

THE COLD VOLCANO: THE ACTIVE LAYER THERMAL REGIME OF DECEPTION ISLAND, MARITIME ANTARCTICA

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ABSTRACT

Permafrost monitoring is a key approach to assess soil responses in paraglacial environments under current climate change. This study investigates the active layer thermal regime of Deception Island by analyzing a seven-year dataset of soil temperature and moisture collected at two contrasting sites: (i) a Haplic Cryosol at Fumarole Bay (FB) and (ii) a Turbic Cryosol at Telefon Bay (TB). Temperature and moisture probes were installed at multiple depths (10–70 cm) and continuously monitored between 2010 and 2016. Statistical analyses included correlation among soil layers and multivariable regression. Results reveal a periglacial soil thermal regime with a shallow active layer, and maximum thaw depths of 86 cm (FB) and 109 cm (TB). At FB, sedimentary discontinuities and marine deposits promoted buffering of the permafrost table, while at TB the uniform volcanic matrix allowed stronger coupling with air temperatures, making permafrost more vulnerable. Although permafrost at FB was warmer, the TB site exhibited greater fragility due to stronger air–soil interactions. No evidence of geothermal heat influence was detected during the monitoring period. These findings provide new insights into permafrost dynamics in volcanic islands of Maritime Antarctica, highlighting the influence of geomorphological and sedimentary settings on active layer variability.

Keywords: Permafrost; Active layer; Thermal regime; Deception Island; Antarctica.

RESUMO

O VULCÃO FRIO: O REGIME TÉRMICO DA CAMADA ATIVA DA ILHA DECEPTION, ANTÁRTICA MARÍTIMA. O monitoramento do permafrost é uma abordagem fundamental para avaliar a resposta dos solos em ambientes paraglaciais frente às atuais mudanças climáticas. Este estudo investiga o regime térmico da camada ativa na Ilha Deception por meio da análise de uma série temporal de sete anos de temperatura e umidade do solo, coletada em dois sítios contrastantes: (i) um Cryossolo Háptico na Baía Fumarole (FB) e (ii) um Cryossolo Túrbico na Baía Telefon (TB). Sensores de temperatura e umidade foram instalados em múltiplas profundidades (10–70 cm) e monitorados continuamente entre 2010 e 2016. As análises estatísticas incluíram correlações entre as camadas do solo e regressões multivariadas. Os resultados revelam um regime térmico periglacial do solo com camada ativa rasa, e profundidades máximas de degelo de 86 cm (FB) e 109 cm (TB). Na Baía Fumarole, discontinuidades sedimentares e depósitos marinhos promoveram o amortecimento da mesa de permafrost, enquanto na Baía Telefon a matriz vulcânica homogênea permitiu maior acoplamento com as temperaturas do ar, tornando o permafrost mais vulnerável. Embora o permafrost em FB seja mais quente, o sítio TB apresentou maior fragilidade devido às interações mais intensas entre solo e atmosfera. Não foram detectadas evidências de influência de calor geotérmico durante o período de monitoramento. Esses resultados fornecem novos insights sobre a dinâmica do permafrost em ilhas vulcânicas da Antártica Marítima, destacando a influência do contexto geomorfológico e sedimentar na variabilidade da camada ativa.

Palavras-chave: Permafrost; Camada ativa; Regime térmico; Ilha Deception; Antártica.

