EVALUATION OF PAST CLIMATE USING BOREHOLE TEMPERATURE MEASUREMENTS

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ABSTRACT

A change of temperature at the surface of the earth produces a perturbation which diffuses slowly into the earth. It is thus possible to deduce the record of past climatic changes from the analysis of temperatures measured within boreholes. This technique was tested at two boreholes (Kaikoura, South Island, 215m deep and Raetihi, North Island, 240m deep). Past surface temperatures were reconstructed over the last 150 years, enabling a comparison to be made with the air temperatures measured at nearby climate stations of the New Zealand Meteorological Service.

Past surface temperatures from Kaikoura show the same trends as the climate records of the New Zealand Meteorological Service. They show that a warming of 0.8°C has occurred this century, and that a cool period in the 1940s was followed by a warmer period in the 1950s, which was followed by a cool period in the 1960s & 1970s, and a warmer period in the 1980s. Past surface temperatures from Raetihi show that a warming of 4°C has occurred this century, most of which is attributed to deforestation.

INTRODUCTION

It is not universally accepted that global warming of about 1°C has occurred this century. A considerable amount of data has been analysed worldwide to look for trends, and the questions being asked are whether any trends observed are universal, and whether they are natural or man-made. The most obvious way of appraising this issue is to examine the paloeclimate, i.e. the climate records extending into the past. Meteorological records of surface air temperatures have been kept throughout New Zealand for over a century, but in order to extend this record further back in time other methods must be used, such as glacier studies, tree ring analysis, or the method used here of analysing borehole temperature measurements.

The borehole temperature method is based on the characteristics of thermal diffusion in a solid, such as the earth, in which heat takes a finite time to diffuse within the solid from one region to another region. For example, ground surface temperature fluctuations propagate downwards into the earth as a temperature wave, and because the process is slow, the near-surface earth contains a history of the most recent surface temperatures, whereas deeper underground the earth contains the history of surface temperatures from further back in time. As the temperature wave propagates down, high frequency variations are attenuated more strongly than low frequency variations, and the ground therefore retains the long period events from its surface temperature history. For example, diurnal temperature variations cannot be detected at depths of more than a few metres, and seasonal temperature variations cannot be detected at depths greater than a few tens of metres. Accurate temperature measurements to depths of hundreds of metres can provide a history of local surface temperatures during the past few centuries; in particular, surface temperature changes occurring over the past four or five centuries can be detected in a bore hole about 600m deep. However, the resolution (in time) of surface temperatures deteriorates rapidly when trying to look beyond about three centuries ago, i.e. only very long period surface temperatures are obtained beyond three centuries ago.

The method requires temperature measurements to depths of several hundred metres made in boreholes using well logging techniques with a temperature sensor which can resolve to better than 0.001°C. The temperature-depth profile obtained shows the effect of past surface temperature changes superimposed on the dominant increase in temperature with depth resulting from heat flowing from the earth's molten interior to the surface (which is usually about 30°C/km). Other effects from water movement or change in thermal properties of rocks may also be seen in the temperature profile. In the absence of temperature changes at the surface and other disturbances, the geothermal temperature profile would be linear. The effect is illustrated in Fig. 1 for two theoretical examples.

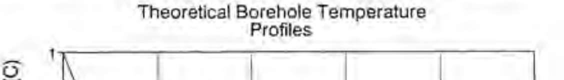

Fig. 1: The theoretical temperature-depth profiles for (a) a step increase in surface temperature of 1°C occurring 30 years ago, and (b) a square wave change in surface temperature of 1°C which began 80 years ago and finished 40 years ago.

Curve (a) corresponds to the deviation in the temperature profile resulting from a step increase in temperature of 1°C occurring 30 years ago, and shows a curved transition from the new surface temperature to the deeper parts of the borehole which have not yet been affected by the surface temperature change. Curve (b) shows perturbations corresponding to a square wave change of 1°C which began 80 years ago and finished 40 years ago, which is a bulged-shaped perturbation, i.e. a curve with a distinct maxima. The depth at which these perturbations occur depends on the thermal conductivity and thermal diffusivity of the sub-surface rocks and the time since the surface temperature changes occurred.

