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Interannual variability of ground surface thermal regimes in Livingston and Deception islands, Antarctica (2007–2021)

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Abstract

The absence of vegetation in most ice-free areas of Antarctica makes the soil surface very sensitive to atmosphere dynamics, especially in the western sector of the Antarctic Peninsula, an area within the limits of the permafrost zone. To evaluate the possible effects of regional warming on frozen soils, we conducted an analysis of ground surface temperatures (GSTs) from 2007 to 2021 from different monitoring sites in Livingston and Deception islands (South Shetlands archipelago, Antarctica). The analysis of the interannual evolution of the GST and their daily regimes and the freezing and thawing indexes reveals that climate change is showing impacts on seasonal and perennially frozen soils. Freezing Degree Days (FDD) have decreased while Thawing Degree Day (TDD) have increased during the study period, resulting in a balance that is already positive at the sites at lower elevations. Daily freeze–thaw cycles have been rare and absent since 2014. Meanwhile, the most common thermal regimes are purely frozen – F1 (daily temperatures $<= -0.5^\circ$C), isothermal – IS (ranging between -0.5°C to $+0.5^\circ$C), and purely thawed – T1 ($>= +0.5^\circ$C). A decrease in F1 days has been observed, while the IS and T1 days increased by about 60 days between 2007 and 2021. The annual number of days with snow cover increased between 2009 and 2014 and decreased since then. The GST and the daily thermal regimes evolution point to general heating, which may be indicative of the degradation of the frozen soils in the study area.

KEYWORDS

active layer, Antarctica, ground surface temperature, permafrost, snow, thermal regime

1 | INTRODUCTION

The Antarctic Peninsula (AP) region is among the areas of the planet where air temperature has increased the most in recent decades. An increase of 0.54°C per decade during the second half of the XX century was reported (Steig et al., 2009; Turner et al., 2005), while cooling occurred between 1998 and 2016 in the western sector of the AP (Oliva et al., 2017). The study of the ground temperatures at the surface and different depths, and the active layer thickness revealed the decrease in the active layer thickness and ground temperatures in Livingston and Deception islands at the South Shetland Archipelago, at the western sector of the AP region in that period (de Pablo et al., 2014, 2017, 2018; Ramos et al., 2017, 2020). However, this cooling event has been interpreted as a short-term climate variability within the long-term evolution of air temperatures in the region (Clem et al., 2020; IPCC, 2019; Turner et al., 2016), as more recently occurred with the heat weaves registered in the same Antarctic area (González-Herrero et al., 2022; Turner et al., 2016). In fact, not all the monitoring sites in the AP region detected the air temperature cooling at the beginning of the XXI century (e.g., Ramos et al., 2020).

In spite of the early XX century cooling event, the air temperatures are still increasing in the whole Antarctic continent and mainly in the AP region (e.g., Clem et al., 2020; IPCC, 2019; Turner et al., 2016), impacting sea temperature (e.g., Auger et al., 2021; Kejna et al., 2013; Meredith & King, 2005; Turner et al., 2013), glacier mass balance (e.g., Abram et al., 2013; Engel et al., 2018; Molina et al., 2007; Navarro et al., 2013), terrestrial biology (e.g., Convey & Smith, 2009; Putzke & Pereira, 2020; Sancho et al., 2017; Snyder & Callaham, 2019), edafology (e.g., González-Guzmán et al., 2017), and ground thermal regime (e.g., Bockheim et al., 2013; Vieira et al., 2010). Changes in the ground thermal regime have also been shown to impact the geomorphological dynamics in the ice-free areas of the AP (e.g., Oliva & Ruiz-Fernández, 2015, 2017). However, there are not many studies on the characterization of the ground thermal regime in the AP region, with only a few local works on the Byers peninsula of Livingston Island (de Pablo et al., 2014) in the western sector and of James Ross Island (Hrbáček, Láska, & Engel, 2016; Hrbáček & Uxa, 2020) in the eastern sector. The AP is also the Antarctic region with the highest modeled near-surface permafrost temperatures: in the western sector, they are generally higher than -3°C, meanwhile in the eastern sector they could reach -6°C (Obu et al., 2020). These temperatures are close to the limit of permafrost presence (Bockheim, 1995; Bockheim et al., 2013; Bockheim & Hall, 2002; Vieira et al., 2010) which, together with the increase in air temperatures, makes frozen soils highly sensitive to temperature changes, and susceptible to degradation under a scenario of global warming, with the implications it may have for all aspects mentioned above.

Therefore, and intending to cover the lack of information on ground surface thermal regimes, the purpose of this research is to analyze the 2007–2021 ground surface temperature (GST) dataset acquired in different monitoring sites of the PERMATHERMAL network focused on the study of the thermal evolution of seasonally and perennially frozen soils in Livingston and Deception islands (de Pablo, 2021, 2022). We focus the research along the 2007–2021 period on: (i) the interannual evolution of the GST and the thermal regimes by studying the mean average ground surface temperature (MAGST), freezing and thawing degree-days (FDD and FDD, respectively); (ii) the number of days of freezing, thawing, isothermal, and freeze–thaw conditions at the different monitoring sites in Livingston and Deception islands; and (iii) the number of days that snow covers the sites. The main objective is to identify patterns and trends in the 2007–2021 period and better understand the reaction of the ice-free areas of the study sites to the reported general warming trend and to the cooling episode that characterizes the beginning of the XXI century in the AP.

2 | STUDY SITES

2.1 | Monitoring stations

We analyze data from eight monitoring sites of the PERMATHERMAL network (de Pablo, 2021, 2022) from two islands of the South Shetlands archipelago (Table 1) in the western sector of the AP region (Figure 1). The first monitoring sites were established in 2000, with GST sensors added between 2007 and 2010, when site standardization was completed.

Livingston Island's monitoring sites are located at both Hurd and Byers peninsulas. In the first former, six sites are located along an altitudinal gradient from close to the beach of the Spanish Cove (16 m a.s.l.) to the summit of Reina Sofía Mount (274 m a.s.l.), the highest elevation in the study area (Figure 1a). Each site is located at different geomorphological and geological settings (Table 1), including raised beaches (Juan Carlos I Station – JC), slope foot deposits (Nuevo Incinerador – NI), bedrock outcrops (Incinerador – IN), moraine deposits (Morrena – MO), or frost-shattered diamictons soils (Collado Ramos – CR, and Sofía – SO). From the geological point of view, the area presents both sedimentary and low-grade metamorphic rocks (Arche et al., 1996; Hobbs, 1968; Pallàs et al., 1995; Smellie et al., 1984).

In Byers Peninsula (Figure 1b), due to the mostly regular, smooth, and undulating topography associated with lithology and its denudation consequence of the deglaciation of the peninsula (Serrano et al., 1996; Mink et al., 2014; Ruiz-Fernández & Oliva, 2016), there is only one monitoring site. It is located at the gentle slopes of the Limnopolar Lake (LL, at about 80 m a.s.l.), representative of the regional geomorphological and geological settings. The site is characterized by volcanic, volcaniclastic, and Cretaceous sedimentary rocks (mainly sandstones, mudstones, and conglomerates) (Hathway & Lomas, 1998). The PERMATHERMAL network has different monitoring stations in the same site in Deception Island, all located very close to each other in the gently sloping southern rim of Crater Lake (CL, at about 85 m.a.s.l.) volcanic structure, north of Mount Kirkwood (Figure 1c). Because of the short distance between the sites, we selected site CL-3 as representative of the area, characterized by coarse pyroclastic materials from the Crater Lake Cone unit of the Pendulum Cove formation, related to an eruption in the XIX century (Smellie et al., 2002). The site shows no present-day geothermal anomalies despite the island being an active volcano with seismic and anomalous geothermal activity in various locations.

