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Global warming and geothermal profiles: The surface rock-temperature response in South Africa

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Abstract. Southern hemisphere and South African regional air temperature anomalies for the period 1860-1996 are compared to borehole-derived surface rock-temperature anomalies to assess the extent to which surface rock temperatures reflect possible global warming in South Africa. The warming of the southern hemisphere since the mid-nineteenth century is evident in the regional air temperatures for South Africa. Following a temperature increase to a maximum in the 1920s, the climate cooled until strong warming recommenced in the mid 1970s. Highest temperatures have been experienced in the 1990s. Borehole-derived surface rock temperatures followed a similar pattern, but with a lag of a few decades in the case of the 1920s maximum. The overall warming trend is clearly evident in the rock temperatures. Despite uncertainties in the different data sets, an encouraging degree of agreement exists between the increase in rock temperatures during the twentieth century, the corresponding regional South African air temperature increase and the southern hemisphere counterpart.

Introduction

Anomalies about mean geothermal gradients determined from borehole temperature profiles have been used in various regions to model past changes of the earth's surface temperature and infer climatic history [*Cull*, 1990; *Lewis*, 1992; *Whiteford*, 1993; *Deming*, 1995; *Huang et al.*, 1996]. In South Africa, temperature profiles measured in deep boreholes have been used to determine the equilibrium geothermal gradient near the earth's surface and the heat flux from the interior at numerous localities [*Jones*, 1987, 1988, 1992]. Deviations from linearity in a few borehole profiles have been used to make a preliminary assessment of palaeotemperatures during the last millennium over the northern parts of the country [*Jones et al.*, 1998]. In this note, data from 40 boreholes are used to determine the extent to which borehole-derived surface rock temperatures have changed since the mid-nineteenth century over much of South Africa. The degree to which the global warming signal evident in the southern hemisphere is detectable in the derived surface rock temperatures is examined.

Data and Methods

Evidence for global warming in the southern hemisphere derives from combined land-marine air temperature anomalies about the 1961-1990 mean that are given in the 1996 IPCC Second Assessment [*IPCC*, 1996]. They are an update of an earlier analysis by *Jones* [1994]. The overall uncertainty of the combined data set is 0.15°C [*Karl et al.*, 1994; *Parker et al.*, 1994; *IPCC*, 1996] and leads to an estimate of 0.3° to 0.6°C for global near-surface warming since the late 19th century for the southern hemisphere [*IPCC*, 1996].

South African air temperature trends have been analysed by *Mühlenbruch-Tegen* [1992], *Karl et al.* [1993] and *Hughes and Balling* [1996]. The longest data set for South Africa was that of *Hughes and Balling*, which is based on the *Jones* [1994] 5° x 5° gridded land and marine data set. For this study an equivalent South African temperature series was calculated using data for 25°–35°S and 20°–30°E from the Jones data set. However, only 15 stations were available in determining the gridded set. The preliminary series derived in this manner proved somewhat erratic for the early years of the century, when even fewer stations comprised the series. Since it was known that many more stations were available to constitute a more representative data set, the Jones data were not used to determine a new South African regional temperature series. Instead, maximum temperatures from 46 mainly rural or small-town stations (Fig.1) with reliable variable-length records of at least 40 years (some from the turn of the century in the south of the country) have been used for the period 1900-1994. Paucity of reliable data before 1900 precludes development of a longer series. Maximum temperature data have been used owing to the relative lack of available minimum temperatures. This may be an advantage since rock temperatures are more closely associated with maximum air temperatures than their mean equivalents. Heating effects are transmitted maximally to the substrate at the time of greatest daily and annual warming in summer. All the boreholes analysed are in the summer rainfall region. The air temperature data have been homogenised following the method used by *Rhoades and Salinger* [1993] for isolated stations with known site changes. In order to compare air temperature anomalies with borehole-derived surface temperature anomalies (which are of necessity presented as decadal averages), air temperature anomalies have been averaged over decades starting with the interval 1896-1905. A weighted regional space-mean anomaly series is derived with weights obtained from Thiessen polygons [*Thiessen*, 1911]. The same weighting scheme has been employed to provide a space-mean surface rock-temperature anomaly series derived from borehole temperature profiles. The uncertainty in the South African decadal air temperature series has been estimated by calculating standard errors of the weighted regional averages. They exceed 0.2° C before 1930. With improving station coverage thereafter, standard errors decline to less than 0.1° C after 1950.