In choosing a borehole for making measurements, it is necessary to select a site at which there is no sub-surface ground water flow which would disturb the conductive temperature regime, i.e. the rocks at the site should be as near to impermeable as can be achieved. If any such flows occur they are easily detected as they cause step or abrupt changes in the measured temperature profile. The past surface temperatures are reconstructed from the measured temperature profile using an iterative inversion process. The ground surface temperature may differ slightly from the air temperature, although the two usually track one another; the relationship between the two depends on factors such as the vegetation cover, the topography, and if a sloping site, the aspect in relation to the sun.

One of the first climate change studies using the downhole temperature method was in the Alaskan Arctic (Lachenbruch and Marshall, 1986) where anomalous curvatures were observed in the upper hundred metres or so of borehole temperature profiles. Unlike most near-surface earth materials, the permafrost is unaffected by circulating ground water so the heat transfer process is exclusively by conduction. Analysis by thermal conduction theory indicated a secular warming of the permafrost surface, generally in the range of 2 to 4°C during the last few decades to a century. However, there was variability from site to site in the amount of warming indicated and in the time in the past at which it occurred. Lachenbruch and Marshall pointed out that there is a complex relationship between the air temperature, the temperature of the surface of the ground, which is frozen and covered in snow for much of the year but thaws out in summer, and the temperature of the surface of the permanent permafrost (which is between 0.2-2.0 metres depth). These temperatures are usually within a few degrees of one another and the principal cause of the difference is probably the variability in the seasonal snow pack on the ground. They expected that the secular change in the mean temperature at the surface of the permafrost will generally represent secular change in the rate of exchange of heat and moisture between the atmosphere and ground surface, that is, changes in climatic processes, however complex and locally variable they may be.

In this sense, the marked secular changes indicated in permafrost temperatures represented secular climate change.

Since Lachenbruch and Marshall's (1986) study the technique has been applied in a number of localities, mostly in the northern hemisphere. In Eastern Canada Beltrami and Mareschal (1991) measured and analysed temperature logs down boreholes at 20 mining exploration sites; several temperature logs were obtained from most of the sites. Sites were chosen in areas which had not been cleared of trees. A simple inversion process was used to reconstruct surface temperature histories, which showed that at all but six sites a warming of 1 to 2°C was indicated. At only three sites there was no indication of warming; and for each of these disturbing factors were believed to be present. Beltrami and Mareschal (1991) noted that with the borehole temperature method, resolution of the climatic signal from the data is good.

Some regional differences in the extent of recent warming has been observed. In Western Utah, U.S.A., analysis of six sites showed evidence of warming this century, but some sites showed recent cooling, the past surface temperature changes at the sites varying from −0.8 to +0.6 (average +0.3) °C (Chisholm and Chapman, 1992). These changes were consistent in trend but smaller in amplitude than the 100 year linear trends in surface air temperature data (average +0.8°C), which were obtained from seven meteorological stations geographically interspersed among the borehole sites and from ground and air temperature records available from four weather stations. They concluded that the veracity with which their observed borehole temperature profiles match synthetic temperature-depth profiles computed from air temperature records leaves little doubt that the solid earth is a valuable recorder of climatic change. The aim of the work reported here is to test the applicability of the downhole temperature measurement technique in New Zealand, and compare the results with existing records, so as to establish past surface temperature over the last few hundred years.

