperature value to each location. The difference between the ground surface temperature and the air surface temperature was then calculated. These differences were then gridded using ESRI's ArcGIS 10.0. A number of different interpolation techniques were trialed however, the distribution of the data caused a number of techniques to produce gridding artifacts it in areas where the data were sparse. The Topo to Raster tool was chosen as it provided an output which highlighted broad trends in the data and avoided creating detail in areas of no data. The Topo to Raster tool is based on the ANUDEM program developed by Hutchinson (1988, 1989). This method uses an iterative finite difference interpolation technique.

While initially this gridding technique may appear an unusual choice due to the intended purpose of creating topographic surfaces, the interpolation procedure was designed to eliminate "sinks" or local minima from the output surface and to develop connected drainage systems and topographic ridges from limited sparsely distributed data. One of the ways this is done is by assuming that all unidentified "sinks" are erroneous data. This produced continuous, smooth surfaces free from gridding artifacts in areas between data points and with limited complexity in areas of densely distributed but variable data (ESRI, 2010).

The output of this method was a single image or set of contours describing the variations between the mean annual air temperature and the ground surface temperature, as shown in Figure 2.

4. RESULTS

The work to date has demonstrated a variation of between <1 °C and 8 °C in the difference between the ground surface temperature and the mean annual air temperature across the Australian continent. This difference can introduce significant errors when calculating a thermal gradient from discrete bottom holes temperatures, particularly in shallower holes. For example a difference in 3° C in the starting temperature will result in a difference of 10° C/km in the calculated gradient over a 300 m section of hole. This demonstrates that care must always be taken when using these types of data and that wherever possible an examination of the local variation should be made, rather than using a uniform value.

The average of the difference between the air temperature and the ground surface temperature (for both the Bureau of Meteorology data and the extrapolated temperature logs) is 3.38 °C. This is consistent with the value calculated by Howard and Sass (1964). However the range of the difference between the air temperature and ground surface temperature at locations across the continent is much greater. This demonstrates the necessity of gaining an understanding of the conditions when working at smaller scales.

The map produced indicates a variation of the relationship between air temperature and ground surface temperature with both (but not only) latitude and distance from the coast. The mapped variations also appear to display influences from other factors that are discussed in more detail in section 5.