RESUMEN

EL VOLCÁN FRÍO: EL RÉGIMEN TÉRMICO DE LA CAPA ACTIVA DE LA ISLA DECEPCIÓN, ANTÁRTIDA MARÍTIMA. El monitoreo del permafrost es una herramienta clave para evaluar la respuesta de los suelos en ambientes paraglaciales frente al actual cambio climático. Este estudio investiga el régimen térmico de la capa activa en la Isla Decepción mediante el análisis de una serie temporal de siete años de temperatura y humedad del suelo, recopilada en dos sitios contrastantes: (i) un Cryosol Háptico en la Bahía Fumarole (FB) y (ii) un Cryosol Túrbico en la Bahía Telefon (TB). Sensores de temperatura y humedad fueron instalados a múltiples profundidades (10–70 cm) y monitoreados de forma continua entre 2010 y 2016. Los análisis estadísticos incluyeron correlaciones entre las capas del suelo y regresiones multivariadas. Los resultados revelan un régimen térmico periglacial del suelo con una capa activa poco profunda, y profundidades máximas de deshielo de 86 cm (FB) y 109 cm (TB). En la Bahía Fumarole, las discontinuidades sedimentarias y los depósitos marinos promovieron el amortiguamiento de la mesa de permafrost, mientras que en la Bahía Telefon la matriz volcánica homogénea permitió un mayor acoplamiento con las temperaturas del aire, haciendo al permafrost más vulnerable. Aunque el permafrost en FB fue más cálido, el sitio TB presentó una mayor fragilidad debido a interacciones más intensas entre el suelo y la atmósfera. No se detectaron evidencias de influencia de calor geotérmico durante el período de monitoreo. Estos resultados aportan nuevos conocimientos sobre la dinámica del permafrost en islas volcánicas de la Antártida Marítima, destacando la influencia del contexto geomorfológico y sedimentario en la variabilidad de la capa activa.

Palabras clave: Permafrost; Capa activa; Régimen térmico; Isla Decepción; Antártida.

1 INTRODUCTION

Deception Island (DI) is the main active volcano of the central Bransfield Strait. It lies northwest of the Antarctic Peninsula, between the Hero Fracture Zone and the Bransfield Trough. Its most recent eruptions occurred in 1967, 1969, and 1970 (Baker et al., 1975; Pallàs, 1996; Smellie, et al. 1990). The island's soils are typically shallow, with frequent lithic or paralithic contacts and permafrost within the first meter, displaying little horizon development, high gravel content, and sandy-skeletal textures (Simas et al., 2015). Volcanic materials on exhibit pronounced andic properties, including high porosity, low bulk density and strong water retention capacity, which significantly affect heat transfer within the active layer. Despite a regional warming trend of ~ 3 °C since the 1950s, permafrost remains preserved above 100 m a.s.l., typically at depths of ~ 40 cm (Simas et al., 2015). This makes DI an important location for international permafrost monitoring initiatives such as ANTPAS (Antarctic Permafrost, Soils and Periglacial Environments Project).

The ANTPAS program promotes interdisciplinary research aimed at understanding the environmental dynamics of Antarctic ice-free areas, which are particularly sensitive to climate change and play a critical role in cryosphere–biosphere interactions (Vieira et al., 2010). Through this initiative, long-term monitoring of the active layer and shallow permafrost has been established at numerous sites across Maritime Antarctica (Almeida et al., 2016; Chaves et al., 2017; Michel et al., 2014; Schaefer et al., 2016). Comparative investigations of active layer dynamics in climatically and geomorphologically contrasted areas of Maritime Antarctica (e.g., Almeida et al., 2016; Chaves et al., 2017; Hrbáček et al., 2016; Ramos et al., 2017) consistently demonstrate that local substrate properties and landform controls shape the propagation of heat through the ground. These studies reinforce the need for continuous multi-year monitoring across varied environments, including volcanic islands such as Deception Island, where thermal regimes are strongly influenced by andic properties and heterogeneous sedimentary structures. These records are essential to evaluate temporal changes in soil thermal regimes and their implications for geomorphological and ecological processes.