2.2 | Climate and frozen grounds

The climate of both islands is similar and characterized by a cold maritime climate at sea level, where the mean average annual air temperatures range from -1.9 to -1.2°C (Bañon, 1994, 2001; Bañon &

TABLE 1 Synthesis of the main settings of the eight monitoring sites here analyzed in an altitudinal gradient in Hurd Peninsula, Livingston Island, as well as in Byers Peninsula on the same island, and on Deception Island, Antarctica (adapted and extended from Ferreira et al., 2017). (two columns table).

Location	Site	Elev.	Established	Geomorphology	Geology	Wind
Livingston Island. Hurd Peninsula	JC	12	2010	Raised beaches	Silt/coarse sand	Low
	NI	19	2007	Slope foot	Silt/coarse sand	Very low
	IN	34	2009	Rock step in slope	Quartzite	Low
	CR	117	2007	Wide flat interfluve	Shallow diamicton	High
	MO	145	2009	Lateral moraine	Shallow diamicton	High
	SO	274	2009	Slope top near summit	Shallow diamicton	Very high
Byers Peninsula	LL	80	2009	Gently slope	Silt/coarse sand	High
Deception Island	CL	85	2009	Gently slope	Coarse pyroclasts	Very high

Vasallo, 2015; Ramos, Vieira, Gruber, et al., 2008). Air temperatures decrease with elevation and reach −4.2°C at Reina Sofía Mount (SO; 274 m a.s.l.) (Ramos, Vieira, Blanco, et al., 2008). Regionally, a variation in the temperatures exists due to orographic variability. The impacts of this heterogeneity are more relevant to snow accumulation and wind exposure. Annual precipitation, mainly as snow, is about 500 mm at sea level, mainly during autumn and summer, followed by spring and winter (Bañón et al., 2013). During the summer, liquid precipitation occurs frequently at low-elevation sites. Winds have a wide range of directions, but SW is the most frequent, with an average speed of about 25 km/h, although peaks of 140 km/h have been recorded close to the study sites (Bañón et al., 2013).

All the studied sites show seasonally frozen ground exists with a thickness of about 40–160 cm depending on the island and the elevation (de Pablo et al., 2013, 2014; Hrbáček, Láska, et al., 2016a; Ramos et al., 2017), but permafrost is absent at low elevations sites (Ferreira et al., 2017). In Livingston Island, permafrost is discontinuous at elevations lower than 150 m a.s.l, and continuous above that elevation (Ramos et al., 2013). On this island, at least 25 m of permafrost thickness exists in Sofía Mount in Hurd Peninsula, as shown by borehole data (Ramos et al., 2020; Ramos & Vieira, 2009). In Deception Island, permafrost may reach from 3 to 25 m in thickness as suggested by both direct thermal measurements and geophysical surveying (Bockheim et al., 2013; Goyanes et al., 2014; Ramos et al., 2013, 2017; Vieira et al., 2008). According to climatic and geophysical records, the permafrost on these islands is close to thermodynamic limits of existence (Bockheim et al., 2013; Hauck et al., 2007; Vieira et al., 2010).

3 | DATA AND METHODS

3.1 | Data

iButtons miniature integrated temperature data logging devices from Maxim Co. have been used to monitor GSTs. Until 2009 the DS1921G model with a resolution of 0.5°C and an accuracy of ±0.5°C was used. Data were stored every 4 h due to memory limitations. The DS1922L model has been used since 2009 due to its higher resolution (0.0625°C) and similar theoretical accuracy (±0.5°C). The higher memory capacity of the DS1922L allowed for logging data every 3 h for more than an entire year. These devices are not waterproof but water resistant. Initially, the devices were inserted into plastic supports DS9093F+ from Maxim Co. and attached to a 20×20 cm stainless steel plate of 2 mm in thickness, aiming to improve contact with soil particles. At each monitoring station, we installed one single metallic plate with the attached device. It was buried at about 2–3 cm under the soil to avoid direct contact with the atmosphere, the solar radiation heating, and snow cover cooling. Due to the damages observed over the years in the devices, they have gradually been inserted instead into waterproof capsules DS9107+ from Maxim Co. of high thermal conductivity. The capsules were attached to the metallic plate and buried in the same way as previously described.

Data were downloaded once per year during the Spanish Antarctic campaigns, between late December and early March. DS1402D-DR8+ device connected by an RJ11 to USB adapter was used together with OneWire Viewer demonstration software freely provided by Maxim Co. Data were downloaded in ASCII format (processing level 0) and processed in different ways to prepare them for analysis (de Pablo, 2022, 2021). Firstly, their inner data format was adjusted (processing level 1), and invalid data at each file's beginning and end were removed (processing level 3). Offsets observed during the zero curtain periods (Outcalt et al., 1990) were corrected in the entire datafile (processing level 4) before merging the yearly data into a single file for each station (processing level 5) and the whole dataset from all the stations (processing level 6). All the processed files were saved in ASCII format into comma-separated values files (*.csv).

Due to sensor failure or logistical constraints limiting maintenance, the data series shows some gaps during the study period. In this analysis, we did not attempt to fill the missing data and use the data as they are, without the use of algorithms to fill missing data. When correlation and determination coefficients are used, *p*-value is shown for the linear fitting of the mean annual temperatures and allows to identify the robustness of the time series.

In order to ensure the consistency of results and quality, in this research we used only the data from complete days. So, daily