Borehole-derived ground surface temperature anomalies are obtained by least squares inversion of down-hole temperature observations using the method of singular value decomposition [*Mareschal and Beltrami*, 1992; *Harris and Chapman*, 1995; *Jones et al.*, 1998]. For each borehole, an *a priori* model of surface

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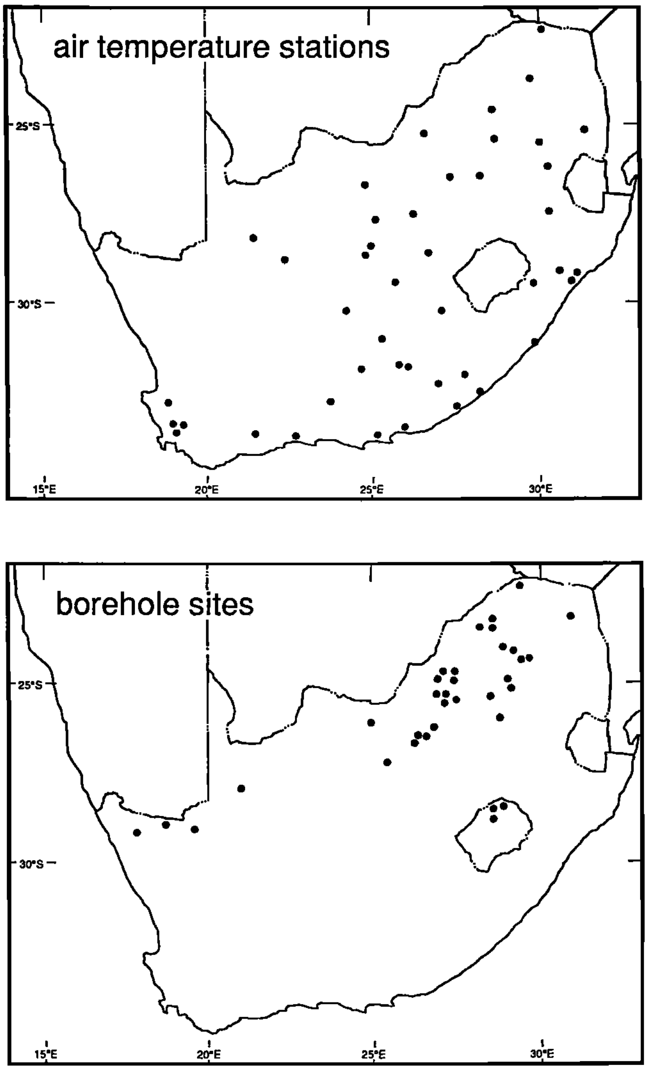

Figure 1. Location of air temperature stations and borehole sites.

temperature history is used to calculate a vertical temperature profile from the heat diffusion equation. The past 1000 years are divided into a number of time intervals which increase in duration with age and each of which has a constant surface temperature. The surface temperature at all ages before 1000 years ago is assumed to be constant. This limits the numbers of unknown parameters, and the problem is over-determined in all the cases studied. The model is physically reasonable, since the ability to resolve climatic events using the method decreases with age and depth. Surface temperature oscillations propagate into the earth such that the amplitudes of waves decay exponentially with depth and shorter-period oscillations are attenuated more rapidly than their longer-period counterparts. The earth therefore acts as a high-frequency filter from which a smoothed temperature series and long-term trends may be derived.