The South Shetland Islands, including DI, experienced extensive glaciation during the

Last Glacial Maximum, with subsequent retreat beginning around 12,000 years BP. More recent advances occurred between ~ 720 – 330 years BP and again after ~ 300 years BP (Pallàs, 1996; Sugden & Clapperton, 1986). These oscillations produced diverse paraglacial landscapes, with freshly exposed sediments reworked by cryogenic and mass-movement processes (Ballantyne, 2002). On DI, the 1970 eruption further intensified this complexity by depositing thick pyroclastic layers, altering meltwater dynamics and promoting heterogeneous permafrost patterns (Orheim & Govorukha, 1982). Permafrost in such volcanic settings is especially sensitive to both climatic forcing and local geomorphological conditions resulting in complex subsurface structures, highlighting the combined influence of geomorphology, parent material and sedimentary layering on permafrost stability.

Previous studies at DI have reported permafrost occurrence and active layer dynamics in different geomorphic contexts, including alluvial fans, volcanic deposits, and crater margins (Goyanes et al., 2014; Ramos et al., 2012, 2017; Vieira et al., 2008). However, continuous and multi-year thermal monitoring remains scarce on the island, particularly in areas influenced by volcanic substrates, andic materials and potential geothermal anomalies. This scarcity represents a key knowledge gap for understanding permafrost sensitivity under ongoing climate warming. Understanding these dynamics is crucial for assessing the stability of permafrost under ongoing climate change, as well as for identifying the geomorphological controls that regulate active layer thickness.

Here, we analyze seven years (2010–2016) of soil temperature and moisture monitoring at two contrasting sites on DI: a Haplic Cryosol developed over reworked marine sediments at Fumarole Bay (FB) and a Turbic Cryosol formed on pyroclastic deposits at Telefon Bay (TB). Our objectives are to (i) characterize the soil thermal regime of both profiles, (ii) evaluate interannual variability in active layer thickness, and (iii) assess the role of geomorphological setting and parent material in controlling permafrost stability. By integrating long-term monitoring with site-specific geomorphic context, this study contributes to a better understanding of permafrost dynamics in volcanic islands of Maritime Antarctica.

2 MATERIALS AND METHODS

2.1 Study area

Deception Island (63°00'S, 60°40'W), the southernmost of the South Shetland Islands, was named by the American sealer Nathaniel Palmer due to the concealed entrance of Port Foster (Figure 1). The island is an active shield volcano located in the Bransfield Strait, with an underwater base diameter of ~30 km and a total height of ~1.5 km (Smellie, 1990). Its highest peaks are Mount Pond (540 m a.s.l.) and Mount Kirkwood (460 m a.s.l.), from which glaciers descend to cover nearly half of the island. The geology is dominated by basaltic lava flows, andesitic tuffs, and pyroclastic flow deposits, with more recent eruptions depositing volcanic ash and debris that currently blanket much of the island's glaciers (Martí et al., 1996). These porous and insulating deposits favor the development of a thin active layer, typically between 30 and 90 cm thick (Vieira et al., 2008).

The local climate is strongly influenced by the island's physiography and volcanic activity. Long-term meteorological records (1948–1967) indicate an average annual precipitation of 510 mm, mostly as

snow, with values ranging between 300 and 800 mm (Igarzabal, 1974). More recent data (2006–2010) from the Spanish Antarctic Station Juan Carlos I located at Livingston Island show a mean annual air temperature of $-1.0\text{ }^{\circ}\text{C}$ (daily minimum $-2.9\text{ }^{\circ}\text{C}$; daily maximum $1.3\text{ }^{\circ}\text{C}$) and annual precipitation of 444.5 mm. Vegetation is sparse, occurring only in moist and stable areas, and is largely dominated by lichens and mosses (Lewis-Smith, 1988). Soils are shallow, gravel-rich (30–90%), and sandy-skeletal, with very low clay contents (30–50 g kg^{-1}), limited horizon differentiation, and grayish colors with low chroma, indicating weak oxidation (Simas et al., 2015).

