



GEOSCIENCES

Apparent thermal diffusivity of soil in ice-free areas of Keller peninsula in maritime Antarctica

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Abstract: Heat transfer process in the soil active layer is important for the knowledge of its thermal properties linked with climate issues. The objective of this work was to analyze the energy flux in different soil profiles by estimating the apparent soil thermal diffusivity (*ATD*). The study was carried out in Keller Peninsula, located at King George Island in four different sites differing by soil characteristics, as well as vegetation coverage and landscape setting. The *ATD* was estimated in function of the long-term hourly temperature records at different soil depths. In addition, we estimated the seasonal mean of the *ATD* and the freezing *N*-factor. Results showed that *ATD* values were smaller at shallow depths and increased with depth. The diffusivity values presented lower variability in colder conditions, especially at deeper soil layers. Water content was the main factor affecting soil thermal diffusivity at sites 1 and 3 (more than 70 and 63% of probability). At sites 3 and 4 lower *N*-factors were observed, suggesting higher snow pack and permafrost closer to the soil surface. Hence, positive *ATD* appears in the summer due to thawing increases soil moisture, while negative *ATD* appears during the freeze of the snow pack and precipitation.

Key words: heat flow, freezing index, seasonal temperature and soil moisture, degree days of soil freezing.

INTRODUCTION

Studies of climate monitoring have been increasingly explored in order to obtain information about the origin and trends of the several climate variables, such as temperature. The soil active layer and permafrost are highly sensitive to climate warming, being important for regulating energy flow and acting as indicators of the current climate trends. The energy flux in soils is the focus of many studies and is recognized as the main component for understanding climate variability at local levels (Almeida et al. 2014). However, the understanding of the thermal state and formation/degradation of permafrost is little known in the Antarctic

region, when compared with other regions of the globe (Bockheim 1995, Bockheim et al. 2008).

Several factors influence the heat transfer processes in the active layer as well as thermal properties of the soil, including soil temperature, moisture and granulometry (stoniness). The snow cover and vegetation act as insulators or buffers, depending on the structure, density and thickness of soil coverage (Almeida et al. 2014). However, the processes of energy transfer between soil and air are more effective in environments with little snow and vegetation coverage. Seasonal coverage of snow during the freezing season may increase the annual average of soil temperature at the surface, causing permafrost

degradation, in regions with continuous permafrost (Bockheim et al. 2008). On the other hand, the absence of snow may be a key factor for the permafrost formation/appearance in regions with discontinuous or sporadic permafrost (Zhang 2005). Almeida et al. (2014) reported mean *ATD* for a 12-month period of ($-4.6 \times 10^{-6} \text{ m}^2/\text{s}$), evidencing that moss carpets in maritime Antarctica can function as an insulating cover, similar to the snow effect, preventing energy flux. Also, these authors reported that *ATD* during winter (21 June to 23 September) was positive at 30 cm depth ($1.7 \times 10^{-6} \text{ m}^2/\text{s}$). In addition, soil thermal regime varies accordingly to the season, especially due to the zero-curtain effect in the late spring (effect of latent heat in maintaining temperatures near 0°C , over extended periods in freezing or thawing soils) and ice/snow melting during the summer (Hinkel et al. 2001, Almeida et al. 2014).

Antarctica is rapidly changing some of its most important features, such as permafrost occurrence, vegetation patterns and soil process due to warmer temperatures in the last decades. In this context, vegetation, permafrost distribution and features such as patterned ground - symmetrical geometries displayed across the surface formed by frost action - in terrestrial environments can be profoundly affected by climate trends. Therefore, thermal diffusivity can be an excellent tool to assess soil temperature patterns at different terrestrial environments in ice-free areas of maritime Antarctica.

In order to estimate the thermal diffusivity, several models have been developed by using long-term records of soil temperature. However, modeling studies incorporating soil moisture parameters are still scarce and little explored. It's extremely important since soil moisture varies greatly in time and space in ice-free areas, leading to alterations on soil thermal

regime (Michel et al. 2014), especially in maritime Antarctica where a greater rain and solar incidence have enhanced soil formation and vegetation growth more than other parts of Antarctica. It is also known that a number of solutes (molecules or ions) dispersed in the soil solution can decrease the freezing point of a non-volatile liquid (cryoscopy). However, in periglacial environments the analysis of soil and air temperature time series are strongly important for soil thermal dynamic studies. However, when considering soil water content on the modeling process, we expect a better understanding of soil thermal dynamic, since in this environment part of the water solidifies and melts seasonally. Hence, the objective of this work was to analyze the energy flux in different soil profiles by estimating the apparent soil thermal diffusivity (*ATD*). In addition, this work aimed to understand the influence of soil moisture on the *ATD*, as liquid water may accelerate soil thermal conductivity, especially in the maritime Antarctica region where temperature is increasing over time.

MATERIALS AND METHODS

Study area

The study was carried out in Keller Peninsula, located at King George Island, part of South Shetlands (Figure 1). The climate, according to Köppen classification is ETf - Oceanic Polar of Southern Hemisphere, with a mean annual precipitation of 400 mm and monthly air temperature of -6.4°C (July) and $+2.3^\circ\text{C}$ (February). The entire area comprises approximately 8 km², with a north-south length of 4 km and 2 km width Francelino et al. (2011). The altitude ranges from 0 to 340 m above the sea level. The lithology is predominantly basalt-andesites and pyritized andesite rocks (Birkenmajer 1980). The soils

are mainly characterized by the low degree of development. Leptosols and Lithic Cryosols are the main soil classes, according to the WRB-FAO classification system (Wrb et al. 2015). Cryoturbation process and coarse materials on the surface are typical features of these soils, whereas glaciers, snow banks, rocky outcrops and rocky fields occupy the remaining area (Francelino et al. 2011).

Soil temperature and moisture monitoring sites

Four monitoring sites (site 1, 2, 3 and 4) were selected. The description of each site is presented in table I. Temporal series of soil temperature and moisture were obtained from November 2011 to December 2014 at Soil temperature probes (model L107E - Campbell Scientific Inc, Utah, USA) with accuracy of $\pm 0.42^{\circ}\text{C}$, were vertically placed at 5, 10, 30, 50 and 100 cm depth. Soil moisture probes (model CS616-L, Campbell Scientific Inc., Utah, USA) with accuracy of $\pm 2.5\%$ were vertically placed at 10, 30, 50 and 100 cm depth. All probes were connected to a datalogger (CR 1000, Campbell Scientific Inc, Utah, USA), recording data at every 1 h interval. An air temperature thermistor with a ventilated radiation shield (accuracy of $\pm 0.1^{\circ}\text{C}$) was installed at 100 cm above the soil surface to measure air temperatures. The temperature and soil moisture monitoring systems were conditioned in a 120 L compartment, which were partially buried in order to protect the system.

