An Acad Bras Cienc (2024) 96(Suppl. 2): e20230743 DOI 10.1590/0001-3765202420230743
Anais da Academia Brasileira de Ciências | *Annals of the Brazilian Academy of Sciences*
Printed ISSN 0001-3765 I Online ISSN 1678-2690
www.scielo.br/aabc | www.fb.com/aabcjournal

FORESTRY SCIENCE

Ground temperature trend and active layer dynamics in the Fildes Peninsula, King George Island - Marine Antarctica

TAMÍRES P. CORREIA, MARCIO R. FRANCELINO, GUSTAVO V. VELOSO, ROBERTO F. MICHEL, CARLOS ERNESTO SCHAEFER, ELPÍDIO INÁCIO FERNANDES FILHO, FLÁVIO B. JUSTINO & GUSTAVO B. LYRA

Abstract: Ground temperature's sensitivity to climate change has garnered attention. This study aimed to monitor and analyze temporal trends and estimate Active Layer Thickness from a monitoring point at Fildes Peninsula, King George Island, in Antarctica. Quality control and consistency analysis were performed on the data. Methods such as serial autocorrelation, Mann-Kendall, Sen-Slope, Pettitt, and regression analysis tests were applied. Spearman's correlation examined the relationship between air temperature and ground depths. The active layer thickness was estimated using the maximum monthly temperature, and the permafrost lower limit used the minimum monthly temperature. Significant summer seasonal trends were observed with Mann-Kendall tau, positive Sen-Slope, and Pettitt slope at depths of 67.5 and 83.5 cm. The regression analysis was significant and positive for all ground depths and in different seasons. The highest correlation (r=0.82) between air temperature and surface ground depth was found. Freezing prevailed at all depths during 2008-2018. The average Active Layer Thickness (ALT) was 92.61 cm. Temperature is difficult to monitor, and its estimation is still complex. However, it stands out as a fundamental element for studies that refer to the impacts of climate change

Key words: Climatic variability, permafrost, ground moisture, temporal trend.

INTRODUCTION

Most studies on modeling and future climate change scenarios show rising air temperatures and sea levels on a global scale, especially at high latitudes (Govil et al. 2018). Other related processes are also predicted, such as ocean acidification, changes in wind patterns and greater depletion of the ozone layer, mainly in Antarctica (Hughes et al. 2017). In addition to the intensification of extreme events, which may also be related to climate change (Polvani et al. 2011). The abnormal heating of the planet has modified the patterns of cyclonic activities, increasing the occurrence and intensity of meteorological phenomena, which affects the availability of water and nutrients, influencing the distribution of vegetation in various regions, in addition to the extinction of several species of the fauna (Fernandino et al. 2018).

Antarctica is the ideal environment to identify the effects of changes and climate variability, considered a great natural laboratory, due to its sensitivity to any change in the global climate (Almeida et al. 2017). Antarctica is responsible for influencing and controlling various processes in the atmosphere and plays an important role in the planet's energy and radiation balance due to latent heat exchanges, the freezing and thawing processes of water, and the high reflective power of the cryosphere (albedo greater than 90%) (Govil et al. 2018). It also stands out as a major energy sink (thermal regulator) and, together with the Arctic, contains the largest reserve of ice and fresh water in the world (Walker & Gardner 2017). The north of the Antarctic Peninsula is the region where atmospheric temperatures showed the greatest increase in the period 1950-2000, around 2.5°C, this is much higher than the global average of 0.6°C for the same period (Turner et al. 2014). As a consequence, the retreat of glaciers in this region has been increasing and the tendency is for a greater increase in the future, exposing new areas to major geomorphological, biological and hydrological changes (Solomina et al. 2016). Due to its proximity to the permafrost climatic boundary, this is a crucial area to analyze climate-ground interactions (Michel et al. 2012, Hrbáček et al. 2017).

Climate variability influences the turbulent flows of the atmosphere and act directly on several meteorological variables, such as air and ground temperature (Bai et al. 2014a). These phenomena also affect ground temperature, which is an important factor because it directly affects biogeochemical cycles, with greater emphasis on the water and carbon cycle, microbial activities, mineralization of organic matter, chemical reactions in the ground, pedogenesis and diffusion of solutes and gases (Jiang et al. 2016). Due to the sensitivity of ground temperature in describing the processes that are taking place in the environment, even more so in areas with the presence of permafrost, it is important to study the temperature patterns in the active layer of the ground, which is dependent on thermal conductivity, specific heat , surface emissivity, as well as being related to external factors, atmospheric conditions and their seasonal variation, and intrinsic factors such as ground texture and composition, cover and relief (Rasmussen et al. 2018).

Most of the studies on ground temperature are concentrated on forecasting and modeling aspects. Recently, some studies have investigated the ground temperature trend, but still with little emphasis on the dynamics of the thermal regime (Bai et al. 2014b, Jiang et al. 2016). This scarcity of studies is due to the unavailability and accessibility of historical ground temperature series, which are more restricted in relation to other hydro-climatic variables (Pingale et al. 2014). Several authors comment on the lag of temporal and spatial data, as restrictive for more detailed studies and consequently for decision-making and/or elaboration of public policies (Fernandino et al. 2018).

Trend analyzes in time series have been frequently applied to perform diagnoses and prognoses (scenarios), and the Mann-Kendall trend test (Mann 1945, Kendall 1975) stands out for detecting monotonic trends in environmental, meteorological series, hydrological and, after the IPCC reports, the use of this test can support responses to mitigate the increase in temperature under different conditions (Panwar et al. 2018).

Due to the importance of trend studies on environmental variables to understand the effects of climate variability and extreme events, the present study aimed to analyze the dynamics, thickness of the active layer and its temporal trend. A series of 10 years of ground temperature, collected at different depths, in the Fildes Peninsula, King George Island, Maritime Antarctica, was used.

MATERIALS AND METHODS

Characterization of the study area

Fildes Peninsula is located west of King George Island, which is part of the South Shetland Archipelago in Marine Antarctica. Fildes Peninsula has approximately 29 km² and stands out for having the largest ice-free area on King George Island.

The climate classification according to Köppen is ET (Tundra climate), because the average air temperature in summer (DJF) is above 0 °C (Michel et al. 2014a). Annual rainfall ranges from 350 to 500 mm, with a maximum in the summer period. The vegetation found is mostly composed of lichens and mosses. The main ground classes are Cryosol and Arenosol; Leptosols, Gleysols and Cambisols also occurent (Michel et al. 2014a). Still according to these authors, the grounds present pedogenetic development according to Antarctic standards and are influenced by cryoturbation and orthogenesis, being shallow and poorly developed. The landscape of the Peninsula is composed of a series of periglacial relief features with an approximate age between 8,000- and 6,000-years BP, being mainly influenced by the advance and retreat dynamics of the Collins Glacier, which exposes a smooth to soft-undulating topography, with a domain of plains cut by rocky basalt outcrops (Michel et al. 2014a).

Time series of ground temperature, ground moisture, air temperature, rainfall, and snow

The coordinates of the ground temperature and moisture monitoring site in Fildes Peninsula are 62°12’21’’ S and 58°57’61’’ W (datum WGS-84). The installation location of the site is in the domain of Túrbic Cryosols at an elevation of 65 m, which is the most common type of ground on this Peninsula, the ground cover is composed of spaced vegetation of mosses and lichens, in a skuas (*Stercorarius antarcticus)* nesting area, with a slope of 3% (Michel et al. 2014a).

The system has four ground temperature sensors at the following depths: 10.5, 32.5, 67.5 and 83.5 cm and a ground moisture sensor at a depth of 83.5 cm, the sensors were installed at the mid-depth of each ground horizon. Thermistors (accuracy of ± 0.2 °C, model 107 Temperature Probe, Campbell Scientific Inc, Utah, USA) were arranged vertically and connected to a datalogger (model CR 1000, Campbell Scientific Inc., Utah, USA), with data recording in a periodicity of 1 hour, starting on March 1, 2008 until December 8, 2018.

Daily data of rainfall (mm), air temperature and fresh snow (cm) were provided by the Polar Research Institute of South Korea, from the meteorological station of King Sejong Station - King George Island, with coordinates: 62 °13’22’’ S, 58°47’18’’ W, at 9 km in a straight line from the monitoring site in Fildes. The snow is measured once a day manually with a ruler at the weather station site, usually at three different points. The precipitation is measured by a heated rain gauge (Young 52202, heated tipping bucket rain gauge, 0.1mm resolution) installed at 1-m above ground level, at 10-minute interval. Air temperature sensor (HMP45D till 2016, later HMP155) was located at 1.5 m above ground level, producing 10-minute interval values (Park et al. 2013).