2.2 Monitoring system and instrumentation

Two permanent monitoring sites were established on Deception Island: one at Fumarole Bay (FB; 62.95°S, 60.71°W) and another at Telefon Bay (TB; 62.91°S, 60.64°W). Geographic coordinates were recorded using a handheld GPS receiver with an estimated positional accuracy of $\pm 5\text{ m}$. The FB site is located at ~15 m a.s.l. on a flat marine terrace where a Haplic Cryosol developed over undifferentiated alluvial and scree

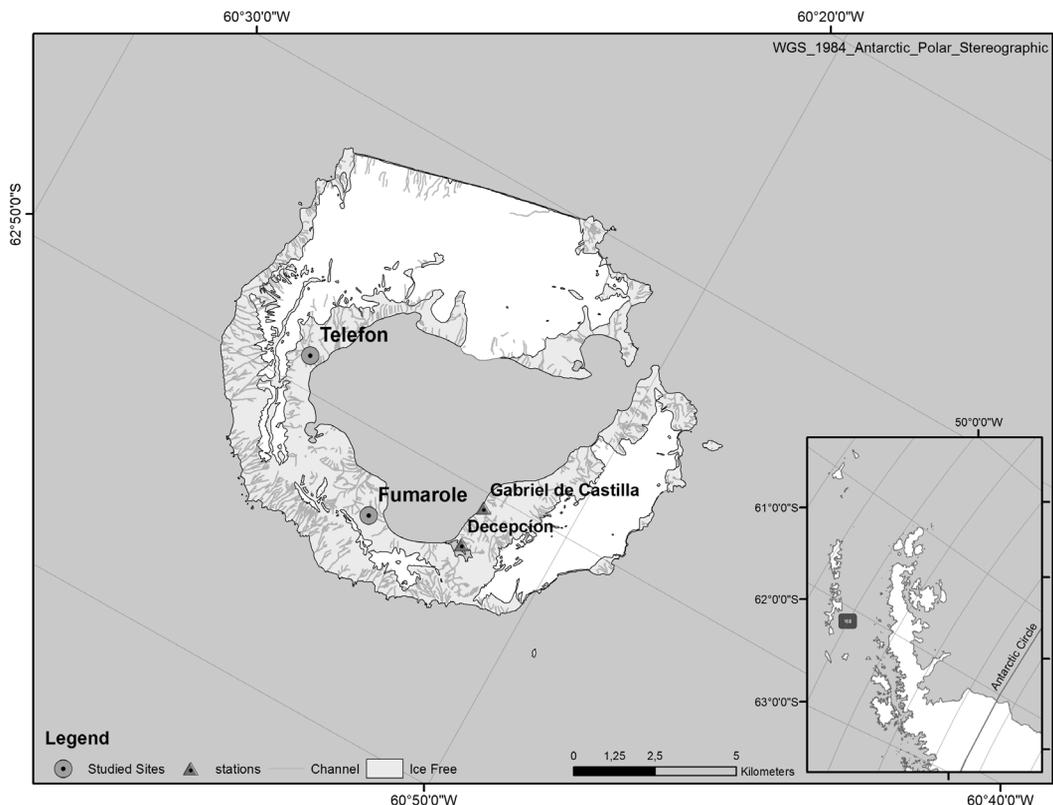


FIGURE 1 – Location map of Deception Island showing study sites at Fumarole Bay (FB) and Telefon Bay (TB).

deposits. The TB site lies at 28 m a.s.l. on gentle slopes formed by pyroclastic deposits from the 1967 and 1970 eruptions, where a Turbic Cryosol occurs. Both sites are situated near fumarolic fields and thermally influenced ground. Each site was equipped with four soil temperature and volumetric water content probes connected to a Campbell Scientific CR1000 datalogger. Soil temperature was measured using L107E thermistor probes (Campbell Scientific Inc., Logan, USA; accuracy ± 0.2 °C), installed horizontally at depths of 10, 30, 50 and 70 cm at Fumarole Bay, and at 10, 30, 50 and 65 cm at Telefon Bay. Air temperature was also recorded using a L107E thermistor mounted at 1.0 m above the ground within a naturally ventilated radiation shield. Volumetric soil moisture was monitored with CS616 water content reflectometer, accuracy of $\pm 2.5\%$, positioned adjacent to each temperature sensor to ensure thermal–hydrological comparability. All instruments were programmed to record data at hourly intervals. Monitoring at FB spanned March 2010 to November 2016 without major interruptions, while TB experienced technical failures, yielding continuous records for 2010–2011, 2012–2013, and 2014–2016.