Estimation of apparent thermal diffusivity (ATD)

The ATD was estimated from the equation of McGaw et al. (1978) (eq. 1):

$$ATD = \left[\frac{\Delta z^2}{2\Delta t} \cdot \frac{T_i^{j+1} - T_i^{j-1}}{T_i^{j-1} - 2T_i^j + T_i^{j+1}} \right] \quad (1)$$

where ATD = apparent thermal diffusivity (m^2/s), Δt = time increments (s), Δz = space increments (m), T = temperature, j = temporal position and i = depth position. Several authors have used this equation to assess the resistance to energy flux in the soil profile (Nelson et al. 1985, Outcalt & Hinkel 1989, Hinkel et al. 2001, Michel et al. 2014, Almeida et al. 2014).

For all sites, ATD was estimated by using hourly records for intermediate depths of both profiles, and mean values were calculated and plotted for each hour. Subsequently, the seasonal mean was calculated, considering the beginning of the seasons, and the average values were calculated and plotted for each day. We determinate: ATD_{10} (diffusivity values among the temperatures of 5, 10 and 30 cm depth; ATD_{30} (diffusivity values among the temperatures of 10, 30 and 50 cm depth) and ATD_{50} (diffusivity values among the temperatures of 30, 50 and 100 cm depth) in the Site 2 and Site 3. Due to the problems with the monitoring system at 50 cm depth, we calculated the ATD_{10} (diffusivity values among the temperatures of 5, 10 and 30 cm depth) and ATD_{30} (diffusivity values among the temperatures of 10, 30 and 100 cm depth) in the site 1. We also calculated ATD_{TB-30} and ATD_{TC-30} (diffusivity values among the temperatures 10, 30 and 80 cm depth, at the polygon border - TB and center - TC) in the site 4 (Patterned ground area).

The N -Factor was used to evaluate the influence of snow thickness on the ATD. The N -Factor relates the air with soil temperature, using freezing degree days values. In order to estimate the N -Factor index ($n - F$), we related freezing degree days of air temperature ($FDDa$) with freezing degree days of soil temperature at 5 cm (FDD), calculated by eq. 2:

$$n - F = \frac{FDD}{FDDa} \quad (2)$$

The temperature at 5 cm was chosen because it is closer to the soil surface, closely

Table I. Description of the studied sites in Keller Peninsula.

Site	Description	Photos
Site 1	62° 05' 09.00" S; 58° 24' 48.97" W, 96 m height. Moss field, flat, andesite, plateau with Leptsols	
Site 2	62° 04' 21.33" S, 58° 24' 58.11" W 70 m height, community mix of vegetation (Usnea, moss, Deschampsia antarctica and Colobanthus quitensis), flat, andesite, felsenmeer with Regossols.	
Site 3	62° 05' 19,14" S, 58° 24' 23.98" W 65 m, without vegetation, flat, andesite + volcanic tuff, patterned ground with skeletal Cryosols (Reductaquic).	
Site 4	62° 05' 20.08" S, 58° 24' 30.31" W 93 m, moss in line, slope of 150, scree slope, andesite with sulphide, Skeletic Turbic Cryosols.	

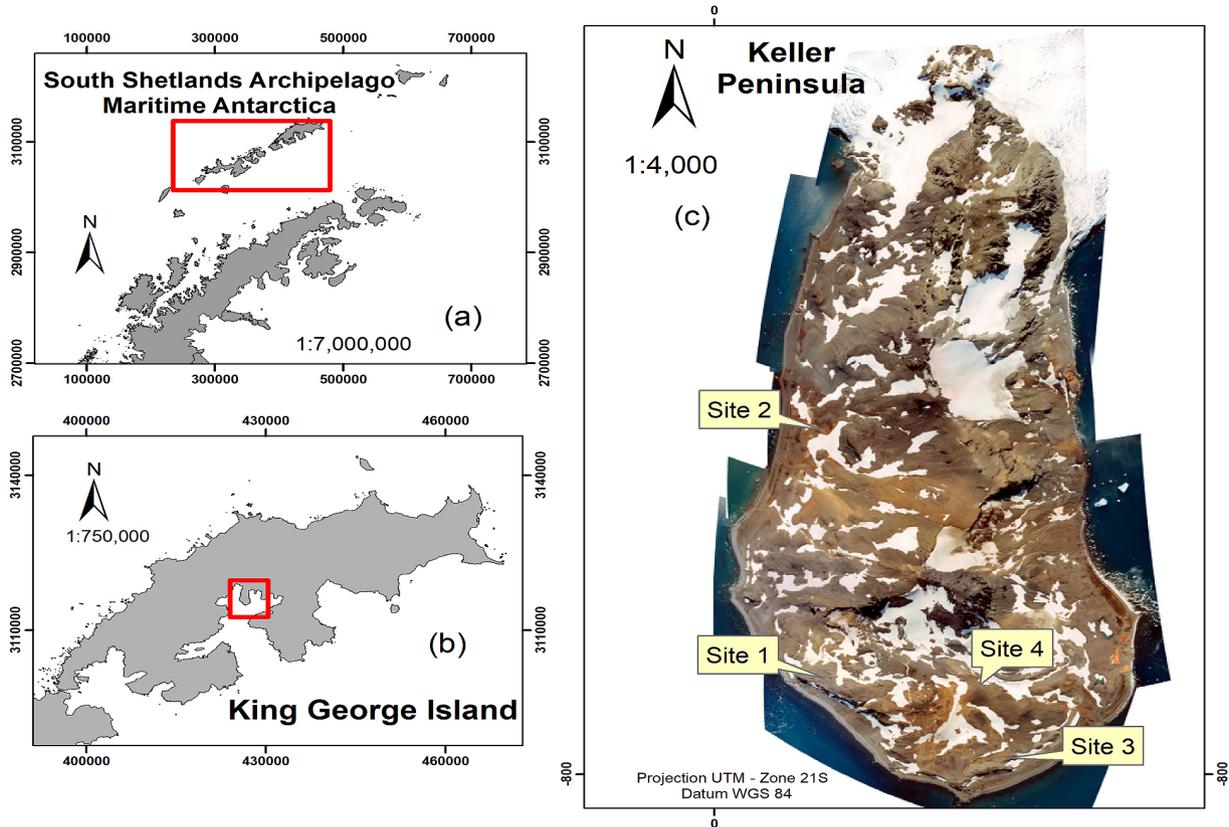


Figure 1. Schematic map showing the South Shetlands Archipelago (a) and King George Island (b), where Keller peninsula is located (c). Studied sites are shown in (c).

related with the snow cover. In this study, we did not measure snow thickness. Simple linear regression tests were performed in the Past 1.34 software (Hammer et al. 2001), in order to verify correlations between moisture and *ATD* values. We generated hourly, monthly and seasonal *ATD* values for the different depths based on modeling tests. The applied multivariate linear regression model was:

$$Y_i = \beta_0 + \sum_{k=1}^n \beta_k X_{i,k} + \epsilon_i \quad (3)$$

where *Y* is the dependent variable (*ATD*); *X* is the explanatory variable, soil moisture at *k* depth; ϵ is the error, considered random and with normal distribution of zero mean and constant variance, β_0 is the regression constant and β_k the coefficients to be fitted. The subscript term

i, indicates the *i*-th observation. The mean and variance of the *ATD* (observed and estimated) were evaluated by the *t*-test and the *F*-test, based on the *p*-value, respectively. The *t*-test was also used to evaluate β_0 significance and the linear regression coefficients ($H_0 : \beta_k = 0$ and $H_a : \beta_k \neq 0$). In addition, regression coefficient was determined, which indicates how much of the *ATD* variability is explained by the explanatory variables.