Rain and snow data were made available with quality control and consistency analysis. Therefore, the following data treatment methodologies were not applied. Data were plotted together with ground moisture at 83.5 cm depth to analyze the effect of precipitation on ground moisture peaks.

Data quality, consistency analysis and exploratory analysis

The first step was to verify the occurrence of time zone errors that occurred while downloading the ground temperature and moisture data. Outliers were identified and removed using the quartile method with a boxplot (interquartile interquartile, utilized 1.9 * IQR). Temperature series that exhibited failures greater than 1/3 of the total (per day or month) were excluded. In cases of missing data, the NA.MA function (utilizing the Weighted Moving Average method) was used to fill in the gaps. An exploratory analysis was carried out to calculate the minimum daily temperature for each depth; maximum daily temperature for each depth; average temperature of the entire series by depth; and maximum daily amplitude for each depth. First, the daily average was taken and then the monthly average was calculated. Over ten years of monitoring, 471,320 data points were generated for temperature and ground moisture. The methods of randomness (Bartels's tests), Independence and stationarity (Wald-Wolfowitz), Stationarity (Dickey-Fuller Test), Standard Normal Homogeneity Test (SNHT) and Normality Test (Kolmogorov-Smirnov), evaluated at the level of 5% probability. These procedures were performed using the R software (Core Team, 2022) and packages desctools, randtests, tseries, trend e stats (Signorell et al. 2022, Caeiro 2022, Trapletti et al. 2023, Pohlert 2020).

To eliminate the influence of seasonality in each time series, the Z statistic transformation was applied in each month of each variable (Figure S1). This methodology allows the normalization of the series, which are considered "anomalies" and dimensionless a methodology carried out by Chaves et al. (2017). These procedures were also performed using the R software (Core Team 2022) together with packages dplyr, fitdistrplus and lmomco (Wickham et al. 2019, Delignette-Muller & Dutang 2015, Asquith 2023). After removing the effect of seasonality, the series is more easily correlated as they vary in the same degree of amplitude—an example of the formula applied to correct the month of January for ground temperature in the Fildes series (Equation 1).

$$Z_{January2008} = \frac{\overline{x}_{January\ 2008\ monthly} - \overline{x}_{all\ months\ January\ of\ the\ series\ (2008\text{-}2018)}}{\sigma_{all\ months\ January\ of\ the\ series\ (2008\text{-}2018)}} \quad (1)$$

where: $Z_{January\ 2008\ Monthly}$ is the monthly average of January ground temperature normalized; $\overline{x}_{January\ 2008\ monthly}$ is the monthly average of ground temperature for the month of January to be normalized; $\overline{x}_{all\ months\ January\ of\ the\ series\ (2008\text{-}2018)}$ is average ground temperature for all months of January for the series (2008 – 2018); σ is the standard deviation of ground temperature for all months of January (2008 -2018).

For the series of rain and snow, the Standarized Precipitation Index (SPI) was calculated, thus normalizing the series so that the mean is zero and the standard deviation is 1 N [0.1]. It indicates the anomaly and allows classifying it. The "SCI" package was used in the R software (Stagee et al. 2016). Rainfall, precipitation and ground moisture were standardized, which allowed a good visual correlation.

Trend analysis, autocorrelation in the data series

The non-parametric Mann-Kendall (MK) statistical test has been widely used to check for trends especially in hydrological data and climatological factors, such as temperature (Pingale et al. 2014). In the test, the order classification of the event and its temporal order matter (Araghi et al. 2017). The Mann-Kendall (MK) measures the degree to which a trend is rising (1) or decreasing (-1) consistently over time, determined on the basis of Mann-Kendall tau, that is, the relative frequency of agreements minus the relative frequency of disagreements (Pingale et al. 2014). Positive values indicate an upward trend and negative values decreasing trend. The null hypothesis of the test is that there is no trend in the data and the alternative is that the data represent a monotonous trend. The original MK test is calculated by Kendall (1975) and Mann (1945).

However, in the case of environmental data with patterns influenced by the effect of seasonality, it is necessary to perform the serial autocorrelation test, since the possibility of series showing autocorrelation can mask the trend test (Hirsch et al. 1982). In a practical way, autocorrelation is identified by making a correlogram, where the autocorrelation coefficients are plotted by different lags. Autocorrelation of Lag-k and coefficient (rk) in a time series can be calculated (Yue & Wang 2004), the tests are evaluated with 95% reliability.

If the sample data is in correlated series, the significance of serial lag-1 autocorrelation at the significance level of $\alpha = 0.1$ of the two-tailed tests is evaluated. If the autocorrelation is significant, in this case, the Mann-Kendall modified test is used. Autocorrelation alters the variance of the Mann-Kendall estimate, and the presence of a trend changes the estimate of the magnitude of the serial correlation. Yue & Wang 2004 describe numerous modified methods of the Mann-Kendall test, adapted by several authors, among them can be cited: pre-bleaching tests (PW), pre-bleaching without trend (TFPW) and modified Mann-Kendall through variance correction, calculating the effective sample size. Noting the serial autocorrelation, for the situation of this analysis the most appropriate test is the method proposed by Hamed & Ramachandra Rao (1998). Regression analysis was also applied, evaluated at a probability level of 5%.

Trend Test – Modified Mann Kendall

Hamed & Ramachandra Rao 1998 proposed an empirically based method used to calculate the effective sample size (ESS). ESS is useful to compensate for the effect of serial correlation variance, called variance correction (VCA). The corrected variance is then used to substitute the old variance for the reconstruction of confidence intervals and critical regions. Finding a positive or negative trend, the trend strength analysis test, measure the degree of slope of the line which must be applied. The tests carried out in the present work to identify trends were applied to the scales: monthly, annual, seasonal (summer/winter) and with lags of 2, 3 and 4 years.

Sen-Slope Test

The Sen-Slope test (Sen 1968), a non-parametric test, estimates the trend slope of the series for each data point for each time interval. The sign of the Q med value indicates the trend of the data, and its value shows the slope of the trend. But it is on the basis of the confidence interval that it is determined whether the slope is statistically different from zero, in the 95% confidence interval. When Maximum Q and Minimum Q have the same sign, med Q is statistically different from 0. With a significant trend, the test to identify at which moment there was a Sudden change in trend must be realized.

Pettitt's Test

Pettitt's non-parametric test is used on data belonging to the same population (Pettitt 1979). It is a test capable of detecting exactly the point of change in a series of data, Pettitt (1979) proposes a new version of the Mann-Whitney statistic to be used to derive probabilities of approximate significance for testing "non-change" against "change". The statistic counts the number of times that a piece of data from the first sample is greater than a data from the second sample. The Sen-Slope and Pettitt tests were applied to the time series on the defined scales, after confirming the significance of the Mann-Kendall test.

The analysis of Trend, Autocorrelation in the Data Series, Trend Test (Modified Mann Kendall), Se n-Slope Test and Pettitt's Test were made in the R software (Core Team 2022) in each of the four depths evaluated. The tests followed the same order described, being used the packages: *dplyr*, *tseries Kendall*, *modifiedmk and trend* (Wickham et al. 2019, Trapletti et al. 2023, Mcleod & Mcleod 2015, Patakamuri et al. 2020, Pohlert 2020).

Interaction between depths and air temperature

Spearman Correlation

Spearman's correlation coefficient, non-parametric, does not require a linear distribution between the variables, also does not show sensitivity of asymmetries in the distribution and is pointed out as an adequate method for the type of correlation required in the work. The method performs rank calculations and considers the order of the data as a relevant factor and not only its value, then suggested to verify the interrelationship of the variable in analysis (de Oliveira & da Cunha 2014). It was used in the study to evaluate the correlation of ground temperature at different depths and air temperature.

Calculation of freezing, thawing, freezing--thawing, isotherms, degrees of freezing and thawing

Freeze days consist of days when all hourly measurements of the ground temperature are negative and at least one reading is colder than –0.5 °C; days of thawing, are the days when all schedules ground temperature measurements are positive and at least one reading is warmer than +0.5 °C; isothermal days are defined as days when all hourly measurements vary by only ±0.5 °C; days of freeze-thaw are the days when there are negative temperatures and positive with at least one value greater than ± 0.5 °C (Guglielmin et al. 2008). Calculations were performed on an annual and seasonal scale for each depth.