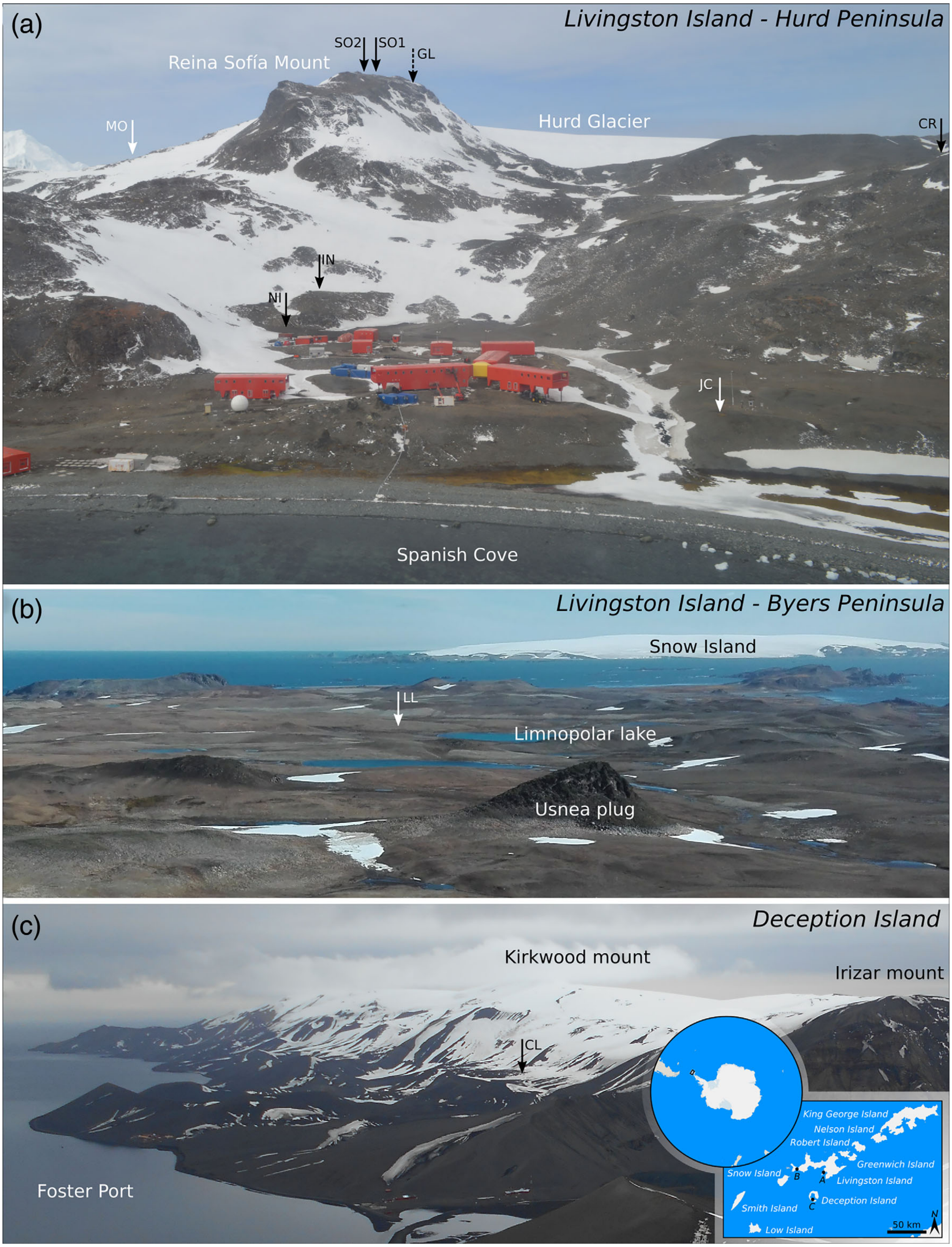

FIGURE 1 Location of the different sites of the PERMATHERMAL network where the ground surface temperature has been monitorized since 2007 in Livingston and Deception islands, Antarctica. [Colour figure can be viewed at wileyonlinelibrary.com]

calculations are made for days with all measurements that day. Monthly calculations are made only for months in which all days are complete of data, and yearly calculations are made when all months have data.

3.2 | Methods

Guglielmin et al. (2008) proposed to use the following variables to characterize the ground thermal regime:

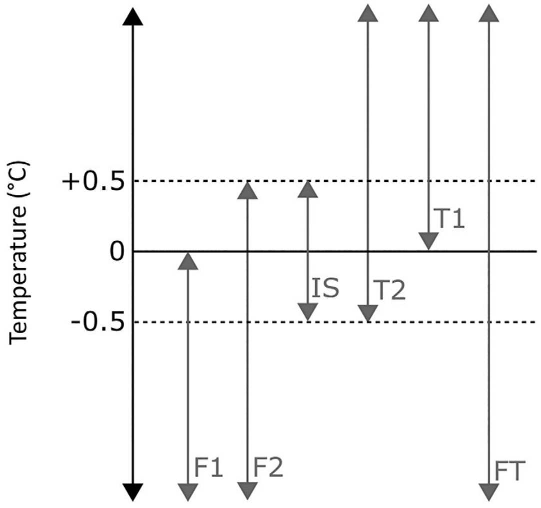

FIGURE 2 Ranges of daily temperatures of each thermal regime: freezing (F1), isothermal (IS), thawing (T1), and freeze–thaw (FT) from Guglielmin et al., 2008; and others here defined: freezing with excursions (F2) and thawing with excursions (T2).

- mean monthly (MMGST) and mean annual temperatures (MAGST),
- freezing degree days (FDD): annual sum of degree days below 0°C (Huschke, 1959),
- thawing degree days (TDD): annual sum of degree days above 0°C (Huschke, 1959),
- number of isothermal days (IS): days in which all measurements are in a range of ±0.5°C (Chambers, 1966),
- number of frozen days (F1): days in which all measurements are negative, and at least one reading is colder than −0.5°C,
- number of thawed days (T1): days in which all measurements are positive, and at least one reading is warmer than +0.5°C,
- number of freeze–thaw days (FT): days in which there are both negative and positive temperatures with at least one value greater or minor than ±0.5°C,

The ground thermal regime classification is a methodology originally implemented by Vieira et al. (2003) using sensors at different depths. The classification used here following Guglielmin et al. (2008) is simpler since it only uses GST data. A similar approach was already used in Antarctica by different authors as it is or with some modifications: Hrbáček, Láska, and Engel (2016); Hrbáček, Oliva, et al. (2016) or Oliva et al. (2017) limited the freezing days to those with measurements lower than −0.5°C, and the thawing days to those with measurements higher than 0.5°C; and de Pablo et al. (2013) used not hourly data but mean daily temperature to classify the days as freezing (<−0.5°C), thawing (>0.5°C) or isothermal (ranging between ±0.5°C), and in any case was calculated the growing degree days factor (Molau, 1996) used by Guglielmin et al. (2008). Here we preferred the original classification adding two new cases, not included in the previous methods, in order to include all the possible thermal behaviors:

- number of frozen days with excursions (F2): days in which all measurements are negative, but at least one reading is between 0°C and +0.5°C
- number of thawing days with excursions (T2): days in which all measurements are positive, but at least one reading is between 0°C and −0.5°C

Including these cases, all the possible thermal behaviors are now considered (Figure 2).

Means daily temperatures were calculated, as well as mean monthly (MMGST) and mean annual (MAGST) when data covered the entire reference periods (month or year). FDD and TDD indexes were calculated annually for the freezing and thawing periods (Houghton, 1985; Klene, 2000; Klene et al., 2001). The calculations are based on the mean daily temperatures (T). Freezing degree-day (FDD) and thawing degree-day (TDD) indexes (°C·day) calculations were done following Equations 1 and 2:

$$FDD = \sum T, T < 0°C \tag{1}$$

$$TDD = \sum T, T > 0°C \tag{2}$$

calculated considering the freezing and thawing seasons, which correspond to the periods with mean average daily temperature below or above 0°C, respectively, along the natural year. The bounding dates of the two seasons vary interannually and from site to site FDD-TDD (°C·day) representing the difference between both periods.

Finally, we used GST data to derive the presence of snow cover. Different methods have been proposed (see de Pablo et al., 2014 for a review). Here we applied the Danby and Hik (2007) criterion, which states that when the daily GST variance is <1°C, the ground is covered by insulating snow. This allowed estimation of the number of days with snow cover (SD) during the year. As in the case of FDD and TDD, and of the analysis of thermal regimes, we only used the days with complete records of temperature. Hence, only full years of data are used for the annual means and corresponding indexes. Despite the gaps in data series, which refer to a small number of years in specific sites, we decided to present the regression best fits for the variables. The reader accounts for this approach when interpreting the data, since the gaps in the data-series may affect the trend. However, we consider that this approach allows for a better understanding of the behavior of the different parameters in the time series.