NEW ZEALAND DATA

Two existing boreholes were used for this investigation, one sited 12km north of Kaikoura at the foot of the seaward Kaikoura range beside the Hapuku River, and the other 2km east of Raetihi, North Island, in rolling farmland. Downhole temperature measurements were made at 2m intervals in each. Temperatures were measured in the Kaikoura borehole to a depth of 215m (the bottom). Temperature in the Raetihi borehole was measured to a depth of 240m (the bottom). The Kaikoura and Raetihi downhole temperatures are plotted in Figs. 2 & 3. The profiles are very close to linear in the deeper half of the holes. Towards the surface the profiles show curvature towards higher temperatures and away from the linear extrapolation of temperatures in the lower part. This curvature is indicative of recent warming of surface temperatures.

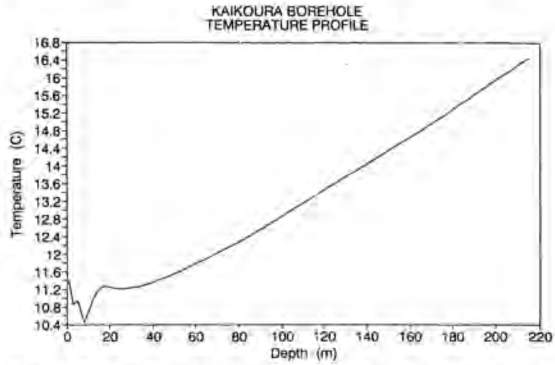

Fig. 2: The measured temperature-depth profile for the Kaikoura borehole.

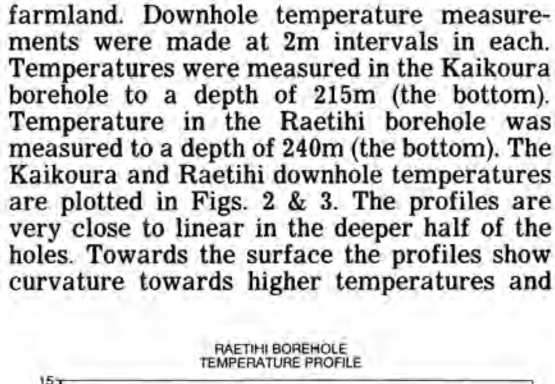

Fig. 3: The measured temperature-depth profile for the Raetihi borehole.

Analysis of Data

The first step in analysis was to remove the natural geothermal gradient from the measured temperature profile. The geothermal gradient is estimated using the temperatures from the deepest portion of the profile which are least influenced by surface temperature variations. A least squares fit of these deepest temperatures to a straight line was used to estimate the geothermal gradient; temperatures from depths of 195 to 213m were used in the Kaikoura borehole, and from 220 to 240m in the Raetihi borehole. The temperatures remaining after removal of the geothermal gradients from the measured temperature profiles (referred to as temperature differences), are plotted for the full depth of the holes in Figs. 4. The curves are almost the

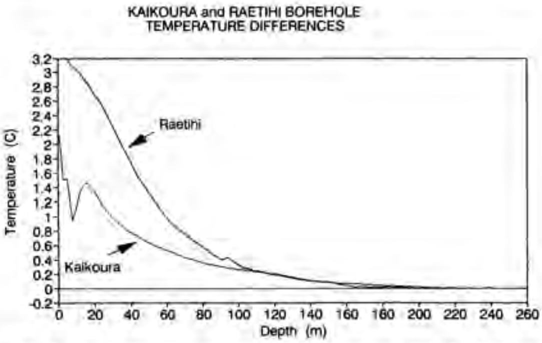

Fig. 4: The temperature differences versus depth obtained after removal of the geothermal gradient from the measured temperature-depth profiles for both the Kaikoura and Raetihi boreholes.

same at depths below 110m but above 110m the Raetihi curve exhibits about twice as much surface warming as the Kaikoura curve. The temperature differences used to calculate the geothermal gradient can also be examined in this latter figure, and it can be seen that they exhibit little variability and are close to linear. These temperature differences were then used to model past surface temperature variations.

