Active layer apparent thermal diffusivity and its dependence on atmospheric temperature (Livingston Island, Maritime Antarctic)

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Summary Antarctica is one of the most sensitive areas in the world to global climate change making it a privileged observatory for the study of this change. Nevertheless, its geographic location and its extreme climate make it very difficult to collect a continuous series of measurements. These adverse factors can be circumvented using boreholes since ground temperature measurements are a reliable and adequate method of detecting climatic trends. Since January 2000, our team has monitored the evolution of the active layer with a 2.4 m deep borehole called Incinerador. It is located near the Spanish Antarctic Base on Livingston Island (62º39'S, 60º21'W) in the Maritime Antarctic. In this paper, the apparent thermal diffusivity has been estimated in Incinerador observing a seasonal dependence. Moreover, the evolution of the temperature signal in the active layer shows two different periodic behaviours, a one-day period in the summer and a 6-to-10-day period in the winter.

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Introduction

Antarctica is one of the most sensitive areas to climate change in the world, especially the maritime Antarctic where the Mean Annual Air Temperature (MAAT) is approximately -2.6º C. This is close to the upper limit for permafrost viability (Bockheim, 1995) and, therefore, studying the distribution and the state of the permafrost is key to monitoring climate evolution.

The climate at sea level is cold oceanic with frequent summer rainfall in the low areas and a moderate annual temperature range, reflecting the strong influence of the circum-Antarctic low-pressure system (King, 1994).

Livingston Island (62º39'S, 60º21'W - South Shetland archipelago) is located some 50 km west of the Antarctic Peninsula. Almost 90% of the island is glacierized and the rest has a seasonal snow cover, coinciding with the periglacial domain. It is thought that most of the ice-free areas support permafrost. During the 2005-2006 Spanish Antarctic campaign, 2-dimensional geophysical inversion schemes were used to analyse the spatial heterogeneity at the field sites and to detect isolated ground ice occurrences.

The results confirm that permafrost is widespread on Livingston Island with high ice content in typical periglacial morphologies like ice-cored moraines and low ice content in the cracks and fissures of frozen bedrock (Hauck 2007).

In January 2000, two shallow boreholes were drilled on Livingston Island (Ramos and Vieira, 2003). One of them is near the Spanish Antarctic Station Juan Carlos I in Cerro Incinerador at 35 m ASL. The other is located on the top of Reina Sofia Hill (275 m ASL). Both boreholes have a data logger chain that monitors ground temperatures at 1 hour intervals. Data is still being continuously recorded at both sites.

Temperatures from these logger chains are used in this paper to characterise ground thermal behaviour using thermal diffusivity according to different temperature periods associated with meteorological variations.

Experiment description

The Incinerador borehole was drilled in quartzite bedrock to a depth of 2.4 m and with a diameter of 90 mm. There is a logger chain inside the borehole pipe. Since January 2004, the chain is composed of six loggers placed at different depths beginning at 5 cm and continuing down to the bottom of the borehole. The interval between consecutive measurements is one hour and the accuracy of the data loggers (tiny talk Gemini Co.) is 0.2º C. The numbers and the depths of the loggers installed in Incinerador are shown in Table 1.

Temperatures from the Incinerador borehole are complimented with other meteorological variables such as wind speed, air temperature, pressure and, since 2006, the thermal gradient in the air interface layer at 5, 15, 25, and 100 cm above the soil surface.

The Sofia borehole was drilled in a quartzite boulder that lies on a matrix supported diamict. The borehole traverses the 0.4 m thick boulder and penetrates the diamict to a depth of 1.2 m. A logger chain composed of four sensors at different depths has been continuously measuring the ground temperature since January 2004. The air temperature is measured in a shield protected from radiation. Temperature is measured every hour. The thermal gradient, since 2006,in the air interface layer is recorded in the same way as at the Incinerador site.

Table 1 Sensor depth distribution in the Incinerador borehole since 2000.

Working period	Sensor depths (cm)
2000 March to 2000 December	25, 230
2001 February to 2001 November	25, 50, 100, 230
2002 March to 2002 November	15, 40, 90, 190
2003 January to 2004 January	15, 40, 90, 190
2004 January to 2005 February	5, 15, 40, 90, 150, 230
2005 January to 2006 February	5, 24, 58, 118, 184, 230
2006 January to 2007 February	5, 24, 58, 118, 184, 230