Correlation of air and ground temperature data in different depths

The data were sent in "csv" format (Korea Polar Data Centre (KPDC)), with the daily averages for the period corresponding to the ground temperature series. From of data organization, a correlation (Spearman correlation) matrix between air temperature and ground temperature at depths 10.5, 32.5, 67.5 and 83.5 cm was created.

Calculation of active layer thickness - ALT

The ALT was calculated according to the maximum temperature. A logarithmic regression model was used to determine the point at which the maximum monthly temperature reached 0°C, this point was determined as the maximum depth of the active ground layer. The lower limit of permafrost was established when the minimum temperature reached 0°C (Biskaborn et al. 2019, Dobiński 2020).

RESULTS

Data quality, consistency analysis and exploratory analysis ground temperature data in different depths

Methods of randomness, the series were all non-random. For the Independence and stationarity test, the series showed no Independence and stationarity (Wald-Wolfowitz). The series were all stationary for the Stationarity test (Dickey-Fuller Test). For the Standard Normal Homogeneity Test (SNHT) with the trend, all showed a trend. In the Normality Test (Kolmogorov-Smirnov), only the series at 10.5 cm did not show normality (Table SI).

Descriptive analysis ground temperature data

in different depths

The thermal regime of the active layer showed a negative average temperature for the entire period (2008 - 2018) for all depths (Table I). In 2017, the highest daily thermal amplitudes occurred for all depths.

In all years and depths, the average annual temperature was also negative, with emphasis on the years 2011 and 2015, with the lowest annual temperatures in the series, and the years 2014 and 2016, with the highest average annual ground temperatures (Figure 1).

Based on the time series, it was observed that with increasing depth, there is less thermal amplitude and delay in the phases of maximums and minimums (Figure S2). Some patterns were observed, in general, the odd years (2009, 2011, 2015 and 2017) had the coldest (extreme) winters. And in even years (2008, 2010, 2014, 2016 and 2018) there were less intense winters, with emphasis on the years 2014, 2016 and 2018. It is possible that there is a correlation between this thermal behavior and phenomena on a local, regional, and even global scale.

Autocorrelation test on the data series

Serial correlation indicates measures of association between instants of time of the same time series (Araghi et al. 2017). To visualize

Table I. Descriptive analysis of ground temperature (maximum, average and minimum), in the period 2008-2018, in Fildes Peninsula, King George Island, Antarctica.

Depth (cm)	Minimum temperature (°C)	Maximum temperature (°C)	Average temperature (°C)	Maximum amplitude (°C)
10.5	-11.39 (06/24/2017)	9.00 (01/24/2015)	-1.03	7.45 (01/19/2017)
32.5	-8.00 (08/06/2011)	3.02 (01/20/2017)	-1.00	1.92 (07/28/2017)
67.5	-6.51 (08/07/2011)	1.19 (02/20/2018)	-1.12	0.63 (06/24/2017)
83.5	-5.49 (08/08/2011)	0.66 (02/23/2018)	-0.94	0.40 (06/25/2017)

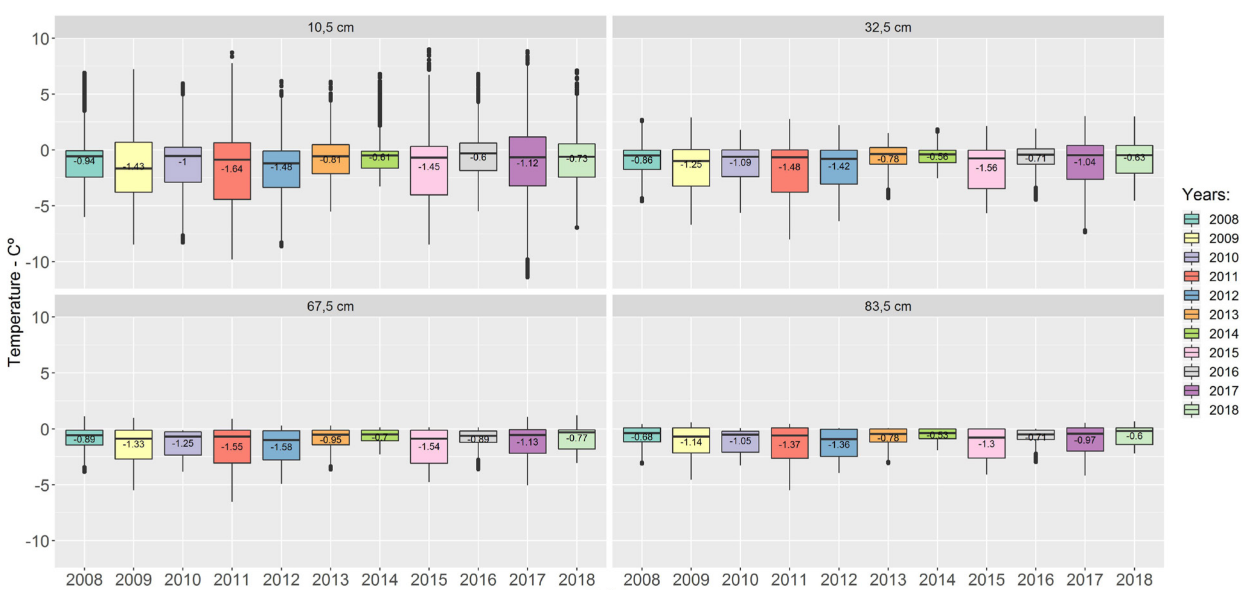

Figure 1. Boxplot of average annual temperatures for depths 10.5; 32.5; 67.5; and 83.5 cm from the ground of the Fildes Peninsula, King George Island, Antarctica.

the autocorrelation coefficients versus different lags, correlograms were plotted, where it is possible to detect the significant non-zero autocorrelation in the different lags (Figure 2). The sample ACF values extrapolate the confidence interval to the 95% confidence level, delimited by the dashed lines. Therefore, the modified version of the MK test by Hamed & Ramachandra Rao 1998 was used for the ground temperature series.

Trend test - Mann-Kendall (MK) modified from Hamed & Rao (1998)

The modified-MK test was efficient in detecting significant trends of increase (positive) or decrease (negative) of ground temperature in different scales: monthly; seasonal; yearly; with lags of 2, 3 and 4 years and for the complete series (2008 – 2018). For monthly analyses, the test was positive and significant for all depths. The months that were significant varied according to the depth, with greater predominance in the months of August, September, and November. For seasonality, only in the summer, the modified-MK was significant, with a positive value, that is, there was a tendency to increase ground temperature for the two greatest depths. However, for the annual test (for each year), the trends were cooling in most years, except for 2010 and 2016, in which the test did not identify any trend (neutral). Likewise, considering different lags (2, 3 and 4 years), only a cooling trend was identified, more frequently in the years 2008, 2009, 2011, 2013, 2014. The test was