Modelling Past Surface Temperature Variations

Past surface temperature variations were estimated using an iterative technique. A series of about 14 square waves covering the past 160 years was constructed and used to calculate a theoretical temperature-depth curve using the method outlined by Jaeger (1965). The amplitudes of the square waves (and sometimes the durations) were adjusted iteratively until the calculated downhole temperature curve gave the best fit to the measured (downhole) temperature differences (Fig. 5). It can be seen that the fit for the Kaikoura

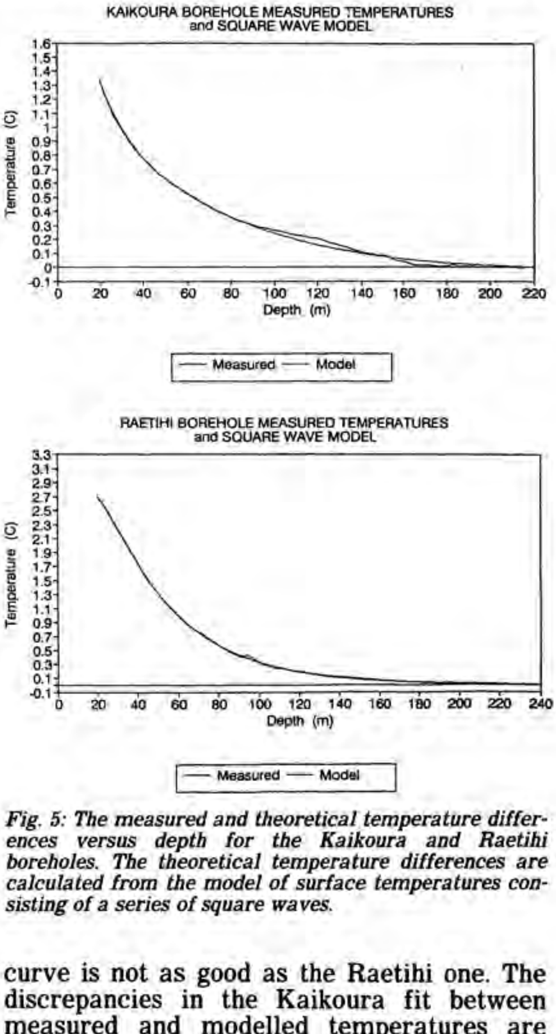

Fig. 5: The measured and theoretical temperature differences versus depth for the Kaikoura and Raetihi boreholes. The theoretical temperature differences are calculated from the model of surface temperatures consisting of a series of square waves.

curve is not as good as the Raetihi one. The discrepancies in the Kaikoura fit between measured and modelled temperatures are thought to be due to slight changes in the thermal conductivity of the rocks with depth in the Kaikoura borehole, however, it does not significantly affect the model as the average fit over the whole curve is good. The resulting square wave models of past surface temperature variations back to 1830 for both holes are plotted in Fig. 6. It can be seen that the curves are generally similar from 1830-1950 but the two curves deviate since 1950, with the Raetihi hole showing much higher surface temperatures than the Kaikoura hole. Both curves exhibit a warming trend since the 1930s, and both curves indicate that a cool period occurring in the latter part of last century was preceded by temperatures similar to those in the first part of this century.

DISCUSSION

Past surface temperatures inferred from the downhole measurements in both the Kaikoura and Raetihi holes show a distinct increase over the last 40 years, as well as an average trend of increasing temperatures over this century. The measurements also indicate that towards the end of last century the surface temperatures were about a degree cooler for about two decades. The similar nature of these trends, which occur at two widely separated geographic locations, appears to indicate that climate changes were widespread. The recent (since 1900) enhanced warming at Raetihi compared with that at Kaikoura must be a local effect.

The average surface temperatures at Kaikoura have increased by about 0.8°C this century, and at Raetihi by about 4°C. The greatly increased warming in surface temperatures at Raetihi in recent times, can be attributed to deforestation occurring over the last 70 years. Lewis and Wang (1992), using the downhole temperature method, noted a temperature 4°C warmer in deforested areas than in surrounding forested areas. This warming must be as great as an urban heat island effect and indicates the very significant effect that deforestation has on the (local) climate. The vegetation at the Kaikoura hole is unlikely to have changed significantly during the period of interest, and the surface temperature changes probably represent climate changes.