4 | RESULTS

4.1 | Mean monthly and annual ground surface temperatures

MAGST in the monitoring sites (Table 2) ranges between −3.3°C (SO in 2015) and +0.9°C (JC in 2018). In Livingston Island, higher and

Year	JC	NI	IN	CR	MO	SO	LL	CL
2007		−0.9		−2.8	−2.3			
2008								
2009			−0.9			−2.6		−2.0
2010	0.5		0.1	−0.6	−0.5		−0.7	−1.3
2011	−0.6	0.0	−0.4	−1.7	−1.5	−3.1	−1.1	−1.7
2012	−0.2	0.5	−0.2	−1.0	−1.2	−2.6	−0.3	−1.9
2013	0.4	0.5	0.4	−1.2	−0.6	−2.1	−0.4	−1.2
2014	0.2	0.2	0.1	−0.9	−1.1	−2.0		−1.5
2015		0.1	−0.2	−2.0	−2.0	−3.3	−1.0	−2.0
2016		−0.2	0.1	−1.2	−0.8	−2.2	−0.7	−0.9
2017	0.0	0.6	0.4	−0.7	−1.0	−2.2		
2018	0.9	0.6	0.4	−0.8		−1.7	−0.6	−1.2
2019	0.5	0.4	0.4	−0.7	−0.4	−2.5		
2020		0.8	0.6	−0.7		−1.6	−0.4	
2021	0.2	0.5	0.6	−0.2		−1.5		−0.4
Trend	0.04	0.08	0.09	0.11	0.09	0.10	0.03	0.10
R^2	0.1	0.5	0.6	0.5	0.3	0.4	0.1	0.5
R	0.4	0.7	0.8	0.7	0.5	0.7	0.3	0.7
p	0.308	**0.009**	**0.001**	**0.008**	0.113	**0.019**	0.466	**0.015**

TABLE 2 MAGST (in °C) at each monitoring site in Livingston and Deception Islands, Antarctica, during the 2007–2021 period. The trend in °C·year of each site after a lineal fitting is shown, as well as the correlation values. *p*-values <0.05 in bold.

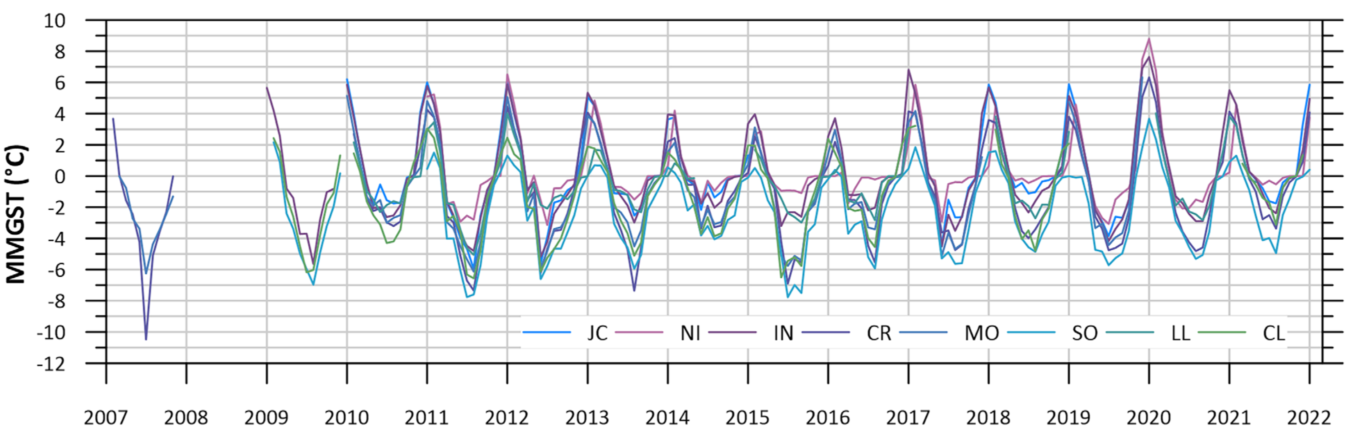

FIGURE 3 Mean monthly ground surface temperature (in °C) at all the Livingston and Deception islands monitoring sites during 2007–2021. [Colour figure can be viewed at wileyonlinelibrary.com]

mostly positive values have been recorded in sites at a low elevation: JC, NI, and IN. On the other hand, lower and even negative values were recorded at high elevations (LL, CR, MO, and SO). In Deception Island, the temperatures registered are negative and like those with similar elevation in Livingston Island (Table 2).

The time series shows some gaps due to sensor failure, resulting in linear fitting with low correlation coefficients (R^2 and R) and high *p*-values in long-term time series in JC, MO, and LL sites (Table 2). MAGST from monitoring sites in the Hurd Peninsula of Livingston Island show increasing trends of 0.09 to 0.11°C·year, except for JC with the lower value (0.04°C·year). However, linear fitting curves are not all the time series statistically consistent as shown by the low correlation rates at JC, MO, and LL sites (Table 2). LL in Byers Peninsula shows the lowest value of all the sites, with 0.03°C·year. CL in Deception Island shows a similar value to Livingston Island at a similar elevation (CR).

The MMGST shows a similar pattern over the years for all the monitoring sites (Figure 3). Positive values are reached between December to April, showing a single peak distribution with the maximum usually occurring in January or February, depending on the stations and the years. The highest values were reached in January 2020 (8.8°C at NI), which is more than 2°C over the MMGST in other years, due to the heat waves that marked the summer of 2020 (González-Herrero et al., 2022). Lower summer temperatures were reached at sites at higher elevations, such as SO, with slightly positive MMGST in 2013, 2014, and 2015.

TABLE 3 Summary of FDD and TDD (in °C·day) at the different monitoring sites during the 2007–2021 period. *p*-values <0.05 in bold.

FDD	JC	NI	IN	CR	MO	SO	LL	CL
Mean	−341	−205	−395	−666	−655	−908	−392	−667
Max.	−128	−46	−211	−360	−432	−643	−261	−236
Min.	−693	−404	−636	−962	−902	−1185	−680	−875
Amp.	565	358	425	602	470	542	419	639
Trend	14.68	14.90	16.85	22.03	−0.05	29.10	5.89	39.92
R^2	0.1	0.2	0.2	0.3	0.0	0.4	0.0	0.5
R	0.4	0.5	0.5	0.5	0.0	0.6	0.2	0.7
p	0.340	0.117	0.121	**0.007**	0.998	0.029	0.706	**0.016**
TDD	**JC**	**NI**	**IN**	**CR**	**MO**	**SO**	**LL**	**CL**
Mean	425	295	436	274	257	84	164	166
Max.	696	580	658	429	506	212	294	240
Min.	211	9	275	112	79	14	36	93
Amp.	485	571	383	318	427	197	258	147
Trend	−2.09	11.79	14.27	12.00	10.00	1.96	3.83	−3.55
R^2	0.0	0.1	0.2	0.2	0.1	0.0	0.0	0.1
R	0.1	0.3	0.4	0.4	0.2	0.1	0.1	0.3
p	0.881	0.348	0.128	0.129	0.536	0.680	0.741	0.396

Negative MMGST values are typically from May to November every year, with a more complex distribution, with single or double absolute minima depending on the year. Minimum temperatures are frequently reached in August, although in some cases, are reached in June, July, or even September. It is common to observe relative minima during the freezing season in most of the monitoring stations. Very low minima occurred in 2007 (−10.5°C at NI), 2011, and 2015 (about −7.5°C both years at SO) with the following winters showing gradually higher minima, and then coming back to a new drop. After 2015 winter temperatures are gradually increasing the next consecutive years (Figure 3).

4.2 | Freezing and thawing indexes

The freezing and thawing period started on different dates depending on the year. The former usually starts in March, when temperatures drop below zero, and finishes in October to November. On the other hand, the thawing period started in November and finished in April. Then, FDD was calculated from March to February next year, and TDD was calculated from November to October next year.