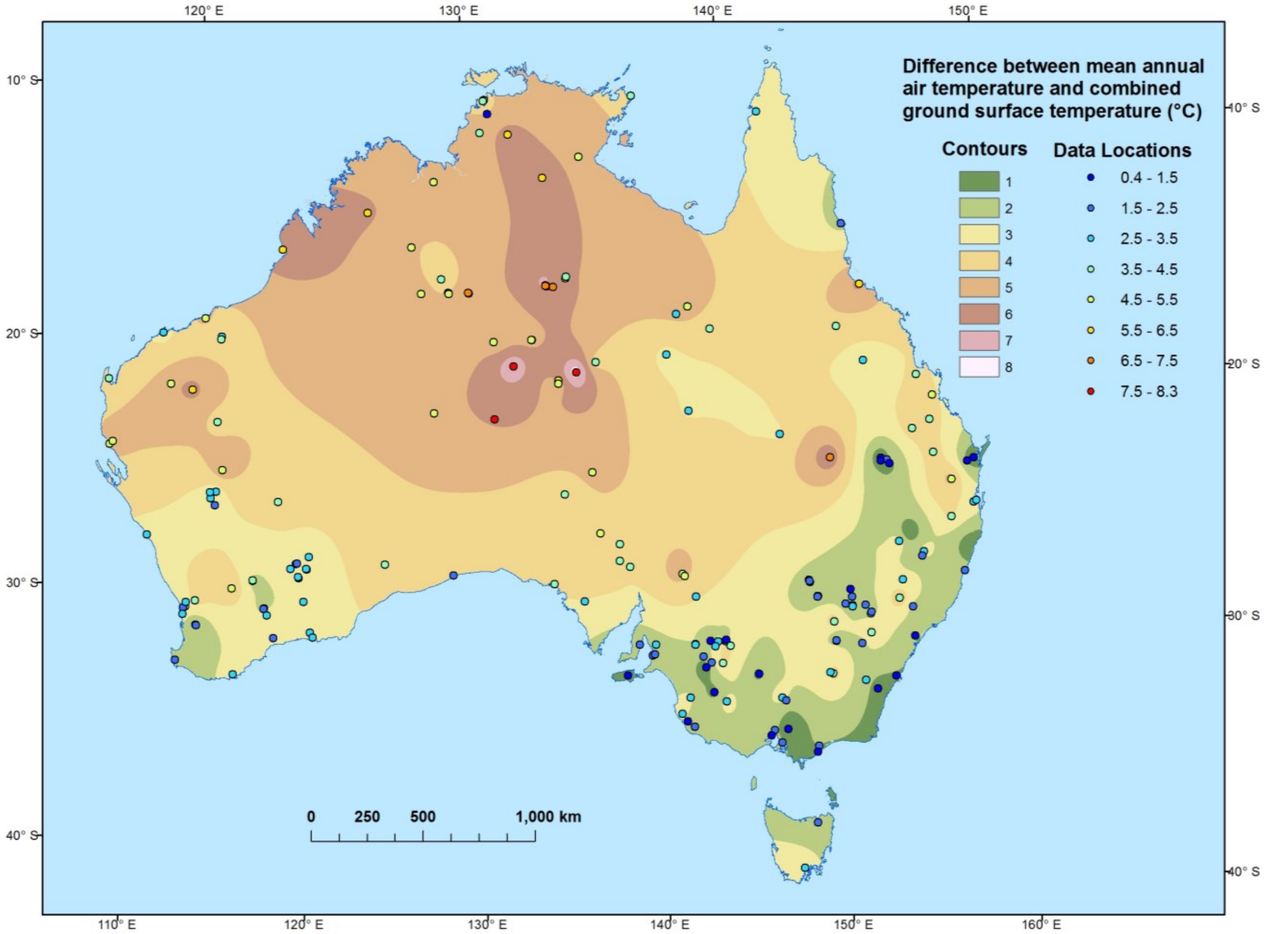

Figure 2: The interpolation of the difference between the ground surface temperature and the average annual air temperature at each location across Australia. The data locations are shown for reference and to highlight the limitations in the distribution of the data.

5. DISCUSSION

From their work at the Emigrant Pass Geothermal Climate Observatory Bartlett et al., (2006) concluded that the primary variable in determining the difference between ground and air temperatures at a single location is variations in incident solar radiation. It is reasonable then to assume that the variation in incident solar radiation between sites will account for a large proportion of the variations in differences between surface ground temperature and the mean annual air temperature. This would suggest that latitude should be an important variable when mapping the variations in ground surface temperatures at a continental scale. However, from a conceptual understanding it could be expected to be a complex interplay between a wide range of climatic and geographic factors that may influence the ground surface temperature both directly (eg solar radiation, rainfall, evaporation, altitude) and also indirectly by impacting incident solar radiation (eg periodic cloud cover, vegetation, topography).

Figure 2 illustrates that the variation in the difference between the ground surface and air temperatures is not simply a function of latitude. Howard and Sass (1964) observe that the extrapolated surface temperatures and the measured air temperatures display a correlation with latitude. There is a variation in the relationships between the extrapolated surface temperatures and air temperature (at the hole location) with latitude (Figure 3a) and between soil temperature and air temperature (at recording site) with latitude (Figure 3b). Further work to examine these relationships is required to fully understand these differences. One possible explanation may be that the quality of the extrapolated surface temperature data (as briefly mentioned in Section 2.2) could be limiting the accuracy of identified trends. Further, it is interesting to note that the R^2 value of the trend line fitted to the air temperatures data in the two plots is significantly different. The cause of this is unknown however we speculate that it could be related to the fact that the soil temperatures are measured at the established meteorological stations from which data was drawn to build the air temperature grids. Additionally, there are certain criteria that are addressed when selecting a location for a weather station and this may lead to more uniform distribution of temperatures.