2.3 Data analysis

Soil thermal regime was characterized using the following indicators (Guglielmin & Cannone, 2008): thawing days, freezing days, isothermal days, freeze–thaw days, thawing degree days (TDD), and freezing degree days (FDD). Active layer thickness (ALT) was calculated annually as the depth of the 0 °C isotherm, determined by extrapolating the thermal gradient between the two deepest positive daily averages (Guglielmin, 2006). Correlation analyses (multi-variable regression) were performed among soil layers and between soil and air temperatures.

In addition, multivariable regression models were applied to predict temperatures at the deepest sensor (70 cm at FB; 65 cm at TB) using air temperature and shallower soil layers as predictors. Statistical analyses were conducted using R software (R Development Core Team, 2008).

3 RESULTS

At Fumarole Bay (FB), mean air temperature during the study period was -1.9 °C, ranging from -18.4 °C to 4.9 °C (Figure 2). Soil annual mean temperatures were consistently negative, varying from -0.9 to -0.2 °C at 10 cm, -0.6 to -0.2 °C at 30 cm, -0.3 to -0.1 °C at 50 cm, and remaining nearly constant at -0.1 °C at 70 cm throughout the monitoring period (Table 1). Thermal amplitude decreased sharply with depth, from up to 3.8 °C at 10 cm to less than 0.5 °C at 70 cm. Surface layers were strongly influenced by air temperature variability, whereas temperatures at 70 cm rarely exceeded 0 °C, indicating the presence of permafrost and a thermally buffered regime at depth (Figures 3a, 3b).

During the monitoring period, thawing days decreased markedly with depth, totaling 291 days at 10 cm, 198 at 30 cm, 20 at 50 cm and none at 70 cm. Freeze days were most frequent near the surface, with 951 days recorded at 10 cm, and became rare at 70 cm, with only 29 days. In contrast, isothermal days dominated the deepest layer, reaching 2426 days at 70 cm. Freeze–thaw days were common at 10 cm, with 138 occurrences, but were nearly absent at depth, with only 5 days at 70 cm. Cumulative thawing degree days (TDD) declined from 702 °C·days at 10 cm to only 5 °C·days at 70 cm, while freezing degree days (FDD) decreased

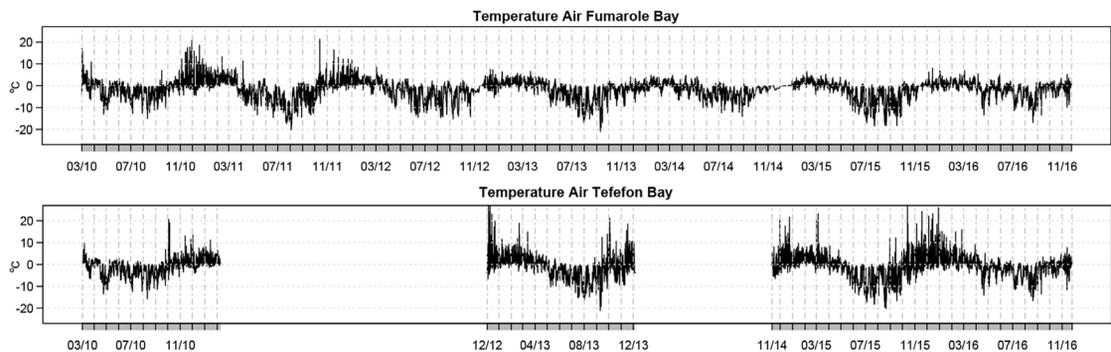


FIGURE 2 – Annual variation of air temperature at both study sites (Fumarole Bay and Telefon Bay). The values shown are daily averages obtained from hourly records.