In summary (Table 3), extreme FDD values reached −1185°C·day at SO in 2011 and 2015, while the lowest values were registered in NI in 2018 at −45°C·day. Mean FDD increased from sites at a low elevation, with JC, NI, and IN ranging between −200°C·day and −400°C·day, while CR, CL, and MO, showed about −650°C·day to −670°C·day. LL shows a mean value of −390°C·day, similar to IN, despite its elevation being similar to CL. Mean FDD showed amplitudes ranging between 350 and 600°C·day along the study period for each site, revealing a high interannual variability. FDD at all sites showed a positive trend along the study period (Figure 4).

TDD had lower absolute values than FDD (Table 3), ranging between 696°C·day in JC in 2019 and 9°C·day in NI in 2016. Mean values ranged between 84°C·day in SO, and 436°C·day in IN, and the interannual amplitude ranged from 197°C·day in SO to 571°C·day in NI. The evolution of TDD during the study period shows a positive trend as well, with an episode of minimum values between 2014 and 2016 at all sites (Figure 4). TDD also changed, decreasing with elevation, but with smaller differences with elevation than in FDD.

Finally, the sum or balance of FDD and TDD values results in a net degree day index (Figure 4) that is positive in JC, NI, and IN and negative on all other sites. However, positive trends are visible in all sites. CR, CL, and LL show a balance close to 0°C·day.

4.3 | Monthly and annual ground surface thermal regimes

The monthly GST is mainly characterized at all sites by three thermal regimes: freezing (F1), thawing (T1), and isothermal days (IS) (Figure 5). Freezing–Thawing days (FT) are less frequent but still remarkable. However, freezing days with excursions (F2) and thawing days with excursions (T2) exist in most of the sites during the study period, although they are much less frequent than F1, T1, and IS.

The IS days are the most common regime at NI, while F1 days are the most common regime in SO. In general, sites at low elevations show a higher number of T2 days or IS days than those at higher elevations, where F1 days and IS are the most common.

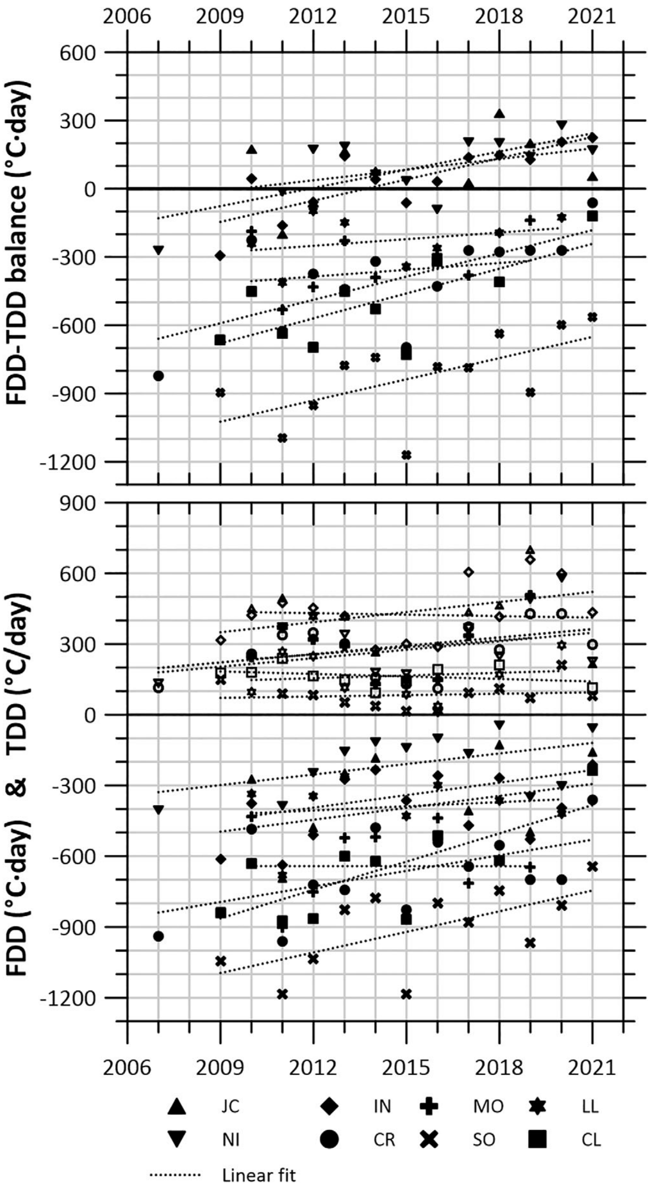

FIGURE 4 Freezing and Thawing degree day (Bottom) and balance (Top) in °C·day and linear fitting lines at all the monitoring sites in Livingston and Deception islands along the 2007–2021 period.

The F1 days extend from March to November, but from June to September they could represent 100% of the month. The IS days usually occur from October to May, although in some sites, there are no IS days in January and February, but rather T1 and T2. FT days usually occur in February, March, and April, at the end of the thawing season and the beginning of the freeze season. This is also when the freezing and thawing days with excursions (F2 and T2) occur.

From 2013 to 2016, IS days increased and were accompanied by a decrease in T1 days in most of the monitoring sites (Figure 5). At a year-scale a decrease in FT, F1, and F2, and an increase in IS, T1, and T2 days are clear (Figure 6). The SO site is where more F1 days occur every year, with 230–250 days, and less than 70 T1 days. On the other extreme, IN shows the highest number of T1 days (150), and the NI shows the highest number of IS days (311). This site also shows the minimum number of F1 days in the network, decreasing since 2011 and reaching the minimum in 2018 (less than 40 days). Changes over time in the number of days per thermal regime are low in the case of sites at high elevations (SO, MO, CR, LL, and CL) and high in sites at low elevations (IN, NI, JC).

4.4 | Snow cover

The total annual days of snow (SD) change from site to site in about 50 days, reaching the maximum difference in 2018 due to the almost permanent snow cover at SO (Figure 7). SD ranges from 240 to 360 days, that is, on average, about 10 months of snow cover every year. A change in SD has been observed in all the monitoring sites, with an increase between 2011 and 2019, reaching the maximum in 2014 or 2015, depending on the sites, and decreasing since then (Figure 7). On the other hand, sites located at lower elevations show fewer snow days than those at higher elevations, fitting a linear equation that shows a change of about 14–15 days of snow cover per 100 m (Figure 8).

5 | DISCUSSION

5.1 | Ground surface warming

The average annual ground surface temperature (MAGST) recorded is positive but very close to 0°C in the sites located at low altitudes (≤50 m a.s.l.), such as JC, NI, and IN. In comparison, negative temperatures of down to −3.3°C are recorded in those located at higher altitudes, as is the case of SO (Table 2).

The ground temperature variations observed from 2007 to 2021 reflect a decrease in 2015 (Table 2 and Figure 6), clearly linked to the longer duration of snow cover (Figure 7). Although snow's effect on soil temperature and permafrost is well known (e.g., Goodrich, 1992; Zhang, 2005), and its duration depends, among other factors, on altitude (Figure 8), this increase in snow duration between 2007 and 2014, and its subsequent reduction between 2015 and 2019, has not been sufficient to change the general ground surface warming trend observed at all sites (Figure 6). Despite the differences in the MAGST and the presence of gaps in the dataset, the trends at most sites are very similar, varying between 0.08 and 0.11°C·year, with JC and LL hardly presenting variation with trends of about 0.04°C·year.