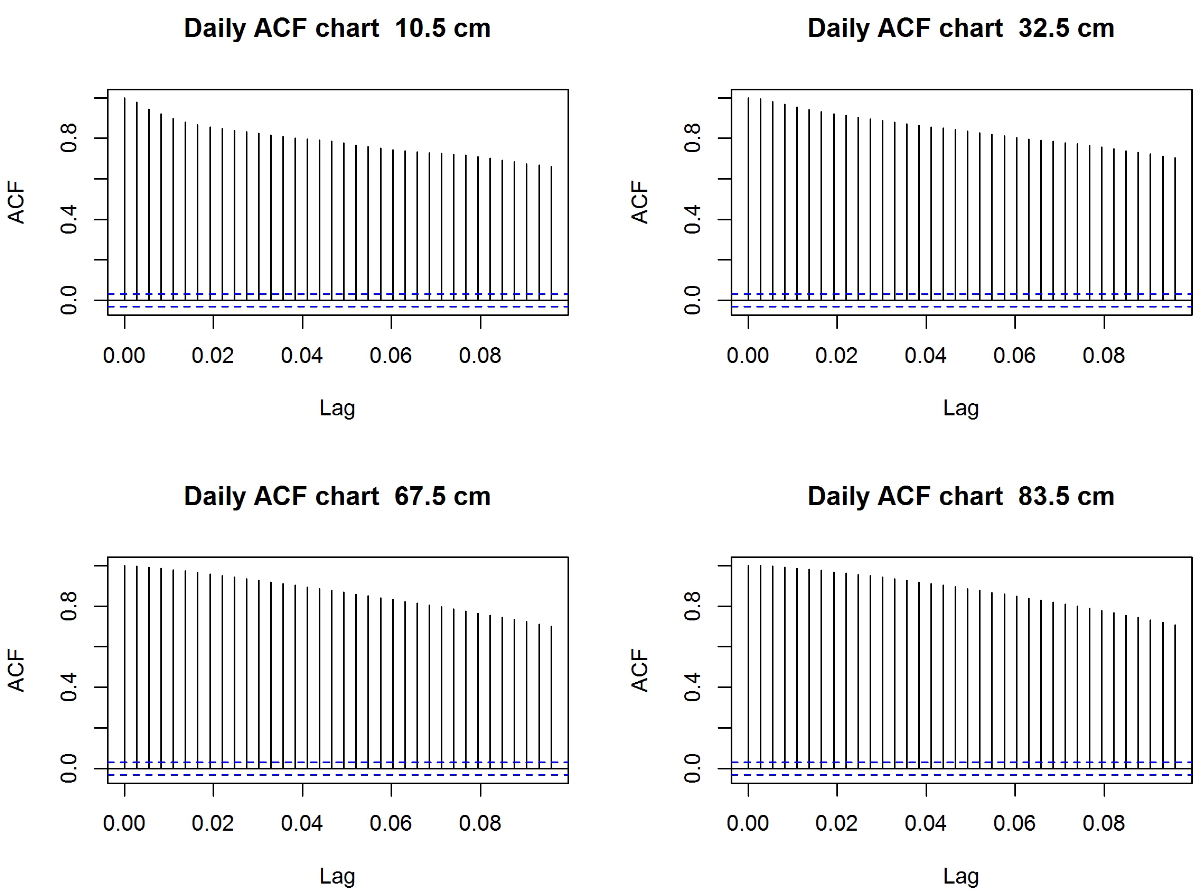

Figure 2. Sample autocorrelation function – ACF for the ground temperature at depths 10.5; 32.5; 67.5; and 83.5 cm on the Fildes Peninsula, King George Island, Antarctica.

not significant for the complete series (2008-2018) (Figure 3).

Although in the complete series using the modified trend method from Hamed & Ramachandra Rao 1998, no significant trend was identified, using the regression method, all depths analyzed were significant (Figure S4 to S22). Testing other modified trend methods, such as the Yue & Wang 2004, would be appropriate. By regression analysis, the series showed a warming trend for all depths. The regression method was also tested for the four seasons of the year and showed a positive trend for all depths in summer and spring; in winter, it was significant and positive for 32.5, 67.5 3 83.5

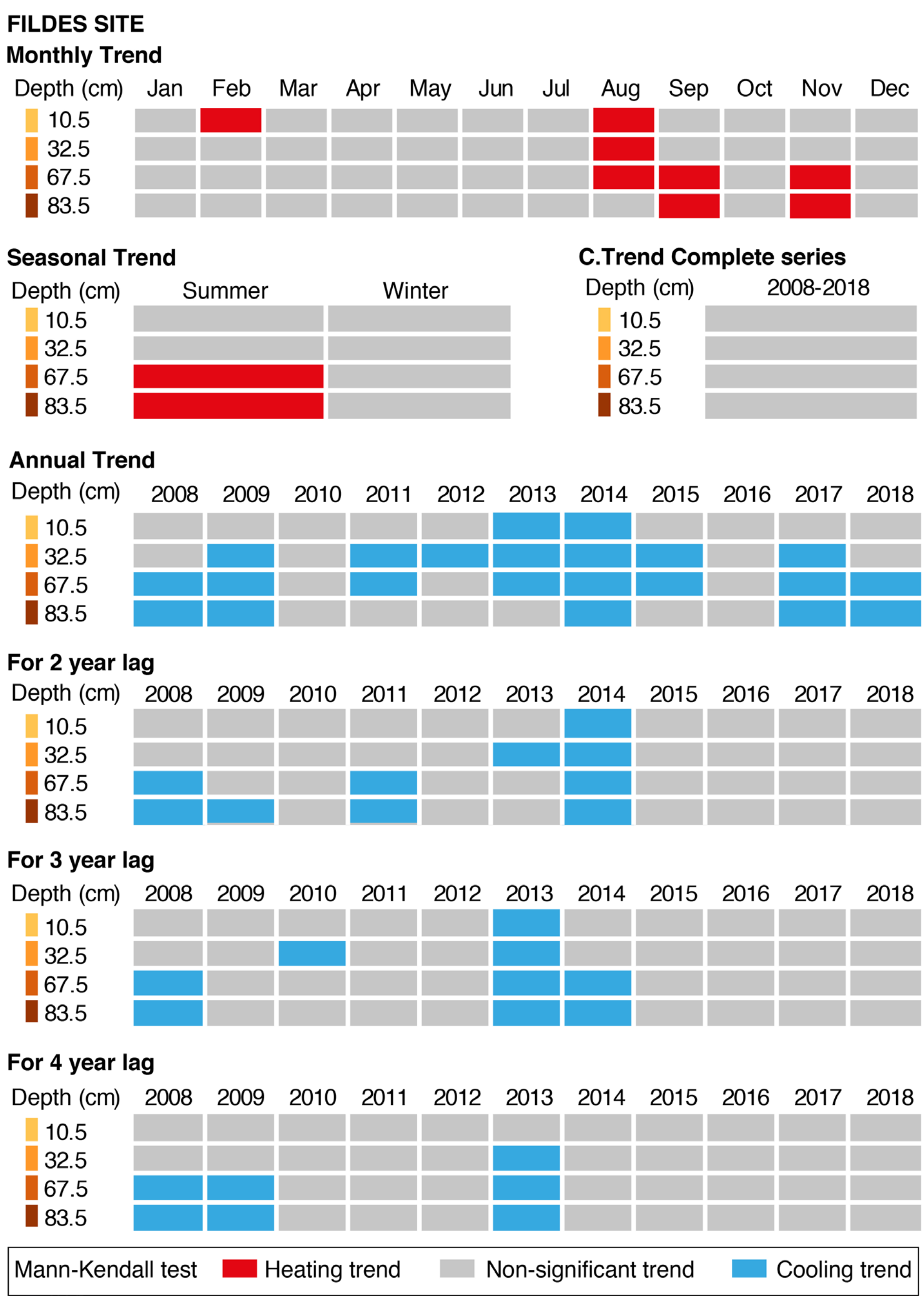

Figure 3. Mann-Kendall test result for full series (2008-2018), seasonal, 2-, 3-, and 4-year lags; Sen-Slope and Pettitt Tests to Fildes Peninsula, King George Island, Antarctica.

cm, and in autumn, it was only significant, and positive for 83.5 cm.

Through the decomposition of the time series (67.5 and 83.5 cm), which showed a positive trend for the seasonal scale (modified method from Hamed & Ramachandra Rao 1998), it is observed that, isolating only the effect of the seasonality trend, there are wave fluctuations (Figure S23). In general, the peaks of maximums and minimums are in accordance with the most rigorous winters and the hottest summers. The years 2009 (07/2009), 2011 (08/2011), 2012 (07/2012), 2015 (09/2015) and 2017 (09/2017), years with the lowest temperatures of the entire series, with emphasis on the harsh winter in 2011, these years formed the trends for the most accentuated valleys. The crests with greater amplitudes, with an upward trend, are formed by the summers of 2008 (02/2008), 2009 (02/2009), 2011 (01/2011), 2017 (02/2017) and 2018 (02/2018), and mild winters with temperatures above average for the series.

Sen-Slope and Pettitt Tests

The Sen-Slope test was appropriate for calculating the slope of the line, which facilitated the detection of changes in the linear trend of the data. From the results of the tests, it was possible to confirm the trend in the slope of the line, indicated by the modified-MK in the significant series.

Therefore, with greater confidence, the result of the first applied trend test (MK-modified) was confirmed, in the seasonal analyzes and in the monthly series, a tendency for temperature increase was observed, whereas in the annual analyzes and with different lag's (2, 3 and 4) tended to decrease ground temperature (Table SII to SVI). In addition to verifying with greater confidence any change in the slope of the line, it was essential to locate the exact point where the sudden change in the data series occurred, as it was possible to have greater precision in the analysis of the processes involved in this temporal change in the data.