The analysis was limited to boreholes which are more than 250 m deep and which display linear temperature profiles at depths approaching 500 m. Initial estimates for the undisturbed geothermal gradient and surface temperature are obtained from the deep linear sections of the profiles and used in the *a priori* models. All boreholes analysed are in uniform rock type whose thermal properties are assumed to be constant and are known from measurement or estimated from published values. With these restrictions a total of 40 boreholes

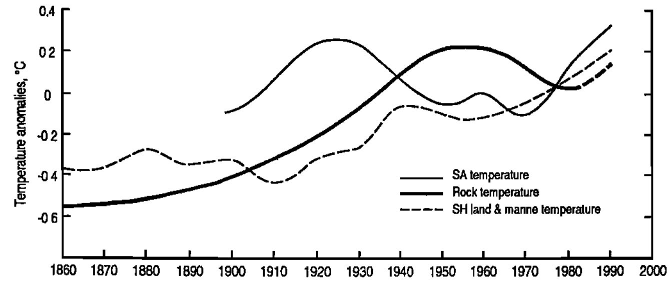

Figure 2. Decadal southern hemisphere combined land-sea temperatures [*after IPCC*, 1996], regional South African air temperatures and South African borehole-derived surface rock-temperature anomalies, °C. The 1990 rock temperatures are best estimates.

are considered to be suitable for analysis; all are located in the mining areas of the country north of 30°S (Fig. 1). It is not possible to co-locate these sites with air temperature stations.

Most of the surface temperature history models derived from the boreholes indicate significant warming during the past two centuries, although there are variations in the amplitude and timing of onset of the warming. For the purposes of this study, smooth curves were fitted to the *a posteriori* ground surface temperature models and decadal averages were determined from these curves for the period 1861-1990. The weighted space-mean anomaly series is shown in Figure 2 (heavy line). The most recent part of the curve (dashed) is less reliable because many of the boreholes were either probed prior to 1990 or lacked data in the uppermost section. For this reason anomalies have been calculated relative to the average of the 1970 and 1980 decadal values. This gives the closest approximation to the 1961-1990 base period used for air temperatures. Standard errors about space-mean borehole temperatures, calculated in the same manner as for air temperatures, are slightly less than their air-temperature counterparts, namely less than 0.1° C after 1940 and less than 0.2° C before then.

Results and Discussion

In general, the rise in derived surface rock temperature over South Africa since the middle of the nineteenth century has followed the trend in southern hemisphere combined land-sea temperatures (Fig. 2). The 15-station *Jones* [1994] mean air temperature series for South Africa shows a weak air temperature maximum around 1940. Regional air temperatures over South Africa derived from the 46-station series of mean monthly maximum temperatures show the maximum to have been earlier by a decade or two (Fig. 2). By 1950, widespread cooling had occurred. In contrast, borehole-derived surface temperatures continued to rise after 1930 to reach a maximum at around 1950. Thereafter, surface rock temperatures declined until the mid seventies. By 1980 regional ground and air temperatures had converged to similar values and were increasing everywhere to their maximum values in the twentieth century. The lag between borehole-derived surface temperatures and air temperatures during the middle of the twentieth century is not readily explained. The lag may be real or be a function of factors other than air temperature, including precipitation, soil moisture content and vegetation cover. Historical changes in these variables may yield surface temperature histories that do not exactly match changes in air temperature. Further investigation will be required in future to clarify the point.

Over the period 1861-1980 the southern hemisphere combined land-marine temperatures rose by 0.48°C. Regionally-averaged South African surface rock temperatures rose by 0.67°C. Over the period for which South African regional air temperature series is extant (1900 to 1980), the hemispheric land-marine temperatures rose 0.38°C, the South African regional air temperatures by 0.21°C, and the borehole-derived surface temperatures by 0.41°C. If the 1990 area-averaged borehole results can be taken at face value, then the 1900-1990 southern hemisphere land-marine temperature increase was 0.52°C, the South African air temperature increase 0.37°C and the mean surface rock temperature increase was 0.48°C. Given the uncertainties in the various data sets, there is an encouraging degree of agreement between the various measures of regional warming in the southern part of Africa.

Conclusions

The general correspondence between the increase in mean regional surface rock temperatures for South Africa and their hemispheric and regional atmospheric counterparts is close. All show evidence of a warm period at some time between 1920 and 1950; all the series show greatest warming since the mid 1970s. Notwithstanding the less-than-ideal quality of the early-century air temperature data, the near mid-century regional peak in air temperature appears to be a reality. There is an apparent lag between the excess regional warming in the lower atmosphere over the country during the 1920s and the borehole-derived surface rock temperatures a few decades later. It would appear that the highly-filtered surface rock temperature increases derived for South Africa are a real manifestation of the global warming signal evident in the climatological records for the southern hemisphere in general and for much of the southern African region in particular.

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