If the trends for air temperature increase in this sector of Antarctica are to be met (Carrasco et al., 2021), the impacts on the soil will also increase. Actually, mean annual air temperatures at SO, an exposed mountain site representative of the regional climate, measured since 2000 show a positive trend (Figure 9), overcoming the cooling described to have occurred from 2000 to 2015 AP (Oliva et al., 2017). This warming shows an increase in the air temperatures of 0.12°C·year from 2000 to 2021, which almost doubles to 0.22°C·year when considering the period of 2007–2021, which is

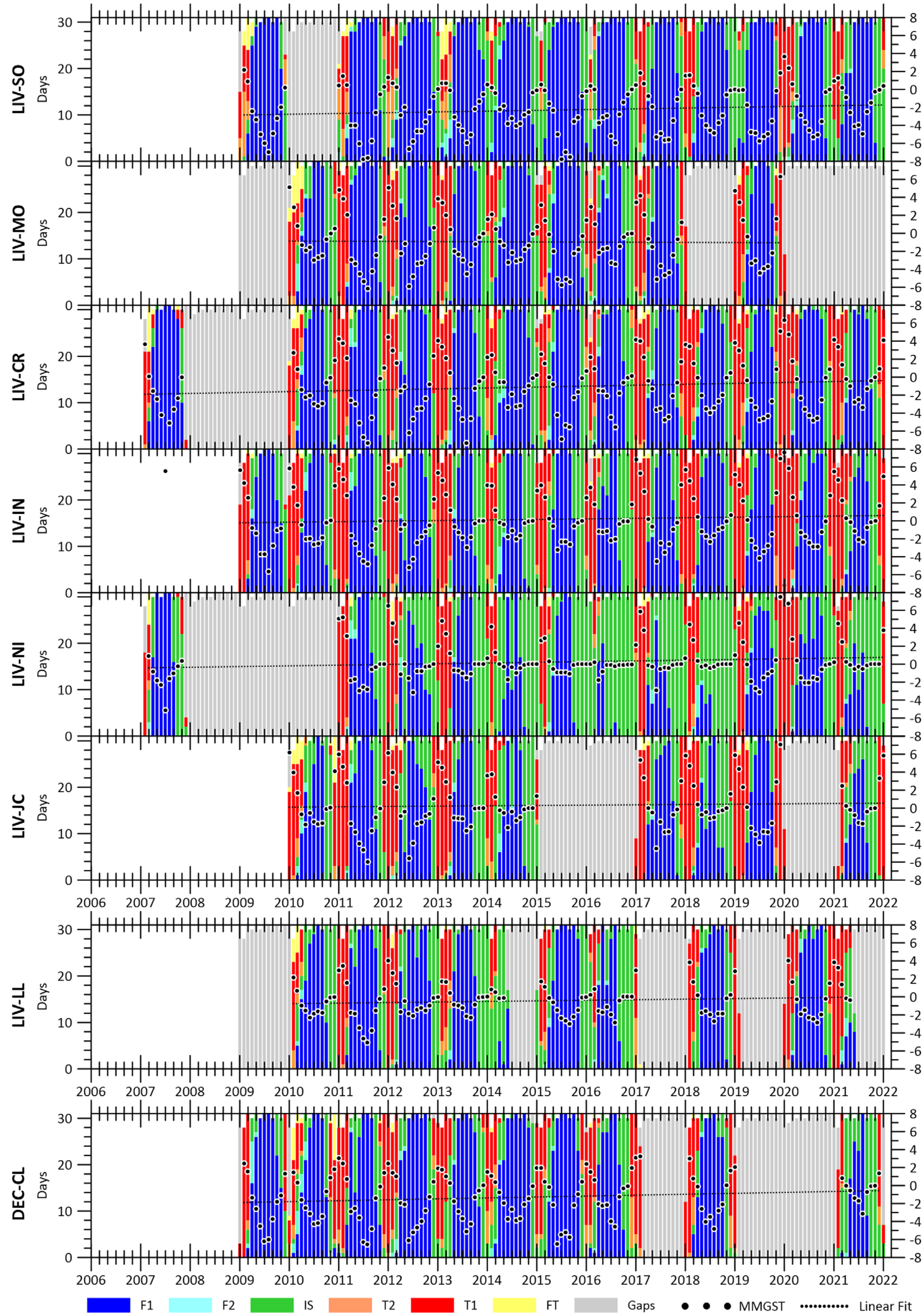

FIGURE 5 Monthly frequency of different ground surface thermal regime classes at eight monitoring sites in Livingston and Deception islands over the study period. [Colour figure can be viewed at wileyonlinelibrary.com]

the one studied for GST. In both cases, the air temperature trend is positive, supporting the coupling between the ground surface and air temperatures. The scarce vegetation cover in the ice-free areas of the WesternAP further exposes the soils to warming promoting the coupling between the ground surface and atmosphere, and also, at depth, with permafrost (e.g., de Pablo et al., 2017; Zhang, 2005).

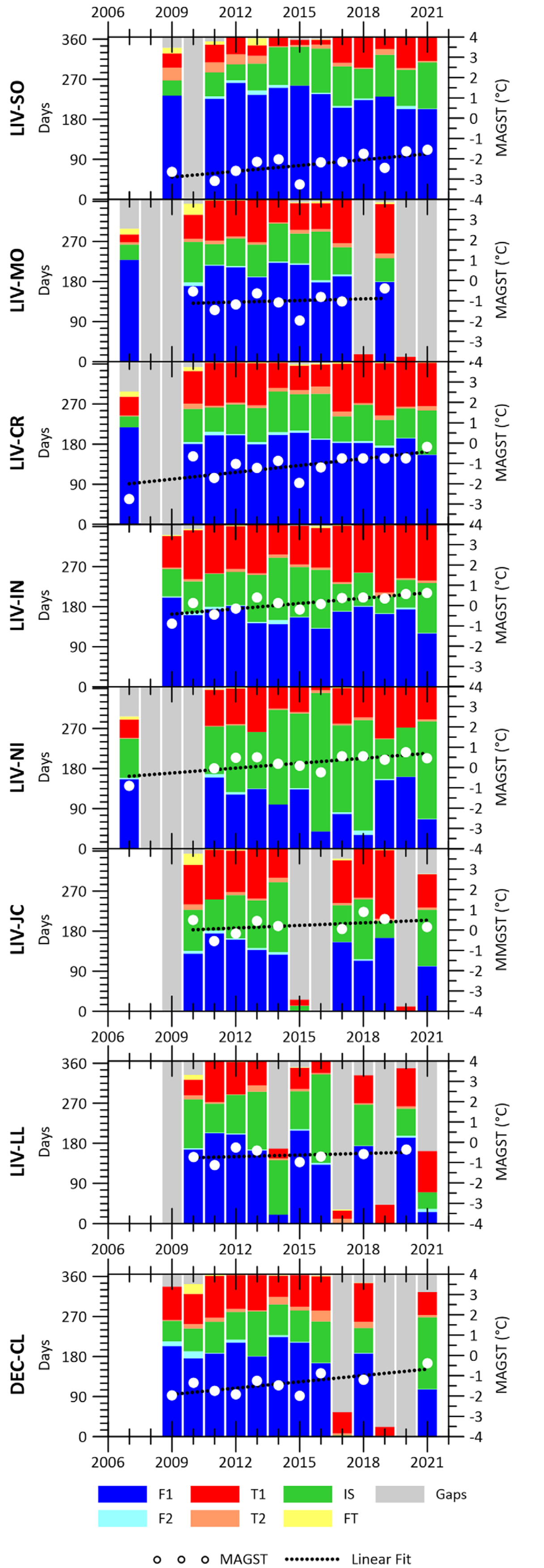

FIGURE 6 MAGST (in °C) and yearly frequency of different classes of ground surface thermal regime (in number of days) at eight monitoring sites in Livingston and Deception islands. [Colour figure can be viewed at wileyonlinelibrary.com]