RESULTS

When average soil temperature varied closer to $\pm 0.03^\circ\text{C}$, the thermal diffusivity estimated by eq. 1 presented values up to three times higher than the other thermal conditions (data not shown). The diffusivity tends to infinity

when soil temperature values closer or in the isothermal status, as the denominator of eq. 1 approaches zero. Hence, based on this restriction and the accuracy of the sensors, we decided to disregard the values of the temperature variation between -0.04°C and $+0.04^{\circ}\text{C}$. The percentage of disregarded data is presented in Table II.

A greater number of disregarded data was registered in the site 3, especially in deeper soil layers, mostly observed in the spring 2012 at site 3 and 4, as well as in the fall 2014 at sites 1 and 2. *ATD* varied seasonally, indicating that soil water content may increase the energy flow through percolation process, but it can also absorb and emit energy in the freezing and thawing processes, as observed in Table III and IV. The *ATD* was calculated based on 47 months in the sites 1 and 2, 36 months in the site 3, and 45 months in the site 4.

At the most superficial depths the *ATD* varied between $-5.5 \times 10^{-7} \text{m}^2/\text{s}$ (ATD_{TB-10}) at site 4 in the winter 2013, and $4.5 \times 10^{-6} \text{m}^2/\text{s}$ (ATD_{10}) in site 1 in the summer 2012. In the site 4, the ATD_{TB-30} values were positive (except in 2013) during the winter season. In the summer, *ATD* values presented a positive trend overall, except for the site 2, which showed negative diffusivity values of ATD_{10} in this period.

ATD values were smaller at superficial soil layers, with a tendency to increase with depth. Higher *ATD* values were observed in summer and fall, when snow cover is reduced. The mean *ATD*, considering all years, was $9.2 \times 10^{-7} \text{m}^2/\text{s}$ (ATD_{10}) and $5.5 \times 10^{-6} \text{m}^2/\text{s}$ (ATD_{30}) at site 1; $9.6 \times 10^{-8} \text{m}^2/\text{s}$ (ATD_{10}), $1.5 \times 10^{-6} \text{m}^2/\text{s}$ (ATD_{30}) and $2.3 \times 10^{-6} \text{m}^2/\text{s}$ (ATD_{50}) at site 3; $2.5 \times 10^{-7} \text{m}^2/\text{s}$ (ATD_{10}), $1.9 \times 10^{-6} \text{m}^2/\text{s}$ (ATD_{30}) and $2.3 \times 10^{-6} \text{m}^2/\text{s}$ (ATD_{50}) at site 2; and $6.4 \times 10^{-7} \text{m}^2/\text{s}$ (ATD_{TB-30}) and $1.1 \times 10^{-6} \text{m}^2/\text{s}$ (ATD_{TC-30}) at site 4.

Moisture influenced more the *ATD* at sites 1 and 3 (more than 70 and 63% of probability, respectively) as shown in Table III. In general,

ATD is influenced by moisture ($p > 0.05$) except for site 1 (ATD_{10} and U_{10} ; $p < 0.05$). Also, the coefficient of determination (r^2) explained the variability in the observed values, with an exception at site 3 (ATD_{50}), presenting a negative correlation with moisture. In the other sites, 2 and 4, moisture influenced the *ATD* ($p > 0.05$), however the coefficient of determination (r^2) did not explain the observed values. The mean seasonal soil moisture was higher at 50 cm (U_{50}) in site 1; at 10 cm (U_{10}) in the summer and at 100 cm (U_{100}) in the other seasons in site 3; at 10 cm (U_{10}) and 30 cm (U_{30}) at site 2. In the site 4, mean seasonal soil moisture comparing the polygon border and center was similar, with differences lower than 0.9% (Figure 2).

The freezing *N*-factor was compared with *ATD* values, in order to evaluate the influence of snow thickness on the thermal characteristics of soil surface (Figure 2). To better visualize the results, the accumulated sum of the *ATD* and *N*-factor data were correlated. Results indicated similar freezing *N*-factor in site 1 ($r^2 = 0.96 ATD_{10}$; $r^2 = 0.98 ATD_{30}$) and site 2 ($r^2 = 0.96 ATD_{10}$; $r^2 = 0.96 ATD_{30}$; $r^2 = 0.98 ATD_{50}$). These sites are characterized by the same vegetation (*Usnea* sp. and *Deschampsia antarctica*), as well as similar influence of active layer.

Soil at site 4 remains frozen longer ($r^2 = 0.88 ATD_{TC-30}$; $r^2 = 0.92 ATD_{TB-30}$), with higher number of freezing degree days accumulated and intermediate *N*-factor in comparison with site 1, 2 and 3. A correlation between the *N*-factor index and the *ATD* ($r^2 = 0.12 ATD_{10}$; $r^2 = 0.84 ATD_{30}$; $r^2 = 0.59 ATD_{50}$) was observed in site 3. In addition, lower accumulated sum of freezing degree days sum and lower *N*-factor index among the studied areas.

The relationship between the cumulative freezing *N*-factor and *ATD* (Figure 3) showed that the accumulated *ATD* calculated near the surface (ATD_{10}) is less correlated with the *N*-factor

Table II. Percentage of discarded data of the temperature variation (Δt) in the different studied sites in Keller Peninsula, Maritime Antarctica.