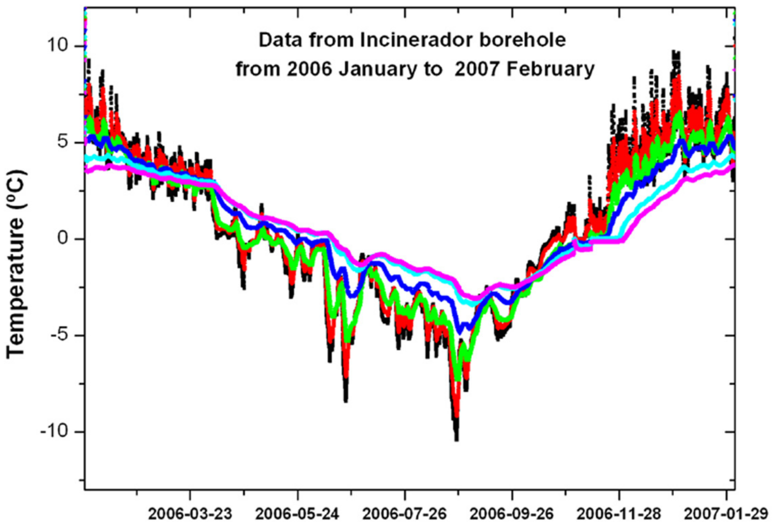

Figure 1. Annual temperature profiles for air measurements taken at depths of 5, 24, 58, 118, 184 and 230 cm in the Incinerador borehole. The colour code is black, red, green, blue, cyan, magenta, and yellow, respectively. Vertical lines mark thawing and freezing periods and horizontal lines the 0-degree isotherm.

Data analysis

As was said earlier, the Incinerador sensors have recorded the ground temperature at different depths for the last seven years. Based on these data, the temperature evolution can be used to define separate periods within a year with particular characteristics. Four periods with different temperature behaviours are observed (Figure 1). From the middle of December to almost the end of March, the temperature is above 0º C with a clear daily period (summer). A rapid decline in temperature is observed next. This freezing interval lasts roughly 1.5 months. Then comes a long winter, from May to November, with temperatures below 0º C and 6-10 day periods (winter). Finally, a very fast thawing period (approximately 20 days) completes the year.

A quasi-stationary sinusoidal temperature variation is observed throughout the year, but the characteristic period and the temperature amplitude change depending on the time of year. According to the 5 cm

Table 2 Selected data interval and fit results.

Temporal interval	Frequency (s^{-1})	d factor (m^{-1})	Period (hours)	Thermal diffusivity (m^2/s)
Summer				
14-17 MAR-04	0.2629	24	23.9	2.1E6
10-13 JAN-05	0.25	26	25.13	2.35E6
6-10 DEC-05	0.2674	24.8	23.5	2.28E6
4-7 JAN-06	0.2521	25	24.92	2.19E6
25-29 JAN-06	0.2623	23	23.95	1.93E6
21-25 FEB-06	0.2577	24	24.38	2.06E6
11-14 MAR-06	0.2314	24	27.15	1.85E6
18-21 SEP-06	0.257	20	24.45	1.43E6
26-30 NOV-06	0.2687	27	23.38	2.72E6
Winter				
10-31 AUG-04	0.03061	52	205.26	1.15E6
7-28 JUN-05	0.03191	67	196.9	1.99E6
7-25 AUG-05	0.03935	42	159.67	9.6E7
21-30 JUL-06	0.0786	39	79.94	1.66E6
6-19 AUG-06	0.04951	51	126.9	1.79E6

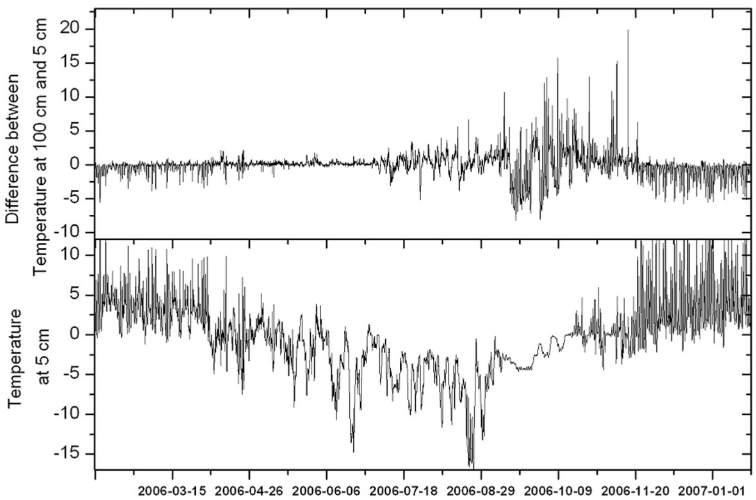

Figure 2. Data from the thermal snow layer probe sited close to Incinderator borehole during 2006. Top: The temperature difference between the readings at 100 cm and 5 cm. Bottom: the annual temperature profile measured at 5 cm above ground at the Incinerador site.

depth sensor, the dominant period in summer is around 24h but disappears in winter, ranging from 6-10 days (Table 2). Nevertheless, the 24 h period is observed throughout the year in the air temperature. The lack of a daily period in winter could be directly related to a layer of snow on the ground. The snow layer functions as a low-pass filter for the temperature signal (Goodrich, 1982). This is clearly observed at the bottom of Figure 2 where the temperature from the sensor at 5 cm above ground isshown. High frequency signals related mainly to an approximate daily period are observed from September to April. This signal almost disappears during the rest of the year (April to November), especially in July when the biggest difference in temperature at 100 cm and 5 cm is recorded (see the top of Figure 2). This result could be explained by a permanent snow layer thicker than 5 cm.