The surface temperatures over the last 60 years obtained for the Kaikoura hole (Fig. 6) shows (a) a cooler period from 1930-1940, (b) a warmer period centred on 1950, (c) a slightly cooler period from 1960-1970, and (d) warming since 1970. The Raetihi surface temperatures over the past 60 years show increasing temperatures, although not at a steady rate.

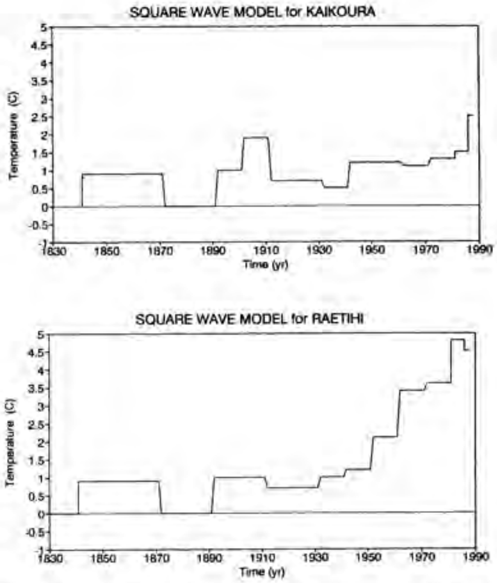

Fig. 6: Past surface temperatures variations from 1830-1990 modelled as a series of square waves for the Kaikoura and Raetihi boreholes.

However, reduced rates partly coincide with the occurrence of cooler periods at Kaikoura from 1960-1970 and 1930-1940, indicating some correspondence between the two.

Similar trends were noted by Salinger et al. (1992) in mean air temperatures measured at climate stations throughout New Zealand. The salient features of his record were (a) a period in the 1940s which was cooler than the 1951-1980 average, (b) a warmer period in the mid-1950s, (c) and then periods that were cooler and warmer than the 1951-1980 average, with most stations recording their warmest period in the 1980s. Regional variations in the mean annual temperatures were observed, and it is interesting to note that during 1981 to 1990 the largest temperature increase in the North Island occurred at Taihape, the closest climate station to Raetihi hole. North Island mean temperatures increased between 1941-1950 and 1981-1990 by 0.8°C and South Island mean temperatures by 0.7°C, and in particular Eastern South Island temperatures increased by 0.7°C. This value of 0.7°C compares very favourably with the 0.8°C obtained from the Kaikoura borehole measurements.

A similar value of 0.5-0.7°C for the global warming in the past century was obtained from meteorological stations distributed throughout the world (Hansen and Lebedeff, 1987). As mentioned earlier, past surface temperatures obtained by the borehole temperature method generally show warming over the last century, and agree well with meteorological air temperature records, with an average of 0.3°C in Western Utah (Chisholm and Chapman, 1992), and higher values in the arctic (Lachenbruch and Marshall, 1986).

CONCLUSIONS

Observations of temperatures in boreholes provide a pattern of past surface temperature variations which is consistent with the meteorological observations. In particular, they show that the surface temperatures have increased this century at both Kaikoura and Raetihi. The extent of the past climate that can be derived from bore holes is dependent on the depth of the hole. In principle, with holes considerably deeper than the 220m depth used here, the limit of detection may extend back as far as 500 years (Lewis and Wang, 1992).

The borehole temperature method provides a valuable means of determining past surface temperatures which not only supplement existing meteorological temperatures, but enable the temperature record to be extended back several centuries. The method has the advantage that the locality of the site for determining past surface temperatures can be selected, providing a suitably deep borehole exists or can be drilled. The existence of several drill holes enables regional variations of past surface temperatures to be studied.

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