% discarded data	Site 1		Site 2			Site 3			Site 4	
	*ATD ₁₀	*ATD ₃₀	*ATD ₁₀	*ATD ₃₀	*ATD ₅₀	*ATD ₁₀	*ATD ₃₀	*ATD ₅₀	*ATD _{TB-30}	*ATD _{TC-30}
Summer_2011	6.4	2.6	3.7	3.3	11	-	-	-	-	-
Fall_2011	4.4	6.4	0.8	10.1	6.2	-	-	-	3.2	9.1
Winter_2011	9.5	5.9	1.3	10.8	4.5	-	-	-	0.7	9.7
Spring_2011	8.1	3.8	7	19	11.7	-	-	-	0.3	0.9
Summer_2012	4.1	1.4	3.1	5.2	7	4	2.9	7.8	4.3	8.1
Fall_2012	6.1	8.5	2.2	6.5	11.3	6	18.5	16.4	10.3	8.5
Winter_2012	9	2.6	1.9	5.2	8.2	6.6	33	33.2	5.4	16.1
Spring_2012	21.6	10.8	3.9	7	15.6	21.1	39.5	72.2	10.9	38.8
Summer_2013	24.2	7.3	1.4	2	5	6.7	17.2	50.3	4	8.1
Fall_2013	14.1	15	3.3	7	14.7	19.3	15.1	18.4	5.5	11.2
Winter_2013	13.5	4.8	1.7	7	2.2	14.9	17	38.2	0	34.2
Spring_2013	13.4	9.3	2.7	10	17.9	8.1	28.6	65.4	4.2	16.2
Summer_2014	9.5	7.2	1.3	2.3	10	8.7	12.2	30.1	3.4	16.3
Fall_2014	15	26.1	19.1	25.3	33.2	20	23.7	31.1	10.2	15.6
Winter_2014	22.4	7.2	1.8	7.7	4.9	8.4	25	15.2	6.7	21
Spring_2014	23.6	10.3	1.1	8.6	20.8	9.8	24.3	57.8	12.1	26.5
AVG	12.8	8.1	3.5	8.6	11.5	11.1	21.4	36.3	5.4	16
STD	6.9	5.9	4.4	6	7.8	6	9.8	21	3.9	10.4

*ATD₁₀ = apparent thermal diffusivity at 5, 10 and 30 cm depth and *ATD₃₀ = apparent thermal diffusivity at 10, 30 and 100 cm depth (site 1); *ATD₁₀ = apparent thermal diffusivity at 5, 10 and 30 cm depth 5, 10 and 30 cm depth; *ATD₃₀ = apparent thermal diffusivity at 10, 30 and 50 cm depth and *ATD₅₀ = apparent thermal diffusivity at 30, 50 and 100 cm depth (sites 2 and 3). *ATD_{TC/TB-30} = apparent thermal diffusivity at 10, 30 and 80 cm depth at the polygon border (TB) and center (TC).

when compared with the values in deeper soil layers. Results of *N*-factor suggest that the snow thickness freezes the soil faster near the surface, and the *ATD* values lower than in the other soil depths.

DISCUSSION

Higher numbers of disregarded data were registered in the site 3, possibly associated to the lower soil temperature variation among soil depths, indicating low heat transfer at this area.

Soil water availability contribute to negative *ATD* values, indicating that the non-conductive effects are oppose or overcome the conductive tendency (Almeida et al. 2014). However, results indicated that positive/negative *ATD* values are associated with higher/lower soil moisture values at Sites 1 and 3, respectively. On the other hand, the opposite was observed at site 2. During part of the winter, especially at the early and later winter, water precipitation probably happened in the studied area. Thus, greater water infiltration occurred, contributing

Table III. Seasonal averages of air temperature (T_{AIR}) and soil (T_s) at five depths; Seasonal thermal diffusivity (ATD_{10} , ATD_{30}) and soil moisture (U%) at different sites in Keller Peninsula, Maritime Antarctica.

site 1	T_{AIR}	Seasonal average temperature of the soil (T_s)					Diff. seasonal average ground		Seasonal soil moisture			
		5 cm	10 cm	30 cm	50 cm	100 cm	* ATD_{10}	* ATD_{30}	U% ₁₀	U% ₃₀	U% ₅₀	U% ₁₀₀
Summer_2011	2.4	3.3	3.2	2.7	2.2	1.9	1.00E-06	1.30E-05	24.5	23.6	28.5	25.6
Fall_2011	-5.1	-3.2	-2.9	-2.2	-1.5	-1.2	-1.60E-08	1.90E-06	19.7	21	26.1	23.5
Winter_2011	-8.3	-5.8	-5.7	-5.4	-5	-4.8	-2.00E-07	1.90E-07	19.1	20.3	25.2	22
Spring_2011	-0.9	-0.3	-0.6	-1.2	-1.6	-1.8	4.50E-07	1.70E-06	21.9	22.7	26.7	22.8
Summer_2012	1.4	3.6	3.4	2.8	?	1.8	4.50E-06	1.10E-05	25.1	24.8	29.4	24.9
Fall_2012	-4.4	-3.9	-3.5	-2.8	?	-1.6	1.00E-07	4.70E-06	25.1	24.8	25.5	21.9
Winter_2012	-5.7	-5	-5	-4.8	?	-4.4	-4.20E-07	2.90E-06	19.1	20.7	24.1	20.6
Spring_2012	-2.6	-1.7	-1.8	-2	?	-2.2	1.60E-07	5.90E-06	19.4	21.2	24.5	20.9
Summer_2013	1.1	1.7	1.4	1	?	0.3	3.30E-06	1.20E-05	23.9	24.7	28.5	24.1
Fall_2013	-2	-1.5	-1.2	-0.8	-0.4	-0.3	5.90E-07	7.60E-06	22	23.1	27.8	23.7
Winter_2013	-6.9	-4.6	-4.5	-4.2	-3.9	-3.7	-2.00E-07	-1.70E-06	19	20.9	24.4	21.4
Spring_2013	-1.8	-0.6	-0.7	-1.1	-1.4	-1.5	1.10E-06	9.00E-06	20.8	22.6	25.5	22
Summer_2014	0	2.4	2.2	1.6	1	0.7	4.20E-06	1.50E-05	25.4	25.3	31.4	25.2
Fall_2014	-2.8	-0.7	-0.5	-0.3	-0.2	-0.2	1.70E-07	3.30E-06	21.4	23.5	28.9	24.5
Winter_2014	-4.6	-2	-1.9	-1.8	-1.6	-1.4	-6.10E-08	-9.40E-07	20.5	21.8	25.7	21.6
Spring_2014	-2.4	-0.9	-1	-1.1	-1.3	-1.3	5.70E-08	2.17E-06	20.7	21.8	25.6	21.6
AVG	-2.7	-1.2	-1.2	-1.2	-1.2	-1.2	9.20E-07	5.50E-06	21.7	22.7	26.7	22.9
STD	3.1	2.9	2.8	2.4	2	2	1.60E-06	5.20E-06	2.4	1.6	2.1	1.6

Table III (cont.).