Based on the Pettitt test, the exact point of sudden change in the slope of the line was reached, confirmed by the MK-modified and Sen-Slope tests. For seasonal analysis, the turning point of the line occurred in December 2015 (12/18/2015) in the different depths. In the monthly analyses, changes in the slope of the line occurred in February, August, September and November, in the years 2012, 2013, 2014, 2015 and 2016.

For the annual analyses, slope changes occurred in all years for different depths, except in the years 2010 and 2016, and the months with the highest frequencies were May, June and July. The analyzes with lags of 2, 3 and 4 years showed a change in the slope of the line in the months of May and June, in the years 2009, 2011, 2013 and 2015 (Table SVII to SXIII).

Interaction between depths and air temperature (Spearman Correlation)

Air temperature had the highest correlation (r=0.82) with the most superficial ground layer (10.5 cm), and it decreased with depth. The lowest depths of the ground presented greater correlations among themselves, as they are more homogeneous. The highest correlation value (0.95) was between the depth 67.5 and 83.5 cm from the ground, followed by the depth 10.5 cm and 32.5 cm with a correlation of 0.93. As expected, the lowest correlation was between the depth 10.5 cm and 83.5 cm with a value of 0.57 (Table II), it is noted that the flow of energy in the ground is not as efficient between the superficial layer and the deepest point of monitoring.

Analysis of annual freezing, thawing, freeze-thaw and isothermal days and by seasons.

Table II. **Spearman correlation between air temperature and ground temperatures at depths 10.5; 32.5cm; 67.5 and 83.5 cm on the Fildes Peninsula, King George Island, Antarctica.**

	Air temperature	10.5 cm	32.5 cm	67.5 cm	83.5 cm
Air temperature	1				
10.5 cm	0.82	1			
32.5 cm	0.72	0.93	1		
67.5 cm	0.53	0.71	0.88	1	
83.5 cm	0.40	0.57	0.77	0.95	1

The number of days of annual freezing was higher than the other processes for the entire series (Figure 4). Common to all depths, the year 2009 (10.5 cm and 32.5 cm), 2010 (67.5 cm) and 2012 (83.5 cm) stands out. The days of thawing tended to decrease with depth, in the years 2009, 2017 and 2018 there was thawing for all monitored depths. At a depth of 10.5 and 32.5 cm, there was thawing in all years. It was noted that the maximum number of thawing was in the year 2017 at 10.5 cm, with 111 days. The freezing-thawing process was only more expressive for the 10.5 cm depth, specifically in 2010, 2013 and 2015.

For the condition of isothermal days, the series (2008-2018) showed behavior contrary to thawing, as there was an increase in the number of days with depth (Figure 5). At all depths, 2014 had the highest number of isothermal days, with a maximum reached at 83.5 cm with 203 isothermal days. Freezing decreases in winter and autumn for every year with increasing depth, but the process is inverse, that is, increasing with depth in spring and summer for the entire series. Observing some patterns in relation to the processes between the seasons is possible. Freeze-thaw is only noticeable in summer at a depth of 10.5 cm. Thawing decreases from summer to autumn in all years and reaches almost 0 days at the bottom of the profile. Isothermal days increase with depth in summer, autumn and winter and decrease in spring in depth for all years.

Cyclical variation with similar patterns was observed between the first depths (10.5 and 32.5 cm) and between the last depths (67.5 and 83.5 cm). At depths of 10.5 and 32.5 cm, freezing days totaled 100% and 96.54%, in winter. In spring the warming process begins, with days between freezing and isothermal. The thawing process occurs with greater intensity in summer, at depths of 10.5 and 32.5 cm.

In the last depths 67.5 and 83.5 cm, the freezing days reached the maximum with practically 100% of the data in the spring, and in the summer the thawing process almost did not occur. In summer, the series remained in the isothermal range, with a decrease in autumn, and in winter, the days gradually change the temperature from isothermal to freezing days, and thus, the cycle ends again with maximum freezing in spring. This pattern was also verified with few fluctuations in all years of the data series for deeper ground temperatures. This fact characterized the effect of latent heat, in keeping the ground temperature close to 0 °C, driven by freezing and thawing in the most superficial layer of the ground, culminating in a strong zero curtain effect, which concerns the dissipation of energy for exchange water phase (latent heat), whether to freeze or thaw (Michel et al. 2014b).

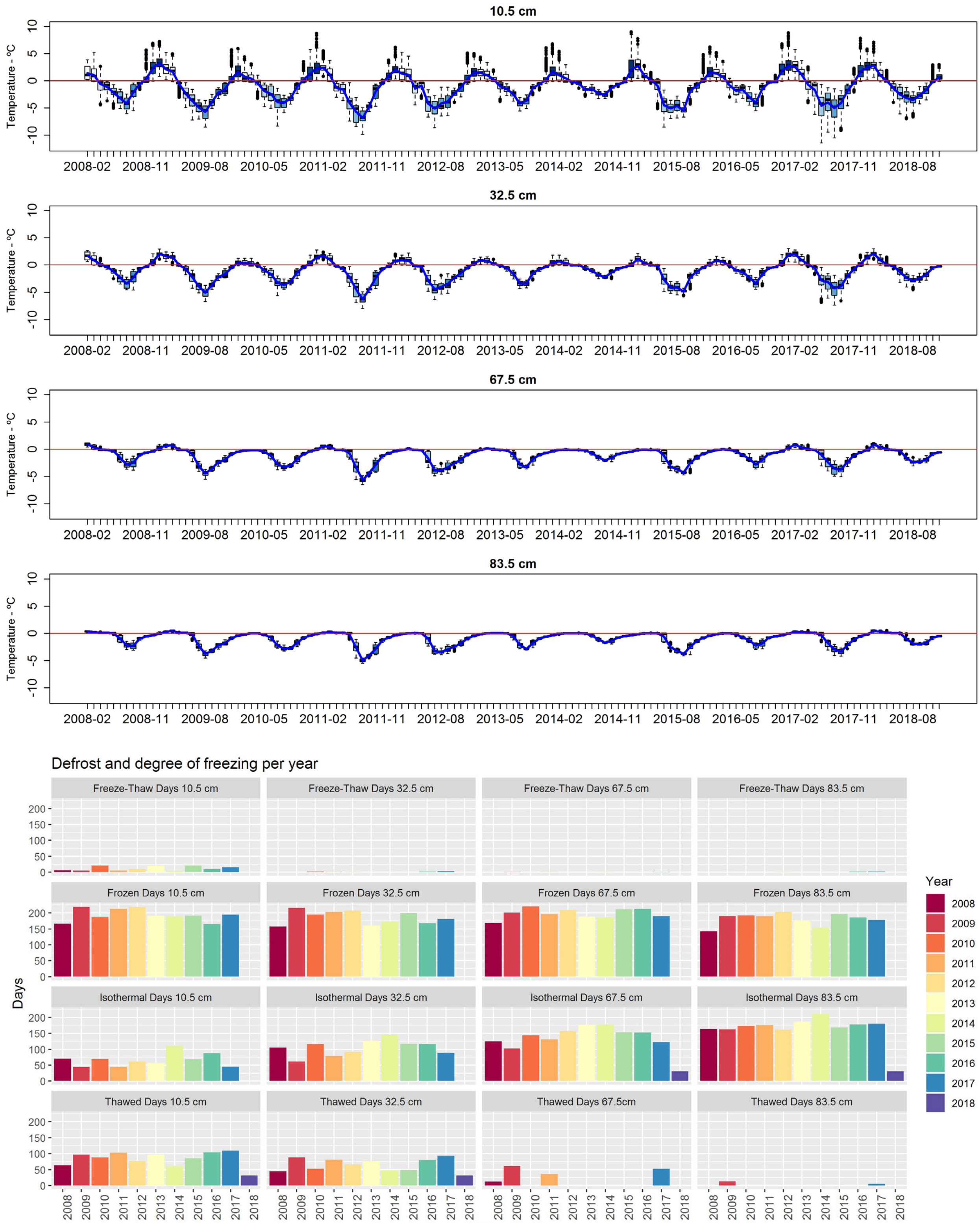

Figure 4. Freezing, thawing, freeze-thaw and isothermal processes for 2008 to 2018 for the ground temperature at depths 10.5; 32.5; 67.5; and 83.5 cm on the Fildes Peninsula, King George Island, Antarctica.