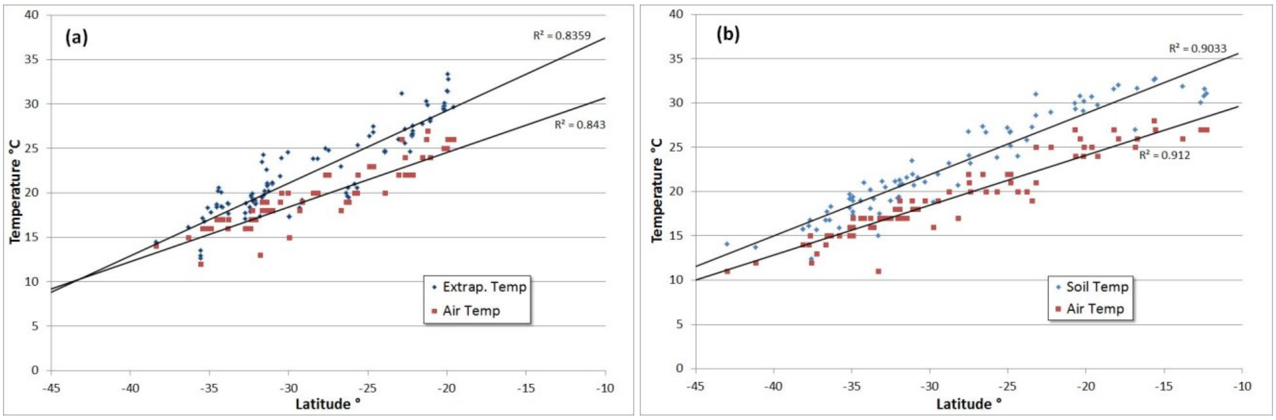

Figure 3: Plots comparing the surface temperature data to the air temperature at the same locations. (a) Surface temperature data drawn from extrapolated temperature logs. (b) Measured soil temperatures at 1 m depth. Note that the measured soil temperatures have a greater northerly extent than the holes in which the temperature logs were recorded.

Looking at the produced map it is possible to start identifying some broad correlations with other climatic factors (and therefore climate zones). The dependencies of these apparent correlations are unknown and would require more detailed investigation, however a visual comparison between the Koeppen Climate Zone Classification major groups (Figure 4) and the map produced by this study identifies some similarities. The Temperate climate zone in the southwest and southeast of the continent are broadly coincident with areas of smaller differences (1-2 °C) between the ground surface temperature and the air temperature. Likewise the zone of larger differences between the ground surface and air temperatures in the centre and north of the continent appear to be reflected in the complexity of the climate zones in the same region.