site 2	T_{AIR}	Seasonal average temperature of the soil					Diffusivity seasonal average ground			Seasonal soil moisture			
		5 cm	10 cm	30 cm	50 cm	100 cm	*ATD ₁₀	*ATD ₃₀	*ATD ₅₀	U% ₁₀	U% ₃₀	U% ₅₀	U% ₁₀₀
Summer_2012	-	2.9	2.8	2.3	1.9	1.2	1.10E-06	2.20E-06	3.50E-06	24	26.6	22.8	27.1
Fall_2012	-	-3	-2.7	-2	-1.5	-1	-2.80E-08	1.80E-06	3.00E-06	19.4	22.7	21.5	23.9
Winter_2012	-	-3.7	-3.7	-3.6	-3.5	-3.3	-1.40E-07	2.40E-06	3.00E-06	18.6	21.4	20.4	21.5
Spring_2012	-	-1.4	-1.4	-1.6	-1.7	-1.8	-2.50E-07	1.30E-06	5.80E-06	18.9	21.9	20.7	21.8
Summer_2013	1.26	1.1	0.9	0.3	-0.1	-0.4	6.70E-07	1.10E-06	-4.50E-08	23.2	25.2	22.4	23.1
Fall_2013	-2.32	-0.7	-0.4	-0.1	0.1	0	6.80E-08	1.40E-06	2.10E-06	21.7	25.3	23.2	26.9
Winter_2013	-6.6	-3.3	-3.1	-2.8	-2.6	-2.3	-3.50E-07	1.90E-06	1.10E-06	19	22	20.9	22.4
Spring_2013	-1.94	-0.6	-0.6	-0.9	-1.1	-1.3	-4.00E-08	7.90E-07	5.10E-06	19.6	22.5	21.1	22.5
Summer_2014	0.19	1.5	1.3	0.7	0.2	-0.2	1.60E-07	1.50E-06	1.60E-06	24.7	25.4	23.2	24.7
Fall_2014	-2.45	-0.8	-0.6	-0.3	-0.1	-0.1	1.30E-07	4.10E-07	4.30E-07	20.2	24.8	23.2	26.5
Winter_2014	-4.16	-2.1	-2	-1.9	-1.8	-1.5	-1.30E-07	1.90E-06	5.10E-07	19.4	21.4	20.2	22
Spring_2014	-1.99	-1	-1	-1.2	-1.3	-1.4	-6.90E-08	1.20E-06	1.20E-06	19.6	21.6	20.3	21.9
AVG	-2.3	-0.9	-0.9	-0.9	-1	-1	9.60E-08	1.50E-06	2.30E-06	20.7	23.4	21.7	23.7
STD	2.4	2	1.9	1.6	1.4	1.2	4.10E-07	5.70E-07	1.90E-06	2.1	1.9	1.2	2.1

site 3	T_{AIR}	Seasonal average temperature of the soil					Diffusivity seasonal average ground			Seasonal soil moisture			
		5 cm	10 cm	30 cm	50 cm	100 cm	*ATD ₁₀	*ATD ₃₀	*ATD ₅₀	U% ₁₀	U% ₃₀	U% ₅₀	U% ₁₀₀
Summer_2011	2.8	3.2	3.2	3.1	2.9	2.6	-1.10E-06	2.40E-06	6.50E-06	31.9	29.5	26.5	27.5
Fall_2011	-4.9	-2.2	-2.8	-2.1	-1.6	-0.9	7.70E-08	1.90E-06	1.50E-06	24.6	24.8	23.4	23.1
Winter_2011	-8	-6.3	-6.7	-6.1	-5.6	-4.6	-1.20E-07	3.20E-06	8.00E-09	24.6	23.3	22.4	20.9
Spring_2011	0	0	0.4	-0.2	-0.6	-1.1	-1.10E-07	1.40E-06	-8.90E-08	27.9	25.6	23.9	24.6
Summer_2012	2.2	4.1	4.2	3.9	3.5	2.6	-5.40E-07	2.40E-06	2.90E-06	29.9	28.8	25.6	25.3
Fall_2012	-4.3	-2.3	-2.8	-2.1	-1.6	-0.8	1.60E-07	2.10E-06	2.90E-06	24.5	24.9	23.5	23.2
Winter_2012	-5.6	-4.5	-4.7	-4.4	-4.1	-3.5	-3.50E-07	2.60E-06	2.50E-06	23.1	23	22.1	20.9
Spring_2012	-1.6	-0.4	0.1	-0.5	-0.8	-1.1	-8.30E-08	1.10E-06	1.80E-06	26.4	24.9	23.3	22.1
Summer_2013	2.4	3.9	4.3	3.7	3.2	2.3	-8.00E-07	2.20E-06	3.50E-06	29.1	28.2	25.1	25.3
Fall_2013	-1.9	-0.5	-0.9	-0.4	-0.2	0.2	-1.60E-07	1.90E-06	3.50E-06	26	26.7	24.9	25.9
Winter_2013	-6.8	-4.5	-4.9	-4.4	-4	-3.1	-2.60E-07	1.90E-06	-5.40E-07	22.3	23.1	22.4	21.5
Spring_2013	-0.6	0.2	0.7	0	-0.3	-0.7	-2.60E-07	9.60E-07	7.40E-07	26.4	25.3	23.8	23.4
Summer_2014	1.3	3	3.3	2.9	2.5	1.9	-2.70E-08	2.20E-06	4.20E-06	28.5	28.4	25.6	25.4
Fall_2014	-2.7	-1.1	-1.4	-1	-0.8	-0.4	1.20E-07	7.50E-07	4.20E-06	24.8	26.7	24.8	25.3
Winter_2014	-4.2	-3.5	-3.8	-3.4	-3.1	-2.4	-3.30E-07	2.80E-06	1.10E-06	22.2	22.8	21.7	21.2
Spring_2014	-1.3	-0.3	0.1	-0.4	-0.7	-1	-2.80E-07	7.20E-07	2.70E-06	26.4	25.3	23.8	22.6
AVG	-2.1	-0.7	-0.7	-0.7	-0.7	-0.6	-2.50E-07	1.90E-06	2.30E-06	26.1	25.7	23.9	23.6
STD	3.3	3.1	3.4	3	2.7	2.2	3.30E-07	7.40E-07	1.90E-06	2.75	2.17	1.4	2.04

Table III (cont.).