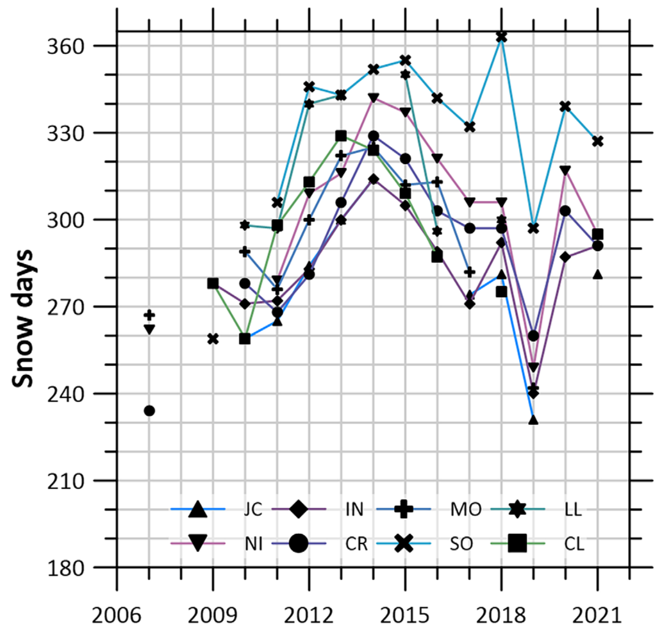

FIGURE 7 Total annual number of days in which the snow covered the ground surface from 2007 to 2021. [Colour figure can be viewed at wileyonlinelibrary.com]

This increase in soil temperature will affect the temperature of the top of the permafrost at the highest sites where it is present (see Ferreira et al., 2017), but also in many areas on the West AP where it shows temperatures close to 0°C (see Obu et al., 2020). Actually, confirmed that permafrost is absent at low elevations in the Livingston Islands.

The imbalance between freezing (FDD) and thawing (TDD) indices that have been identified at all elevations, supports the trend for warming and degradation of permafrost since the trend is positive in all stations (Figure 4). This positive balance results essentially from markedly lower cooling during winter, rather than from an increase in warming during summer, except in JC, NI, and IN (Table 3). In these three sites, located at low elevations, where a positive DD balance have prevailed since 2014 (Figure 4).

5.2 | Thermal regime

The most frequent thermal regimes from 2007 to 2021 are freezing (F1), isothermal (IS), and thawing (T1) regimes, as expected in a polar region with average air temperatures close to 0°C. From the geomorphological point of view, these regimes are also consistent with the presence of the periglacial landforms mapped on the South Shetlands, including blockstreams, stone sorted circles, stone stripes, or lobes of solifluction among others (e.g., Dąbski et al., 2017; López-Martínez et al., 1992, 2012, 2016; Oliva & Ruiz-Fernández, 2017; Pallàs et al., 1995; Ruiz-Fernández & Oliva, 2016). On the other hand, the freeze–thaw regimes with excursions around 0°C (F2 and T2, respectively) are significantly reduced in all stations throughout the period studied, resulting in an increase of days with freeze–thaw (FT) or isothermal (IS) regimes.

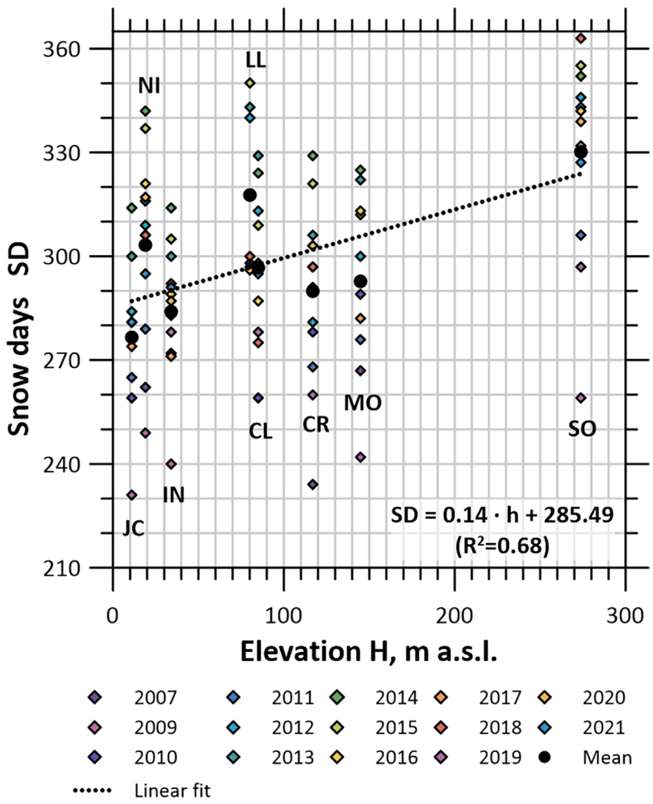

FIGURE 8 Correlation between mean days with snow versus elevation at each monitoring station along the study period. [Colour figure can be viewed at wileyonlinelibrary.com]

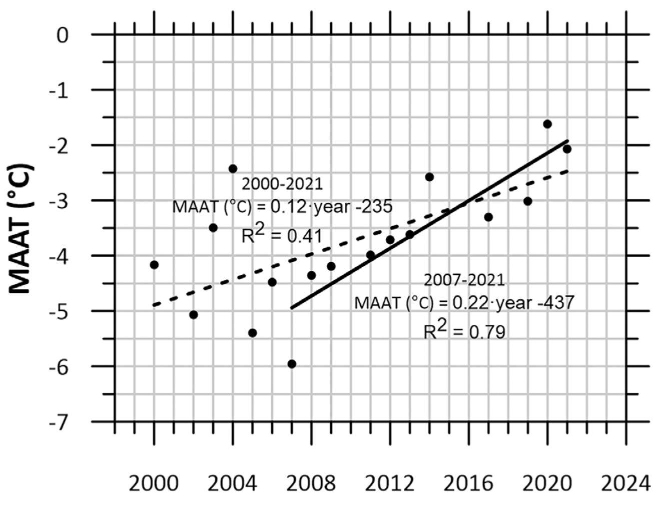

FIGURE 9 Mean annual air temperature at SO site (274 m a.s.l.) in Hurd Peninsula, Livingston Island, Antarctica. Linear fit parameters and curves of the 2000–2021 (dashed line) and 2007–2021 (solid line) periods are shown.

The relative abundance of the days of isothermal IS regime is striking, indicators of very stable temperatures close to 0°C. This behavior is typical of the curtain effect, in which the ground remains isothermal at around 0°C while freezing/thawing water occurs in the ground (e.g., Outcalt et al., 1990). These days occur during autumn (scarcer) and late spring (more abundant). The greater abundance in the spring reveals a more significant presence of water in the soil, coming from melting the snow cover. Different authors concluded that an increase in water content in soils results in an increase in the soils' thermal conductivity (e.g., Abu-Hamdeh & Reeder, 2000; O'Donnell et al., 2009; Rasmussen et al., 2018; Schjønning, 2021; Wessolek et al., 2023). This could facilitate heat transmissivity from the surface to the ground. Then, as (1) we observed an increase in the FT and IS days, (2) a positive trend in temperatures at all stations, (3) a positive trend in air temperatures, and being (4) the temperature of the top of the permafrost relatively high (in South Shetland Islands in general and in Livingston Island in particular) (Obu et al., 2020), we can predict a quick permafrost degradation at medium to high elevations. On the other hand, days with freeze–thaw (FT) cycles, although less frequent, are important since freeze–thaw affects soil structure and rheology (e.g., Hall, 1988; Matsuoka et al., 1990; Matsuoka & Moriwaki, 1992; Marion, 1995; Batista et al., 2022), including the generation of voids through which meltwater circulates (e.g., Leuther & Schlüter, 2021). In silty-clayey, loamy sandy soils, the connected pore-system may be particularly sensitive to freeze–thaw effects, which promote subsurface water circulation and may accelerate erosion (Lehrsch, 1998; Leuther & Schlüter, 2021). Although some of the sites show this type of soil (LL and NI), no evidence of increased erosion has been observed. FT days show no increase in the frequency during the study period (Figures 5 and 6).