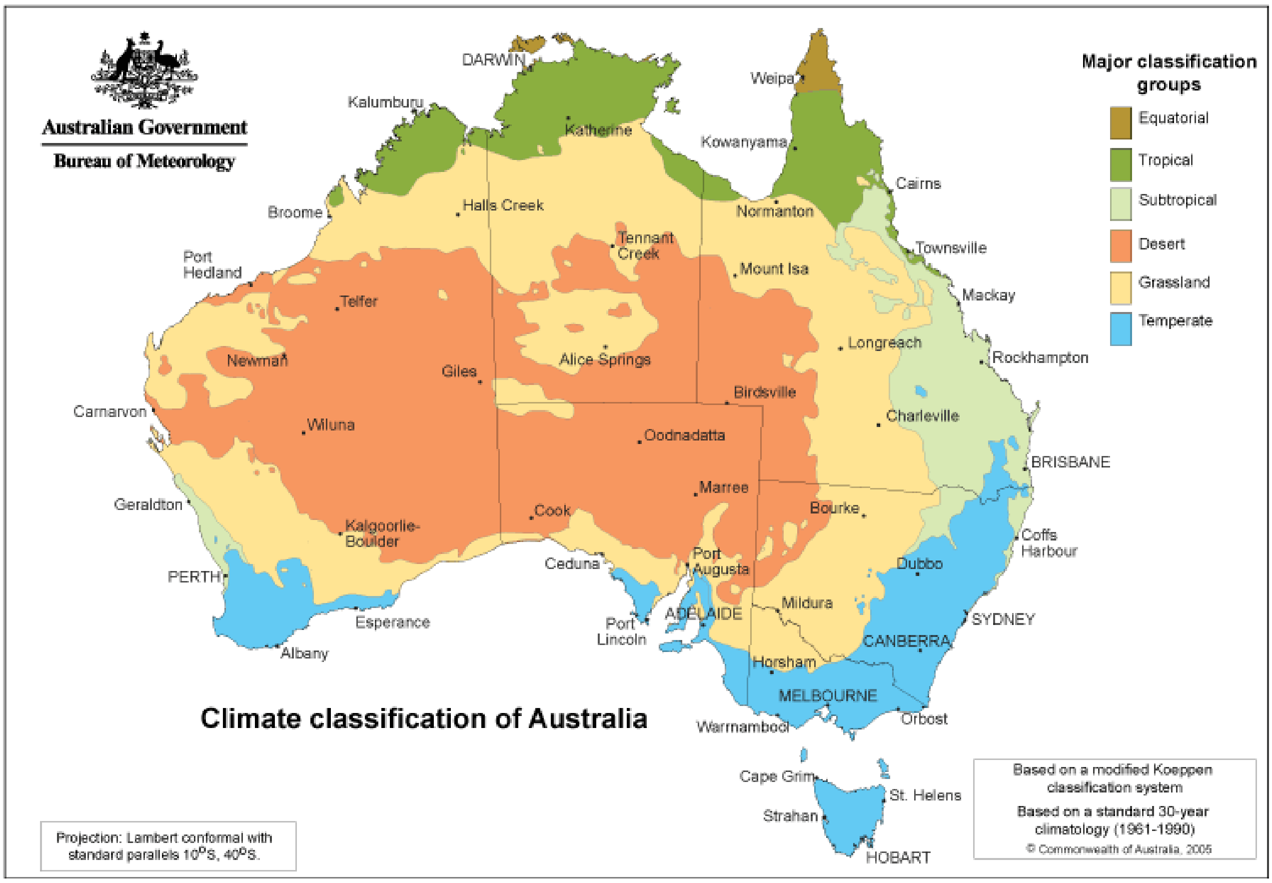

Figure 4: Major classification groups based on the Koeppen classification system (Bureau of Meteorology).

Similarly if we examine a map of the average evaporation for the Australian continent (Figure 5), similar trends are displayed. The higher rate of evaporation in the Tennant Creek area in central Northern Territory appears to be reflected in the larger differences between ground surface and air temperatures. Likewise, some smaller regions on the northern Queensland coast appear to be displaying similarities. The fact that some of the similarities are not completely resolved may be due to a number of influences. For example, because the difference between ground surface and air temperatures likely reflects multiple influences, comparing the mapped result to maps of any one of those influences individually may be misleading without considering the impact of other factors. Similarly the distribution of the data upon which the surface temperature map is based is less than ideal and is clearly limiting the available detail of the correction map at smaller scales, i.e. with further data and improved interpolation, the correlations with various climatic conditions may well increase.