site 4	T_{AIR}	Seasonal average temperature of the soil						Diffusivity seasonal average ground		Seasonal soil moisture	
		TB_{10}	TB_{30}	TB_{80}	TC_{10}	TC_{30}	TC_{80}	$*ATD_{TB-30}$	$*ATD_{TC-30}$	$UB_{80}\%$	$UC_{80}\%$
Fall_2011	-5.5	-2.6	-2.2	-1.6	-2.2	-1.8	-1.4	7.80E-07	2.80E-06	22.7	23
Winter_2011	-8.8	-5.2	-5	-4.4	-5	-4.8	-4.3	6.20E-07	-7.50E-08	21.8	22.1
Spring_2011	?	-1.5	-1.8	-2.2	-1.7	-1.9	-2.2	-3.10E-07	-8.10E-07	22.2	22.4
Summer_2012	0.8	0.7	0.2	-0.4	0.4	-0.1	-0.5	1.80E-06	2.70E-06	23.4	23.1
Fall_2012	-4.8	-3.3	-2.6	-1.7	-2.8	-2.3	-1.8	1.40E-06	2.50E-06	23.7	22.7
Winter_2012	-5.8	-4.4	-4.4	-4.1	-4.4	-4.3	-4.1	1.50E-06	9.80E-07	22.1	21.9
Spring_2012	-2.1	-2.2	-2.3	-2.5	-2.3	-2.4	-2.5	1.80E-07	-3.40E-07	22.4	22.2
Summer_2013	0.8	-0.3	-0.5	-0.9	-0.4	-0.6	-0.9	-1.30E-08	1.90E-06	22.8	22.7
Fall_2013	-2.4	-1.7	-1.5	-1.4	-1.5	-1.4	-1.3	1.00E-06	1.70E-06	22.8	22.6
Winter_2013	-7.3	-4	-3.8	-3.4	-4	-3.8	-3.5	-5.50E-07	-4.70E-07	22.2	22.1
Spring_2013	-2.4	-1.1	-1.4	-1.8	-1.3	-1.5	-1.8	3.80E-07	3.20E-07	22.5	22.4
Summer_2014	-0.5	-0.2	-0.3	-0.6	-0.2	-0.4	-0.6	3.30E-07	2.00E-06	23	22.8
Fall_2014	-3.1	-2.3	-2.1	-1.7	-2.2	-2	-1.7	1.60E-06	3.20E-06	22.8	22.5
Winter_2014	-5.1	-2.8	-2.8	-2.7	-2.8	-2.7	-2.6	4.80E-07	4.10E-07	22.4	22.2
Spring_2014	-2.8	-1.6	-1.8	-2	-1.7	-1.8	-2	3.10E-07	2.10E-07	22.6	22.3
AVG	-3.5	-2.2	-2.1	-2.1	-2.1	-2.1	-2.1	6.40E-07	1.10E-06	22.6	22.5
STD	2.9	1.6	1.4	1.2	1.5	1.4	1.2	7.10E-07	1.30E-06	0.5	0.4

AVG = average; STD = Standard deviation; $*ATD_{10}$ = apparent thermal diffusivity at 5, 10 and 30 cm depth and ATD_{30} = apparent thermal diffusivity at 10, 30 and 100 cm depth (site 1); ATD_{10} = apparent thermal diffusivity at 5, 10 and 30 cm depth 5, 10 and 30 cm depth; ATD_{30} = apparent thermal diffusivity at 10, 30 and 50 cm depth and ATD_{50} = apparent thermal diffusivity at 30, 50 and 100 cm depth (sites 2 and 3). $ATD_{TC/TB-30}$ = apparent thermal diffusivity at 10, 30 and 80 cm depth at the polygon border (TB) and center (TC).

Table IV. Multivariate linear regression between the apparent thermal diffusivity of soil (ATD) and soil moisture (U) in Keller Peninsula, Maritime Antarctica.

Sites			Coeff.	Std.err.	t	p	r ²	
Site 1	ATD ₁₀	Constant	-1.00E-05	2.00E-06	-4.91	0	0	
		U10	1.10E-06	2.00E-07	5.44	0	0.95	
		U30	-5.20E-07	2.60E-07	-1.97	0.08	0.86	
	ATD ₃₀	Constant	9.00E-06	1.10E-06	8.11	0	0	
		U10	1.90E-05	1.00E-05	1.92	0.09	0.79	
		U30	-3.10E-05	1.80E-05	-1.76	0.12	0.77	
		U100	1.40E-05	8.00E-06	1.78	0.11	0.71	
	Site 2	ATD ₁₀	Constant	-2.30E-06	3.40E-06	-0.67	0.52	0
			U10	-4.20E-09	8.40E-08	-0.05	0.96	0.19
U30			-3.30E-07	3.20E-07	-1.04	0.33	0.19	
U50			4.40E-07	4.50E-07	0.99	0.35	0.16	
ATD ₃₀		Constant	2.20E-05	9.80E-06	2.28	0.05	0	
		U10	-5.50E-07	2.40E-07	-2.34	0.05	0.14	
		U30	2.10E-06	8.90E-07	2.36	0.05	0.05	
		U50	-2.50E-06	1.30E-06	-1.99	0.08	0.07	
ATD ₅₀		Constant	-3.30E-05	2.80E-05	-1.18	0.27	0	
		U30	-6.60E-07	1.90E-06	-0.34	0.74	0.46	
		U50	2.80E-06	3.60E-06	0.77	0.47	0.45	
		U100	-6.10E-07	6.30E-07	-0.98	0.36	0.3	
Site 3	ATD ₁₀	Constant	-2.30E-06	3.00E-06	-0.77	0.47	0	
		U10	1.70E-08	1.60E-07	0.1	0.92	0.74	
		U30	2.20E-07	4.20E-07	0.53	0.61	0.75	
		U50	-1.50E-07	4.40E-07	-0.33	0.75	0.63	
	ATD ₃₀	Constant	-1.20E-05	1.90E-05	-0.62	0.55	0	
		U10	-6.60E-07	9.90E-07	-0.67	0.52	0.68	
		U30	3.00E-06	2.60E-06	1.14	0.29	0.83	
		U50	-1.90E-06	2.70E-06	-0.71	0.5	0.76	
	ATD ₅₀	Constant	8.90E-05	1.00E-04	0.88	0.41	0	
		U30	4.60E-06	5.40E-06	0.85	0.42	0.02	
		U50	-1.60E-05	1.60E-05	-1	0.34	0.03	
		U100	6.40E-06	5.60E-06	1.15	0.28	0.05	
Site 4	ATD _{TB-30}	Constant	-2.10E-05	2.00E-05	-1.02	0.33	0	
		UC80	-3.10E-07	2.60E-06	-0.12	0.91	0.35	
		UB80	1.30E-06	1.90E-06	0.68	0.52	0.38	
	ATD _{TC-30}	Constant	-6.30E-05	3.10E-05	-2.06	0.07	0	
		UC80	3.60E-06	3.90E-06	0.93	0.38	0.46	
		UB80	-7.50E-07	2.80E-06	-0.27	0.79	0.42	

$p = p_value$; $r^2 =$ determination coefficient; Stat err = mean standard error. *ATD₁₀ = apparent thermal diffusivity at 5, 10 and 30 cm depth and ATD₃₀ = apparent thermal diffusivity at 10, 30 and 100 cm depth (Site 1); ATD₁₀ = apparent thermal diffusivity at 5, 10 and 30 cm depth 5, 10 and 30 cm depth; ATD₃₀ = apparent thermal diffusivity at 10, 30 and 50 cm depth and ATD₅₀ = apparent thermal diffusivity at 30, 50 and 100 cm depth (sites 2 and 3). ATD_{TC/TB-30} = apparent thermal diffusivity at 10, 30 and 80 cm depth at the polygon border (TB) and center (TC). U = Soil moisture at 10, 30, 50, 80 and 100 cm depth. UC = Soil moisture at polygon center; UB = Soil moisture at polygon border.