Studying permafrost and the thermal regime of the active layer requires knowledge of their thermal properties, particularity thermal diffusivity. This parameter is key to a natural system because it controls thermal response. The general features of the thermal regime in the active layer, such as the exponential attenuation of the temperature wave with depth and the lag in phase, can be analysed assuming heat transference by conduction.

When diffusion is the heat transfer mechanism, the temperature regime is governed by the heat conduction equation:

$$\frac{\partial T}{\partial t} = \alpha_H \frac{\partial^2 T}{\partial z^2} \tag{1}$$

where T is temperature, t is time, z is depth, and α_H is thermal diffusivity.

The temporal temperature series show, at different times of the year, a clear sinusoidal behaviour with different periods. During these intervals, the thermal signal can be used to estimate thermal diffusivity and the characteristic periods (Ingersoll, 1954; Lachenbruch, 1959; Hinkel, 1990). These periods are necessarily associated with atmospheric phenomena. Diurnal periods are directly observed during the summer, disappearing during winter in response to the presence of a snow layer.

Assuming that the 5 cm deep temperature reading is a sinusoidal function of time:

$$\Delta T_{-5} = T_0 \sin(\omega t) \tag{2}$$

where ΔT_{-5} is the difference between the temperature at a depth of 5 cm and the mean temperature at the same depth throughout the studied interval, T_0 is the amplitude, and ω is the characteristic frequency. The solution to Eq-1 is:

$$\Delta T_{-z} = T_0 e^{-\frac{z}{d}} \sin(\omega t - dz) \tag{3}$$

where z is the sensor depth with respect to the 5 cm depth sensor, and d reflects the exponential decay and the phase lag. If the characteristic frequency and d are estimated, it is possible to calculate ground thermal diffusivity using the following expression:

$$\alpha_H = \frac{1}{2}\omega d^2 \tag{4}$$

Expressions 2 and 3 can be used as fit functions for data at different depths. After fitting, d and ω are obtained as fit parameters, and then thermal diffusivity is directly calculated. The fit procedure used is based on the minimization of the CHI-square function, while the Levenberg-Marquardt procedure is the algorithm employed. An example of this fit can be seen in Figure 3. Scatter plots are the temperature data from the sensor at depths of 5, 15, and 40 cm recorded from 14-17 March 2004. The continuous lines are the fit curves and the fit results are summarized in the lower right-hand box. Here, a period of 23.899 h and a thermal diffusivity of 2.1×10^{-6} were obtained.

In order to check the heat diffusivity evolution, a systematic search of clear sinusoidal behaviours over a 3 year interval was carried out. The result is shown in Table 2 and Figure 4. The thermal diffusivity ranges from 0.96 x10^{-6} to 2.72x10^{-6} m^2/s, showing seasonal variations and minor values in winter. This variation could be due to water in the quartzite pores. Another possible cause of the diffusivity evolution could be a change in the heat transfer mechanism. If water content is high enough, the convection process can be important to heat transfer and the apparent thermal diffusivity could be greater (Kane, 2001). In addition, thermal diffusivity is inversely related to temperature below 0º C (Figure 5). In the temperature interval below 0º C, diffusivity rises when the temperature decreases. Plotting thermal

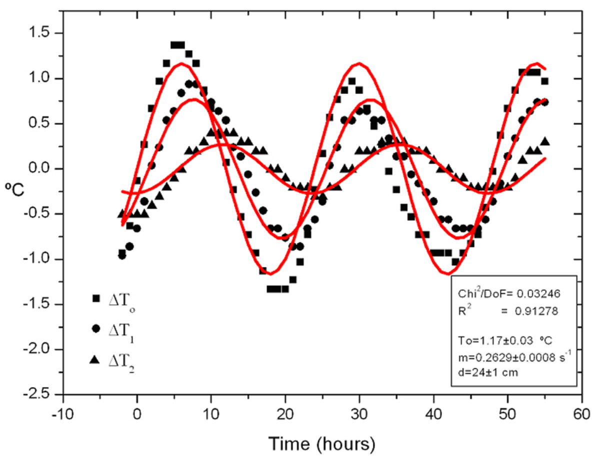

Figure 3. Hourly temperature series at depths of 5, 15, and 40 cm. Continuous lines and box data are the fit results.