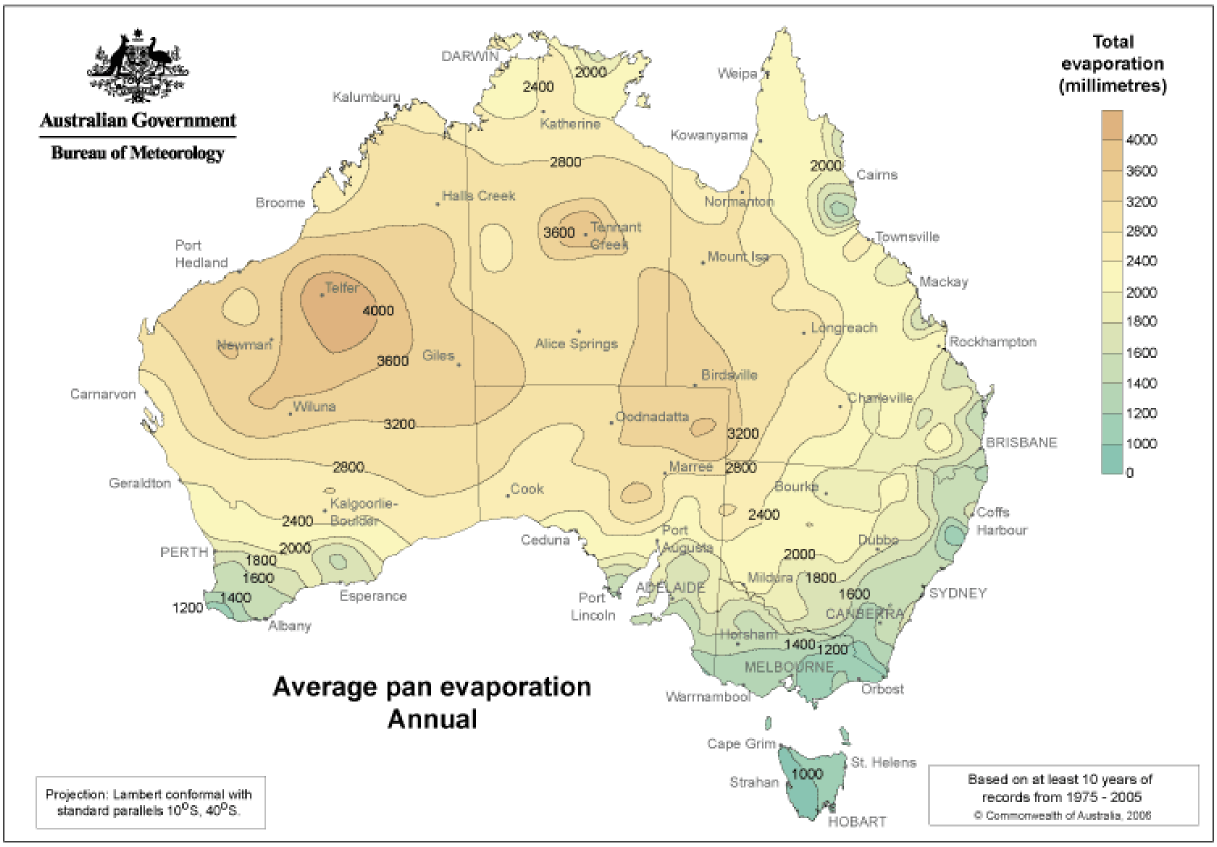

Figure 5: Average annual evaporation. (Bureau of Meteorology)

A study of the variability of the temperature in the top 1 m of soil would be beneficial to confirm the validity of the approach that has been used in this study. The two data sets used in this study suggest that there is some variability between the ground surface temperatures extrapolated from borehole logs and the measured soil temperatures that perhaps makes the 1 m depth temperature not the best analogue for ground surface temperature. Unpublished data provided by the National Geophysical Research Institute of India from their observatory near Hyderabad, India indicates that temperature at 1.5 cm and 99 cm below surface can vary by more than 7 °C (Figure 6). However, over a two year period from May 2010, the average difference in temperature at these depths was about 1 °C (Dr Sukanta Roy, pers comms. 2012). This is similarly reflected in the difference between the 5 cm and 1 m depth temperatures in the Bureau of Meteorology data, where the comparisons were able to be made. However the Bureau of Meteorology dataset from 5 cm depth was not complete enough to conduct a thorough analysis of this or to use the 5 cm depth data in place of the 1 m depth measurements. Figure 6 also shows that the temperature at 99 cm is less variable and lags the shallower temperature slightly. Both these aspects of the data are due to the thermal diffusivity of the soil/rock and highlight the necessity of using temporally extensive data to remove the seasonal variations if directly measuring the ground surface temperature.

One parameter of thermal modelling that does not appear to influence the ground surface temperature greatly is the surface heat flow. This may initially appear counter-intuitive however solar irradiance is disproportionately large compared to terrestrial heat flux. The average heat flux for continental crust is considered to be approximately 65 mW/m^{-2} (Pollack et al. 1993) while the daily global solar exposure is typically between 1 and 35 MJ/m^2 (or ~11-400 W/m^2) (Bureau of Meteorology). It is therefore apparent that terrestrial heat flow will have an indistinguishable impact on the ground surface temperature.