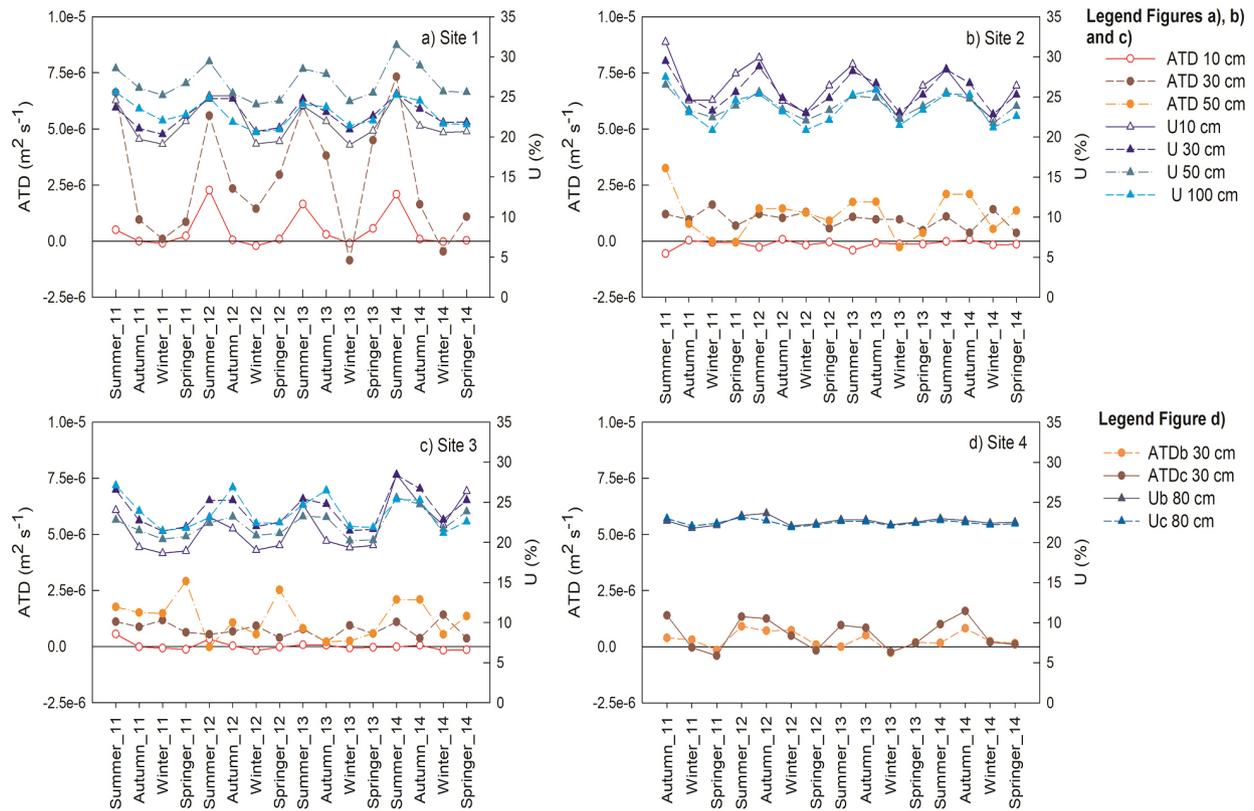


Figure 2. Relationship between apparent seasonal thermal diffusivity of soil and seasonal soil moisture in the Keller Peninsula, Maritime Antarctica. *ATD₁₀ = apparent thermal diffusivity at 5, 10 and 30 cm depth and ATD₃₀ = apparent thermal diffusivity at 10, 30 and 100 cm depth (site 1); ATD₁₀ = apparent thermal diffusivity at 5, 10 and 30 cm depth 5, 10 and 30 cm depth; ATD₃₀ = apparent thermal diffusivity at 10, 30 and 50 cm depth and ATD₅₀ = apparent thermal diffusivity at 30, 50 and 100 cm depth (sites 2 and 3). ATD_{TC/TB_30} = apparent thermal diffusivity at 10, 30 and 80 cm depth at the polygon border (TB) and center (TC). U = Soil moisture at 10, 30, 50, 80 and 100 cm depth. Uc = Soil moisture (%) at polygon center; Ub = Soil moisture (%) at polygon border.

to generate negative *ATD* values during the winter at shallow soil depths. Soil surface is covered by snow during the winter, associated with low soil moisture. Hence, the heat transfer in the soil is dominated by conduction. On the other hand, during the spring as a consequence of early thawing, water infiltration produces a thermal pulse in the active layer that significantly accelerate the soil heating (Almeida et al. 2014).

Despite rainfall (water precipitation) be more common during the summer season, associated with air temperature above 0°C (Rosa et al. 2015), precipitations can also occur during

the winter. Climatologic data from Admiralty Bay (PROANTAR/CPTEC/INPE 2016) evidenced 26.0 and 59.1 mm of water precipitation during the winter and summer, based on temporal series from 1986 to 2010. The *ATD* values presented lower variability in colder conditions, essentially at deeper layers, as reported by Almeida et al. (2014). Also, they report that the *ATD* average values were positive in the winter ($1.7 \times 10^{-7} m^2/s$) at 30 cm depth, corroborating with the results in Keller Peninsula.

Michel et al. (2014) reported higher *ATD* values, being: $6.3 \times 10^{-6} m^2/s$ (2011) and $6.8 \times 10^{-6} m^2/s$ (2012) during winter season and