Figure 5. Freezing, thawing, freeze-thawing and isothermal processes by season for 2008 to 2018 for ground temperature at depths 10.5; 32.5; 67.5; and 83.5 cm in Fildes Peninsula - King George Island, Antarctica.

Analysis of ground moisture, rainfall and snow

The maximum ground moisture peaks (83.5 cm) occurred in 2008, 2009, 2011 and 2017, and coincide with the summer periods with greater ground thawing, as well as with the maximum peaks of rainfall and snowfall. Comparing the period, with the highest moisture content comprising the range from 2008 to 2012, with an average of 37.62%, and a minimum value of 27.03% of moisture, with the rest of the series (2013 - 2018), with an average of 30.37%, and a minimum value of 23.81%, it can be seen that it was consistent with the highest precipitation indices for the series, and the drop in humidity is also related to the decrease in rainfall (Figure S24).

Based on meteorological data, it was observed that from 2008 to 2012, 55.4% (3,531 mm) of total rainfall (6,368 mm) and 50.1% (3,529 cm) of total precipitated snow (6,987 cm) were precipitated. The year 2014 and 2016, similar to 2008, were the years with the lowest rates of rain and snow (Figure S25), all these years had El Niño – Southern Oscillation (ENSO) anomalies. The humidity sensor did not identify the peak of snow and rain, which occurred in the winter of 2015, probably because it was a year with a high rate of freezing, which may have favored the recharge of glaciers with the precipitated volumes of snow.

Thickness of the active ground layer - ALT

The ALT ranged from 75.9 cm in 2010 to 114.6 cm in 2009, with an average depth of 92.61 cm (2008 - 2018). The behavior of the annual thickness of the active layer corresponded to the dynamics of soil ground moisture at 83.5 cm, that is, at the highest moisture peaks, the highest thicknesses of the active layer also occurred. The highest ALT values occurred in 2008, 2009, 2011 and 2017, and the lowest were in 2010, 2015 and 2016. In 2015, the second lowest thickness of the active layer in the series was estimated (Figure 5). Therefore, there was intense freezing, with a smaller active layer, among the other years studied, thus, the humidity sensor did not identify the peak of precipitation and snow in this year. The estimated ALT for each year can be viewed in Figures S26 to Figure S36.

DISCUSSION

Thermal characteristics of the active layer

The surface layer of the ground, with greater influence of air temperature (correlation coefficient of r=0.82), presented more accentuated peaks of maximums and minimums. This behavior was also verified in other works in the region (Almeida et al. 2017, Chaves et al. 2017, Michel et al. 2012, Michel et al. 2014b). A possible explanation of the results is the energy balance, since a portion of the incident radiation, is intended to heat the air (convective flux of sensible heat), and another part of the ground (flux by conduction of heat in the ground), and evapotranspiration and/or transpiration (latent heat flux) (Rasmussen et al. 2018).

The flow of energy in the ground follows seasonality, and consequently there is a difference in the available water content in each season of the year, and the water content in the ground exerts a great influence on temperature control and heat transfer in the ground. With more intensity in the summer, with the warming and thawing of the surface layer, there is greater percolation of water in the profile (Yang et al. 2020). Hence, greater humidity (ground with good drainage) even in the last layer, where water accumulates due to drainage restriction, due to the presence of the impermeable top of permafrost (Hinkel et al. 2001).

The type of cover on the ground surface also influences the thermal dynamics in depth, in the Fildes site, the vegetation is composed of mosses and lichens. According to Hrbáček et al. 2020a, the moss cover produces more buffering effect in the summer, with ground temperature up to 8 times lower than in bare ground. During the winter the temperature difference between mossy and uncovered ground is smaller. In spring, there is also a delay of more than 40 days in the thawing of the surface layer, in the ground with moss compared to the ground without cover.

It is observed that the temperatures at 67.5 and 83.5 cm in Fildes suffer a strong ground buffering effect, both in summer and winter. In winter, temperatures naturally decrease, but temperatures at depth (67.5 and 83.5 cm) are higher than at the surface (10.5 and 32.5 cm). In summer the temperatures at 10.5 and 32.5 cm depth are higher and show a lot of variation in maximum and minimum.

In 2014, the highest ground temperatures occurred in the deepest horizons, a fact also recorded by Chaves et al. 2017, on the Keller Peninsula, located on the same island. In the years 2009, 2011, 2012 and 2017, there were annual temperatures below the average of the other studied years. (Oliva et al. 2017a), studying the active layer in three different basins on the Byers Peninsula (Livingston Island), found a thermal regime similar to Fildes. With an increase in the number of isothermal days at depth, and a decrease in thawing days with depth. The sandy loam texture of the ground in Fildes, and the good condition of drainage and porosity, lead to an increase in isothermal days during the thaw season, with a strong zero curtain effect (Michel et al. 2014b, Oliva et al. 2017b).

The humidity peaks in the summers of 2008-2009, 2010-2011 and 2016-2017 are consistent with the maximum rainfall and snow recorded for these periods. The greater presence of water increases the heat flux, and absorbs a greater amount of energy to freeze (Dobiński 2020).

Behavior of the active layer in relation to air temperature

The correlation between air temperature and temperature in the depths of the ground were greater in the present work than those found in the work of (Chaves et al. 2017, Michel et al. 2014b). Air temperature correlated better with the topground layer, and it decreased with depth. This occurs because the radiation directly reaches the most tenuous layer of the ground and, by heat transfer, more slowly, heats the other layers (Molin & Rabello 2011, Bai et al. 2014b).

According to Guglielmin et al. (2008), not only direct radiation influences the higher temperature in the surface layer, since it also expresses the maximum biological activity, which exerts a great influence on the thermal regime, as it modifies the physicochemical properties of the active layer. The upper limit of the active layer is the one that most suffers from rapid and intense processes of heat exchange with the atmosphere, from weathering, and is also the one that is most exposed to solar radiation (in summer), which favors the constant thawing of the snow deposited in the other seasons of the year (Almeida et al. 2017).

As in the work by (Chaves et al. 2017, Michel et al. 2014b) it is possible that there is a delay in the response of air heating in relation to ground heating, which was not evaluated in this work. The process of thawing water in the ground can change the thermal regime of the ground, which produces interference due to the release of latent heat and protects the ground from sudden changes in temperature. The effect of water in the liquid phase is clearer when freezing begins to occur again and thus generates stronger temperature gradients on the ground surface (Dobiński 2020).

Mann-Kendall time trend

The modified-MK test was important to understand the trend behavior of the entire time series, which is widely used in studies of environmental series (Pingale et al. 2014). In the work by Araghi et al. (2017) found autocorrelations of the temperature data, and to circumvent this effect, they used modified Mann-Kendall (MK) tests by the authors Hirsch et al. (1982) and by Hamed & Ramachandra Rao (1998). Panwar et al. (2018) also used this technique and highlighted the importance of evaluating the slope of the line to verify the significance of the MK results.

The summer warming trend observed in the present study is also due to a long period of positive phase of the Antarctic Oscillation (AAO), with a consequence of an increase in air temperature in South Shetland and the Antarctic Peninsula. As well as the intense ENSO phenomena in the period from 2008 to 2018. The effects of the ENSO phenomena may have influenced even the points of sudden changes on the Pettitt test line. The turning points of seasonal trends were in December 2015, when El Niño reached its maximum value (2.6 °C). The monthly MK-modified turning points also predominated in some ENSO months, such as September/2016 and November/2015. Pattern changes in data behavior may be linked to the occurrence of the presented phenomena. However, other systems may be acting together. The intensification of the warming trend in the summer and in some months of the year, may also be linked to a series of changes reported in other studies, such as melting of the polar ice caps, new ice-free areas, greater surface heating, advection of heat and humidity, among others (Thomas et al. 2015, Pedro et al. 2016). Estimates through climate modeling, estimate the even greater strengthening of these processes (Bracegirdle et al. 2013, Mayewski et al. 2017). Climate variability and changes can substantially alter permafrost (Dobinski 2011, van Gestel et al. 2019, Dobiński 2020, Hrbáček & Uxa 2020)

The annual modified-MK tests and for the different lag's were negative for most of the years. This result can be related not only to the ENSO and AAO events, which induce extreme events of both negative and positive temperature, as well as the presence of phenomena such as coreless winter (Guglielmin & Cannone 2012, Guglielmin & Dramis 1999, Goyanes et al. 2014), as well as a greater occurrence of westerly winds, making the weather cloudier in Maritime Antarctica (Hrbáček et al. 2020a). Other studies, such as Chaves et al. (2017) also found antagonistic trends in a patterned ground on the Keller Peninsula, on the same island of this study, with warmer summers and colder winters. Turner et al. (2016), with the same method (MK), found a cooling trend in the air temperature close to the surface (up to - 0.47 °C in the period 1999 – 2014) in the Antarctic Peninsula, although it is the region with the greatest warming in Antarctica.