Although it is not the objective of this work, the presence of daily or annual temperature cycles is of great importance from the edaphic and ecological points of view. They facilitate the mobility of certain chemical compounds, such as C or N, in the soil (e.g., Aislabie et al., 2004; Batista et al., 2022; Claridge, 1965; Cowan et al., 2014; Edwards & Cresser, 1992; Otero et al., 2013; Zhu et al., 2011) and the development of fauna and flora (e.g., Cannone, Ellis-Evans, et al., 2006; Green et al., 2007; Knox et al., 2016, 2017; Melick and Seppelt, 1992; Miranda et al., 2020; Sander-DeMott et al., 2019; Sierra-Almeida et al., 2018; Yergeau & Kowalchuk, 2008). All these implications require a more detailed study, considering that these thermal regimes existed between 2007 and 2013 in some stations, they have shown low frequency since 2014.

The detailed analysis of the evolution of the ground surface thermal regimes shows the decreasing trend in the number of days with the F1 regime, and the consequent increase in the number of days with IS and T1 regimes (Figures 5, 6, and 10). Only two exceptions are observed: the decrease in IS days in LL, and the decrease in T1 in CL, which would require a more detailed study of the local conditions, if it is not linked to the lack of punctual data in these stations. Despite these exceptions, the observed changes reach up to 60 days in general, although there are seasons where the changes are up to 90 days. These values indicate a marked change in soil thermal regimes in both Livingston and Deception islands, consistent with the results of other recent studies elsewhere in Antarctica using both in situ and remote sensing data (Kuentz et al., 2022), which seems to indicate a regional impact, rather than local one that may be affecting other regions in the Antarctic.

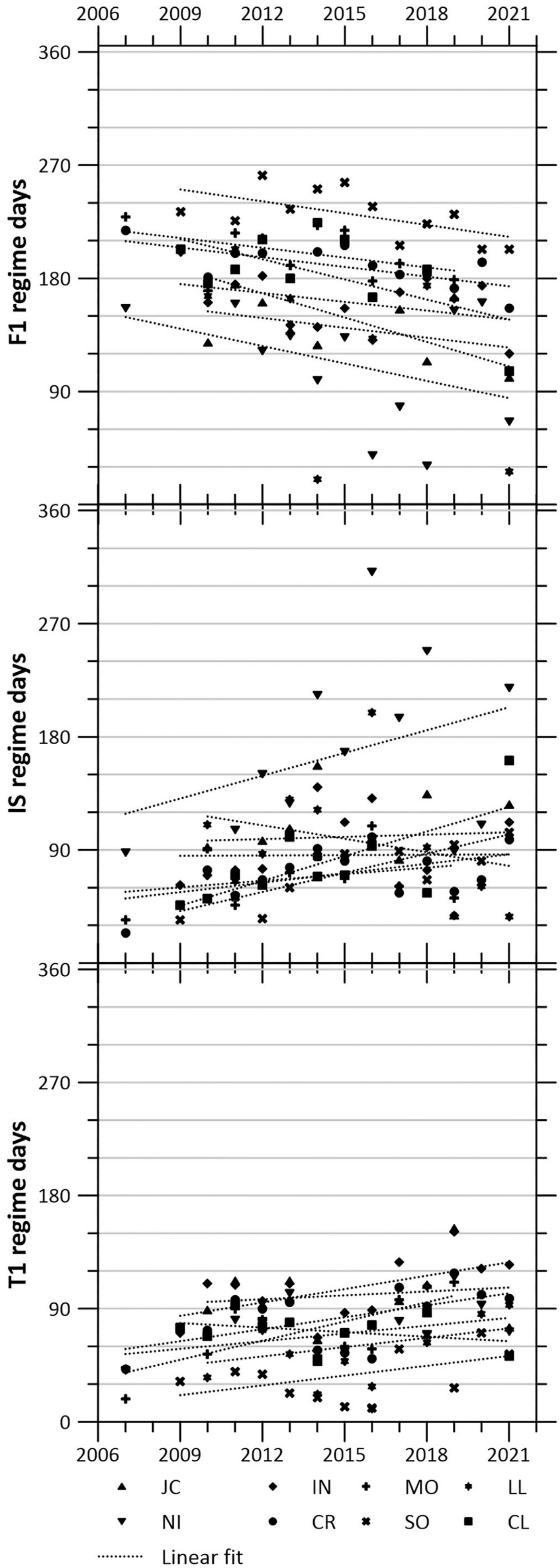

FIGURE 10 Evolution of the number of days per year under the most frequent thermal regimes (F1, T1, and IS) at all the monitoring stations and their linear fit curves, showing a general decrease on purely freezing days, and an increase on isothermal and purely thawing days.

It should be noted that the trend observed in the thermal regime of soils does not reflect the cooling trends of air temperatures identified by other authors for this sector of the AP region since the beginning of the XXI century (Oliva et al., 2017), but that the soil has shown, since 2006, a general trend towards increasing temperature despite the punctual decrease registered in 2014 and 2015 (Figure 6). This behavior agrees with a new change in the air temperature trend since 2015 and defines the end of the described cooling period, probably related to the normal short-term climate variability in a long-term warming trend (e.g., Turner et al., 2016).

6 | CONCLUSIONS

Despite the short gaps in the data series, the study of the ground surface thermal regime in Livingston and Deception islands has shown:

- A general soil surface warming, with rates between 0.08 and 0.11°C·year between 2007 and 2021, was not affected by the 2000–2015 air temperatures cooling period, and neither by the increase in the snow cover duration in 2007–2014.
- Changes in snow cover duration affected the FDD and TDD, but both of them showed a warming trend in the study period.
- FDD-TDD balance remains negative at medium- to high-elevation sites, but it is already positive in low-elevation ones.
- Soil thermal regime has been revealed to be very sensitive to the increase in temperatures.
- An increase in the GSTs is also reflected in the most frequent thermal regimes (F1, IS, and T1), which tend to decrease in the case of freezing and increase in the other two, with changes of about 60 days along the study period.
- The increase in FT and IS days is indicative of more water content in the soils, which could contribute to the quick degradation of permafrost due to the increase in the soils' thermal conductivity.

The results presented here reveal that the ground surface is warming in Livingston and Deception islands, which is a factor that needs to be accounted for as it has potential implications to the degradation of permafrost, especially in a region of the AP where permafrost is at its climatic boundary and in the fringe of disappearing.

AUTHOR CONTRIBUTIONS

Data curation, M.A. de Pablo; Field data acquisition: M.A. de Pablo, M. Ramos, G. Vieira, A. Molina, and M. Prieto; Investigation, all authors; Writing—original draft, M.A. de Pablo; Writing—review & editing, all authors. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

No conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in PERMATHERMAL community in ZENODO repository at https://zenodo.org/, reference number 10.5281/zenodo.8398398.

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