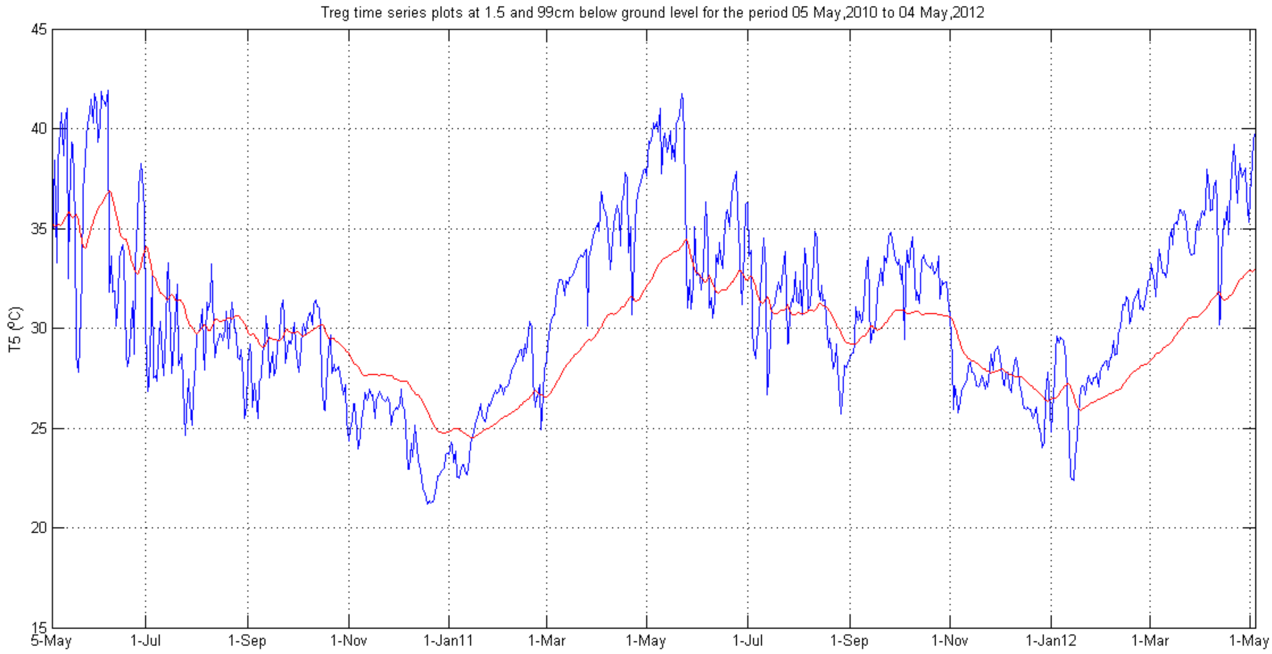

Figure 6: Plot showing the difference between the temperature at 1.5 cm depth and at 99 cm depth in the National Geophysical Research Institute's borehole temperature observatory, Hyderabad, India over a period of two years from May 2010 to May 2012. The blue line plots the temperature at 1.5 cm and the red line the temperature from 99 cm depth.

5. CONCLUSIONS

There has been an identified need for more accurate estimations of ground surface temperature to help constrain conductive geothermal potential mapping and estimations (Beardsmore el al. 2010). While this work is still a coarse estimation of the discrepancies between the air temperature and the ground surface temperature, it provides much greater detail to the problem than has existed previously. This will provide more robust estimations of surface temperatures for large scale resource potential estimations in conductive regimes. When working at smaller scales it is still recommended that more detailed data is utilized to establish greater knowledge of the local ground surface temperatures.

The continent-wide average of the difference between the air temperature and the ground surface temperature at 3.38 °C is remarkably close to the 3 °C estimation drawn from just 11 holes by Howard and Sass (1964). However, the range of values highlights the need to take the spatial variations in the correction into account when working at large scales.

There is considerable scope for further work to produce a more robust surface temperature map. Some areas that could be pursued would be the variation of temperature in the top 1m of soil/rock to determine the most appropriate depth to utilize and an examination of the consistency between the extrapolated temperature log ground surface temperature values and the measured soil temperature values.

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