The results of these studies indicate that warming or cooling trends are not generalized across Antarctic regions. Because in Antarctica, there is a wide variety of climates, with interference from natural variability modes of large, meso and small scale, and local factors inherent to each site, such as ground type, cover, water regime, geology, and topography. The latter influencing exposure to wind and solar radiation.

In the present study, some months showed a warming trend, for monthly analyzes of modified-MK, and some years had a cooling trend, for annual tests (Figure 6). This antagonistic result can be explained by local scale events, the air temperature fluctuates considerably in the daily, monthly and seasonal scale, with warmer months, and others with lower temperatures. These effects are due to local systems, for example coreless winters, which drop up to 2 degrees in air temperature and are common in the South Shetlands. However, in other months there may be greater advection of westerly winds and the temperature increases (Turner et al. 2014). Therefore, month to month the results may be different, and considering an average of more months, the trend may change. However, local-scale climatology in Antarctica is generally

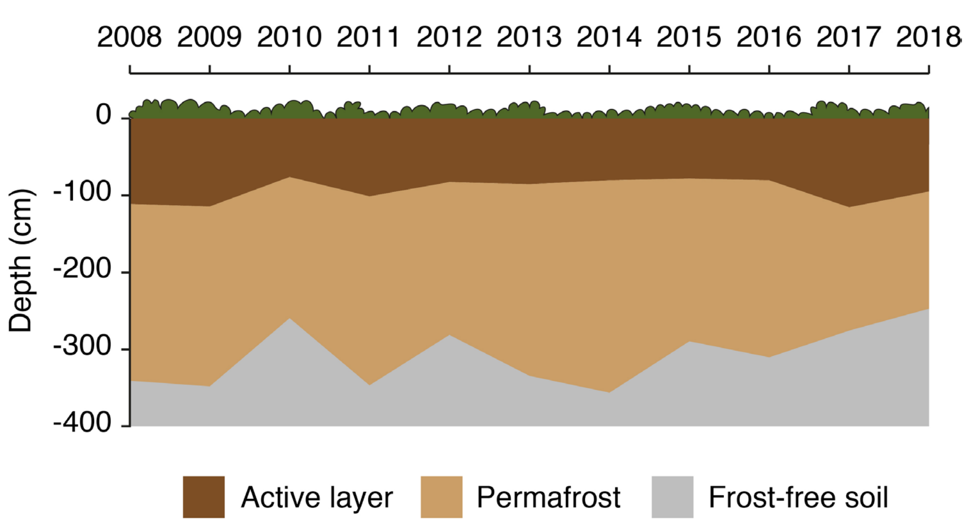

Figure 6. Annual behavior of active layer thickness, in the period 2008-2018, in Fildes Peninsula, King George Island, Antarctica.

deficient in information, presenting an obstacle to a complete understanding of the thermal variability in each monitoring site (King & Turner 1997).

The Fildes hydrothermal regime is representative of the South Shetlands, with an average thickness of the active layer (92.6 cm) consistent with the literature. Despite variations in the modified-MK test for the different approaches (seasonal, monthly, and annual), the complete series (2008-2018) showed no trend. Therefore, it can be said that in Fildes the processes of global warming and the intensification of extreme events have not yet significantly modified the thermal regime of the ground. Warming or cooling trends for Antarctica can modify a number of important aspects, such as cryogenic activity and other geomorphic processes, depending on the intensity of cold, humidity, duration of ground freezing, as well as sudden fluctuations in air temperature (de Oliveira et al. 2014).

Ground moisture

The amount of precipitated snow and rain in the Fildes Peninsula, notably, was what most influenced the ground moisture regime. In 2012, the decrease in ground moisture began (Figure S15) and the thickness of the active layer decreased (Figure S29), which was consistent with the decrease in precipitated snow, which was decreasing from 2012 to 2016 (from 982 cm to 90 cm, respectively). Except for the year 2015, with a strong El Niño event, in practically every month there was an intense deposition of snow (1,602 cm) and above average rainfall (803 mm). A lower volume of precipitation can decrease the depth of the active layer and the ground water regime (Guglielmin & Cannone 2012, Dobiński 2020, Du et al. 2020).

Ground moisture at 83.5 cm, averaged 30%, with peaks reaching 70%, and favored an increase in isothermal days in depth. Humidity has a great influence on the freezing and thawing cycles of the active permafrost layer, due to the direct relationship with the soil's thermal conductivity and total heat capacity (Li et al. 2019). When ground moisture is low, ground pores are filled with air instead of water and ice, air has greater resistance to heat conduction between ground particles, and less ability to absorb heat (Gao et al. 2020). As the air is expelled to enter the water, the total heat capacity of the ground is increased, due to the greater capacity of water to absorb heat in the ground (Hinkel et al. 2001). It is also known that the thermal conductivity of ice is 3 to 4 times greater than water itself (Hinkel et al. 2001).

The reduction in ground moisture, for a cycle of 5 consecutive years, as observed in this study, is alarming in environments with permafrost. According to Chen et al. (2020), water content and vegetation cover are important factors that mitigate the effects of global warming at high latitudes. With less precipitation, the ground becomes less humid, it is consequently less able to retain heat and less energy is needed to heat the ground, in addition to affecting the thermal conductivity of the ground itself (Hrbáček et al. 2020a).

Studies on the presence of permafrost in places with vegetation, such as the Central Plateau of Tibet, report the importance of vegetation (Chen et al. 2020). Vegetation, in addition to being a thermal insulator, also has the potential to modify the ground`s hydrothermal regime, depending on water retention capacity (Hrbáček et al. 2020a). Mosses exercise control over ground temperature, play the role of increasing water infiltration capacity into the ground, due to the dampening of raindrops, attenuating erosion processes and favoring a more humid microclimate, in relation to a cover of gravel. The presence of moss also decreases the magnitude of ground temperature oscillations, with the potential to decrease ground freezing and thawing cycles (Hrbáček et al. 2020a).

Ground texture is an important component of moisture, silt has twice the thermal capacity of fine sand (Carson 2019). The ground of the site in Fildes is a Turbic Cryosol, has a sandy loam texture, with good drainage, in addition to vegetation, the area also has nesting of Skuas (*Stercorarius antarcticus*) (Michel et al. 2014a)the landscape in these areas evolved under paraglacial to periglacial conditions, with pedogenesis marked by cryogenic processes. We carried out a detailed soil and geomorphology survey, with full morphological and analytical description for both areas; forty-eight soil profiles representing different landforms were sampled, analyzed and classified according to the U.S. Soil Taxonomy and the World Reference Base for Soil Resources (WRB. Ground temperature consequently also fluctuates due to evaporation and differences in precipitation, and in the vertical movement of water in the ground (Li et al. 2019, Du et al. 2020).

Permafrost and depth of active ground layer

According to Dobinski (2011), the definition of permafrost is based on its temperature and resilience. However, the perception of its permanence is changing. The observations made indicated its stability, mainly the studies carried out in Siberia, imposed a premise that its stability was "eternal" (hence the prefix "perma"). However, other observations in areas where it occurs discontinuously, the incidence of permafrost demonstrated temporal variability. As suggested by Dobinski (2011), it became mandatory that the term be adjusted and applied, which in principle would be permanently frozen ground, the term "perennially" frozen ground was also used. The term "frozen" refers to its durability, but "permafrost" no longer means that the ground will be eternally frozen. In order to explicitly define the area of occurrence of permafrost, it ended up being defined as a characteristic of long-term freezing, two consecutive years, and as such was included in this newer definition.