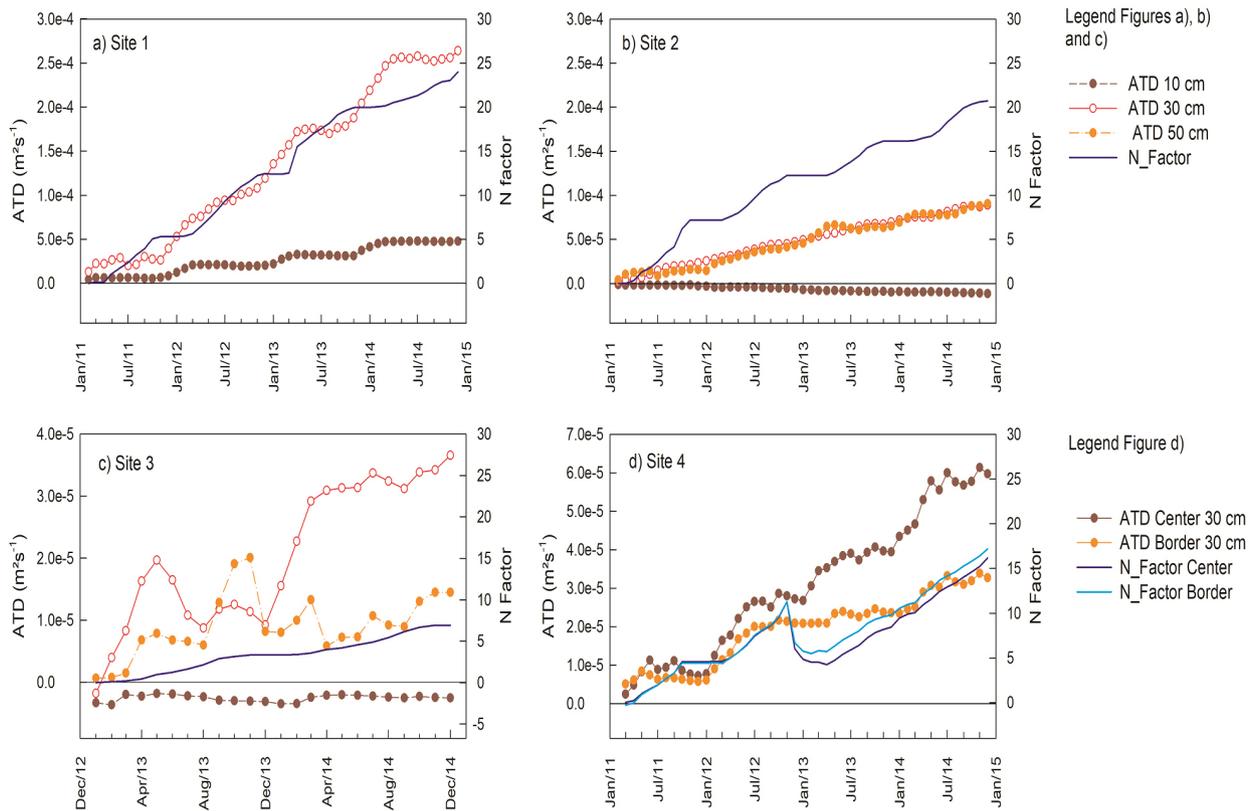


Figure 3. Relationship between the accumulated N-factor and ATD in Keller Peninsula, Maritime Antarctica. *ATD₁₀ = apparent thermal diffusivity at 5, 10 and 30 cm depth and ATD₃₀ = apparent thermal diffusivity at 10, 30 and 100 cm depth (site 1); ATD₁₀ = apparent thermal diffusivity at 5, 10 and 30 cm depth, 5, 10 and 30 cm depth; ATD₃₀ = apparent thermal diffusivity at 10, 30 and 50 cm depth and ATD₅₀ = apparent thermal diffusivity at 30, 50 and 100 cm depth (sites 2 and 3). ATD_{TC/TB_30} = apparent thermal diffusivity at 10, 30 and 80 cm depth at the polygon border (TB) and center (TC). U = Soil moisture at 10, 30, 50, 80 and 100 cm depth. UC = Soil moisture at polygon center; UB = Soil moisture at polygon border.

$3.5 \times 10^{-5} m^2/s$ (2009), $2.3 \times 10^{-4} m^2/s$ (2010) and $2.9 \times 10^{-5} m^2/s$ (2011) during the summer season, for all depths from 10.5 and 32.5 cm at Fildes Peninsula, maritime Antarctica.

Low soil diffusivity indicates lower capacity to transfer energy and greater capacity to store energy, and vice versa. Comparing all sites, sites 2 and 1 presented the lowest and highest ATD values near the surface, respectively. Thus, the most sensitive to temperature change was observed in site 2. With this, it takes longer to reach a new equilibrium condition at site 2, with a rapid thermal response at

site 1. Lower soil water content results in low thermal conductivity and relatively high thermal diffusivity (Seybold et al. 2009). However, at the beginning of soil thawing (spring-summer), soil moisture is enhanced with higher ATD values. In this case, water fills soil pores and act as a link between soil particles, leading to an increasing in heat propagation and consequently thermal diffusivity (Colabone 2002). Thus, ATD was positive in the summer overall. The exception was site 2, which obtained the highest number of thawing days (431 days), considering all years and depth of 10 cm. This caused an increase

in soil moisture on the surface, resulting in negative and positive diffusivity at the surface and in deeper soil layers, respectively.

N-factor values are influenced by depth and soil thermal properties, as well as the dominant processes of the active layer are related to the phases of soil freezing and thawing (Riseborough 2003). High *N*-factor values during the winter can be related to the temperature sensor burial during the winter; this would limit temperature changes in both air and temperature sensors at 5 cm depth. When snow cover is relatively thin with high albedo, the soil surface becomes colder. With an increase in the snow thickness (greater than 40 cm), the insulation effect of the snow cover enhances, buffering temperature. This occurs because there is a freezing front blocking, which delays the heat flow in depth, as well as lower absorption of solar energy, with decreasing soil surface temperature (Zhang 2005, Hinkel et al. 2001).

The beginning of freezing conditions started from June/September, and remained stable up to November/March in sites 1, 2 and 3, according to the *N*-factor values obtained in this work. Site 4 showed a marked decrease of temperature between 11/2012 and 01/2013. In this period, the El-Niño – South Oscillation (ENSO) signal was negative when compared to the other years (positive values). This phenomenon may have influenced the snow thickness in these months. However, this same pattern was not verified in the other sites. Site 3 presented lower *N*-factor values followed by sites 4, 2 and 1. This shows the influence of the landscape setting in site 3, protecting the studied area from strong winds and controlling snow coverage over time. According to Zhang (2005), seasonal snow coverage is one of the main factors that influence the soil thermal regime. This result can be explained by factors such as albedo, emission and energy absorption, low thermal conductivity and latent

heat. The *N*-factor index varies between years and sites. These differences can be observed due to the variations on snow characteristics (grain size and shape, surface roughness, liquid water content, and other impurities), thickness and duration, as well as their distribution, which can significantly influence the soil thermal regime (Zhang 2005, Almeida et al. 2014).

CONCLUSIONS

The estimation of apparent soil thermal diffusivity allowed inferring about thermal properties of different soils in ice-free areas of maritime Antarctica. Soil diffusivity tends to infinity when soil temperature values are closer or in the isothermal status. Hence, mean soil temperature variation values approaching $\pm 0.04^{\circ}\text{C}$ must be disregarded during the modeling process. *ATD* increased with depth. All studied sites showed negative (*ATD*₁₀) and positive tendency (*ATD*₃₀ and *ATD*₅₀) during the winter. Most of the *ATD* values were negatives during the winter, indicating the influence of rainfall on the thermal dynamic. Soil moisture influenced more the *ATD* at sites 1 and 3 (more than 70 and 63% of probability, respectively). Soil moisture appears to influence the *ATD* ($p > 0.05$) in site 2 and 4. However, the coefficient of determination (r^2) did not explain most of the variability in the observed values. The *N*-factor varied among years and between sites. The relationship between accumulated freezing *N*-factor and *ATD* was inversely proportional comparing the diffusivity near the surface (*ATD*₁₀). And, the correlation between the *N*-factor and *ATD* increases with the soil depth.

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DANIELA A. CHAVES performed field work and, data analysis and wrote the paper. GUSTAVO B. LYRA performed field work and advised on the methodologies and corrected the manuscript. MÁRCIO R. FRANCELINO performed field work, provided comments, and improved the quality of the manuscript. ANDRÉ THOMAZINI performed soil analysis, prepared the results for discussion, and helped on the writing. LEONARDO D.B. DA SILVA and CARLOS E.R.G. SCHAEFER gave significant comments and fundamental improvements to the data interpretation and manuscript elaboration.