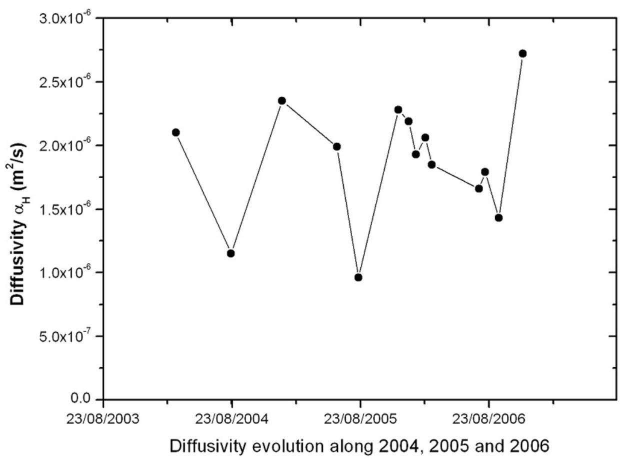

Figure 4. Evolution of the thermal diffusivity from 2004 to 2006. Scatter plots represent the calculated diffusivity.

diffusivity vs. the difference between air and ground temperature amplitudes could shed some light on this subject (Figure 6). A negative linear dependence can be seen in this Figure. The lowest thermal diffusivity value is reached when the difference between temperatures is highest. This might be due to a thicker snow layer on the soil surface.

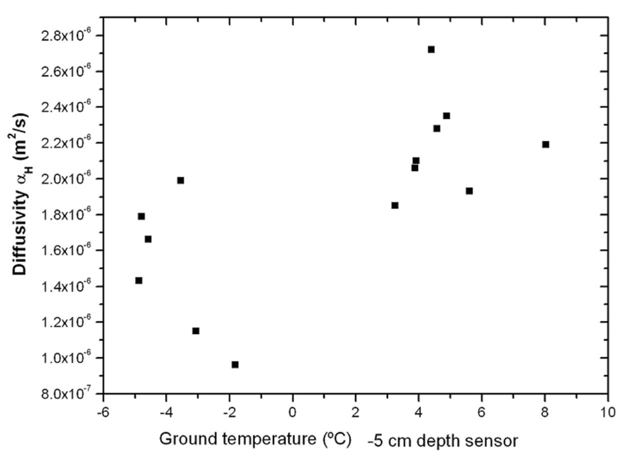

Figure 5. Thermal diffusivity compared to ground temperature.

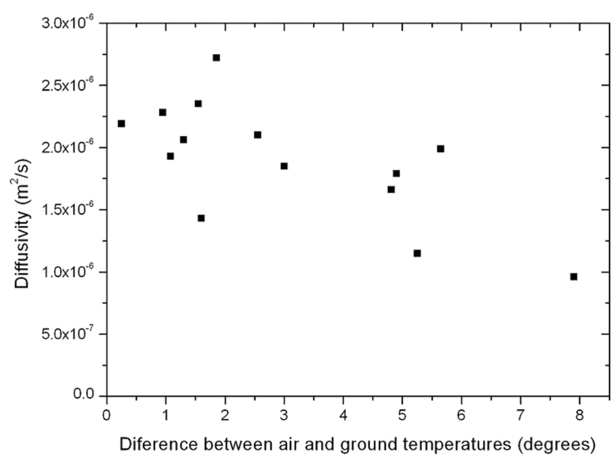

Figure 6. Thermal diffusivity from 2004 to 2006 vs. the difference between air and ground temperatures.

Final remarks

This paper reports the temperatures recorded over a 3 year interval in the Incinerador borehole at five different depths ranging from -5 cm to -230 cm. The borehole is located on Livingston Island close to the Spanish Antarctic Station. The temporal temperature profiles show a clear sinusoidal behaviour and the high-frequency filtering by the ground allows an easy analysis of the relevant periods to be made. Moreover, assuming quasi stationary diffusive heat transfer, thermal diffusivity is estimated for different times.

The results can be summarized in the following points:

* The temperature behaviour divides each year into two main episodes: summer, with a mean temperature above 0º C and a daily period, and winter, with a mean temperature below 0º C and a characteristic period ranging from 6-10 days.

* The daily period is not observable during winter because of the presence of snow on the ground, which functions as a low-pass filter.

* Thermal diffusivity is temperature-dependent and varies with the annual seasons, being lower in winter. Both facts seem to confirm the existence of water which freezes and thaws depending on the season.

* Finally, an inverse relation between the differences in ground and air temperature and thermal diffusivity is observed.

In future papers, the Incinerador results will be compared with those from the Sofia borehole as a means of investigating thermal regime dependence in relation to altitude and soil composition.

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