The ground temperature values in Fildes always presented negative readings when considering the whole period (10 years) and in the annual averages at all depths. However, when considering the daily averages, it raises the discussion of the permafrost concept itself. Although it is a purely thermal concept (Tedrow 1966), the temporary nature of keeping the temperature below 0 °C during two years is still debatable. The need for two years implicit in its concept does not make it clear what the periodicity to be considered, whether it would be hourly, daily, monthly or even yearly.

One of the main functions of thermometers inserted at different depths in the ground is to evaluate the thermal activity and the thickness of the active layer and its variation over time. ALT is strongly influenced by local lithology, snow cover and duration, ground water regime, and local topography (Oliva et al. 2017a, Dobiński 2020, Hrbáček, et al. 2020a). According to Dobiński (2020), the active layer is present in more than 25% of land and coastal areas, closely related to the seasonal patterns of ground freezing and thawing, that is, periods in which the temperature varied above or below 0 ° C.

At the Fildes site, the influence of ground moisture and precipitation on the thickness of the active layer can be seen. In years of higher moisture peaks, the active layer was thicker, and with the decline in ground moisture, thinning also occurred in the ALT from 2012 to 2016 (Figure 6). In the year that accumulated the highest volume of rain and snow, the highest thickness of the active layer was also observed.

According to Dobiński (2020), ALT can change due to two factors, the first is due to changes in climatic conditions that jointly affect the atmosphere and lithosphere. The second factor is the geophysical properties of the lithosphere, which influences heat conduction along the profile. In all scenarios, the maximum depth at which the water phase changes to the liquid state, increasing ground moisture, is crucial in determining the ALT (Dobiński 2020). According to Hrbáček et al. (2018) a reduction in the thickness of the active layer was found, in all locations of the western Antarctic Peninsula including the points (CALM-S) in the South Shetlands, from 2009 to 2015. This thinning in the ALT can be explained by the cooling in the region (Turner et al. 2016, Oliva et al. 2017a), and by changes in the duration of precipitated snow, which even occurs in summer, which reduces the thawing of the active layer (de Pablo et al. 2017). According to Hrbáček et al. (2018) and Ramos et al. (2020), the specific factors of each site also influence the seasonal melting, such as the presence of snow, vegetation cover and the physical properties of the ground, and are important elements in the reduction of ALT.

The mean ALT found in Fildes, 92.61 cm (2008 -2018), is in line with the mean ALT found in the literature for that region (Guglielmin et al. 2008, Cannone & Guglielmin 2009, Vieira et al. 2010, Goyanes et al. 2014, Michel et al. 2014b, Oliva et al. 2017c, Hrbáček et al. 2020a). Hrbáček et al. (2020b), on Signy Island, found an ALT of up to 181 cm (2016/2017) in bare ground and a maximum of 55 cm in ground with moss. Oliva et al. (2017a) found an ALT of 115 cm (Escondido), 90 cm (Cerro Negro) and 85 cm (Domo) on the Byers Peninsula, on Livingston Island, also in South Shetland.

The thermal evolution of the active ground layer is a key point for several studies involving changes in climate (Dobiński 2020, Du et al. 2020). The expanded active layer advocates that the greater the evidence of climate variability and global warming, and the more tenuous, the lower the ambient temperatures and the deposition of the snow layer (Oliva et al. 2017a, c). The active layer fulfills ecological, chemical, physical and hydrological functions, which are very important in high latitude regions, in addition to being responsible for the interaction of permafrost with the atmosphere (Dobinski 2011). The ground`s active layer is influenced by several factors, such as the snow layer itself, ground permeability, temperature and surface cover, ground properties, climatic factors (relief, altitude, air masses, sea level, etc.) and climatic elements, such as radiation and temperature (Biskaborn et al. 2019, Dobiński 2020). The ALT and its variability are also important for the different cryoturbic processes of grounds, such as the existence of patterned grounds (Chaves et al. 2017).

CONCLUSIONS

The Mann-Kendall test showed a positive and significant result for all depths in the monthly analyses, predominantly in August, September, and November. In the seasonal test, summer was significant and positive at greater depths. However, in annual tests, trends were negative (cooling) for all years except 2010 and 2016 (no trend). The test with different lags showed a cooling trend (more frequently in 2008, 2009, 2011, 2013, 2014) and no trend was identified in some years.

The MK test showed no trend, considering the complete series (2008-2018), and is a good indicator for a region sensitive to changes in climate. However, testing other trend methods is recommended, as the regression was significant for all ground depths for the complete series and seasons. The air temperature obtained the highest correlation with the most superficial point of the ground (10.5 cm), and it decreased with depth, showing the resistance of the ground in the transfer of energy with the points at greater depths and tamponade of the ground, favored by the cover characteristics and ground texture. The number of isothermal days increased with depth. Seasonal variation of the freezing period was identified, with increasing depth, with the migration of the maximum number of freezing days from winter to spring. Ground moisture (83.5 cm) showed higher maximum peaks according to the rainfall and precipitated snow. The decrease in rainfall directly influenced the decrease in ground moisture and active layer thickness (ALT).

Climate change is a reality, and despite being linked to global warming caused by anthropogenic changes according to the IPCC, each environment responds differently to these disturbances, requiring specific monitoring, as was the case in this work. Despite the limited size of the Fildes time series about works in places with greater accessibility, monitoring in Fildes reveals the attention that government authorities must have when it comes to measures to mitigate changes in land use and occupation in the country - worldwide and exhaustive use of natural resources as well as waste generation. We are part of an interconnected ecosystem, and the results of studies in environments such as Antarctica make this clear to us.

Acknowledgments

We would thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the Postgraduate Scholarship. We also thank the Korea Polar Data Center (KPDC) for sending meteorological data from King Sejong Station in Antarctica.

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SUPPLEMENTARY MATERIAL

Figure S1-S36.
Table SI-SXIII.

How to cite

CORREIA TP, FRANCELINO MR, VELOSO GV, MICHEL RF, SCHAEFER CE, FERNANDES FILHO EI, JUSTINO FB & LYRA GB. 2024. Ground temperature trend and active layer dynamics in the Fildes Peninsula, King George Island - Marine Antarctica. An Acad Bras Cienc 96: e20230743. DOI 10.1590/0001-3765202420230743.

Manuscript received on June 30, 2023;
accepted for publication on February 4, 2024

TAMÍRES P. CORREIA[1,2]
https://orcid.org/0000-0002-1303-8273

MARCIO R. FRANCELINO[3]
https://orcid.org/0000-0001-8837-1372

GUSTAVO V. VELOSO[3]
https://orcid.org/0000-0002-9451-2714

ROBERTO F. MICHEL[4]
https://orcid.org/0000-0001-5951-4610

CARLOS ERNESTO SCHAEFER[3]
https://orcid.org/0000-0001-7060-1598

ELPÍDIO INÁCIO FERNANDES FILHO[3]
https://orcid.org/0000-0002-9484-1411

FLÁVIO B. JUSTINO[3]
https://orcid.org/0000-0003-0929-1388

GUSTAVO B. LYRA[1]
https://orcid.org/0000-0002-9882-7000

[1]Federal Rural University of Rio de Janeiro, Department of Environmental Sciences, Km 07, Zona Rural, BR-465, 23890-000 Seropédica, RJ, Brazil

[2]Federal Institute of Southeast Minas Gerais, Campus Barbacena, R. Monsenhor José Augusto, 204, São José, 36205-018 Barbacena, MG, Brazil

[3]Federal University of Viçosa, Department of Soils, Av. Peter Henry Rolfs s/n, Campus Universitário, 36570-900 Viçosa, MG, Brazil

[4]Santa Cruz State University, Campus Soane Nazaré de Andrade, Rod. Jorge Amado, Km 16, 45662-900 Ilhéus, BA, Brazil

Corresponding author: **Tamíres Partélli Correia**
E-mail: tamirespartelli@gmail.com

Author contributions

CORREIA TP, Data analysis, Scientific investigation, Methodology, Data curation, Visualization, Writing – original draft. SCHAEFER CE, FRANCELINO MR, JUSTINO, FB, LYRA, GB, Project administration, Funding acquisition, Supervision, Data collection during the Antarctic expedition, Methodology, Data curation, Writing – review & editing, and approval of the final version. VELOSO GV, Software, Methodology, Validation, Visualization, Discussion, MICHEL RF, Acquisition of data from the Antarctic expedition, Interpretation, Discussion, and translation. FILHO EIF, Funding acquisition, Software, Methodology, Validation, Visualization, Writing – review & editing.