TABLE 1 – Yearly soil temperature average, maximum, minimum and Standard Deviation at FB and TB, Deception Island.

<i>Fumarole Bay*</i>				
<i>Year</i>	<i>10 cm</i>	<i>30 cm</i>	<i>50 cm</i>	<i>70 cm</i>
2010	-0.7 (2.2 / -4.6 / 1.0)	-0.4 (1.1 / -1.9 / 0.5)	-0.2 (0.0 / -0.4 / 0.1)	-0.1 (-0.1 / -0.1 / 0.0)
2011	-0.4 (4.2 / -5.0 / 1.9)	-0.3 (2.3 / -3.5 / 1.1)	-0.3 (0.6 / -1.4 / 0.4)	-0.1 (0.0 / -0.3 / 0.1)
2012	-0.7 (6.0 / -9.9 / 2.4)	-0.6 (3.0 / -5.3 / 1.4)	-0.3 (0.8 / -1.8 / 0.5)	-0.1 (0.1 / -0.5 / 0.1)
2013	-0.3 (3.9 / -2.9 / 1.3)	-0.2 (1.6 / -1.7 / 0.7)	-0.2 (0.2 / -0.7 / 0.2)	-0.1 (0.0 / -0.2 / 0.0)
2014	-0.2 (2.1 / -1.5 / 0.6)	-0.2 (0.8 / -0.8 / 0.3)	-0.1 (0.0 / -0.1 / 0.0)	-0.1 (0.0 / -0.1 / 0.0)
2015	-0.9 (3.5 / -7.2 / 1.7)	-0.6 (1.7 / -3.8 / 1.0)	-0.3 (0.0 / -1.5 / 0.4)	-0.1 (0.2 / -0.6 / 0.2)
2016	-0.5 (2.1 / -3.4 / 1.0)	-0.4 (0.8 / -2.0 / 0.5)	-0.2 (0.0 / -0.8 / 0.2)	-0.1 (0.3 / -0.2 / 0.1)
<i>Telefon Bay*</i>				
<i>Year</i>	<i>10 cm</i>	<i>30 cm</i>	<i>50 cm</i>	<i>65 cm</i>
2010	-1.5 (5.4 / -7.2 / 2.2)	-1.4 (1.4 / -6.0 / 1.5)	-1.3 (0.2 / -4.7 / 1.3)	-1.2 (0.1 / -3.6 / 1.1)
2011				
2012				
2013	-0.8 (8.2 / -6.6 / 2.8)	-0.9 (3.1 / -5.6 / 1.8)	-0.9 (0.8 / -4.7 / 1.4)	-0.9 (0.1 / -4.0 / 1.1)
2014				
2015	-1.6 (6.0 / -11.8 / 3.2)	-1.6 (2.6 / -7.1 / 2.3)	-1.6 (0.4 / -5.6 / 1.8)	-1.6 (0.1 / -5.0 / 1.6)
2016	-0.7 (7.3 / -6.3 / 2.3)	-0.9 (1.7 / -4.3 / 1.3)	-0.9 (0.1 / -3.6 / 1.0)	-0.9 (0.1 / -3.3 / 0.8)

*Average temperature, °C (Maximum/ Minimum/ Standard Deviation)**

from -1997 to -262 °C·days over the same depth interval (Figures 4a, 5a).

Soil moisture at FB was generally low, averaging between 6 and 8%, but exhibited seasonal summer peaks approaching 30% in the upper soil layers. At 70 cm, moisture variability was less pronounced, although occasional peaks close to 30% were recorded. Correlation between air and soil temperatures decreased with depth ($r = 0.62$ at 10 cm and $r = 0.19$ at 70 cm), while strong correlations were observed between adjacent soil layers, particularly between 10 and 30 cm ($r = 0.91$), decreasing at greater depths ($r = 0.70$ between 50 and 70 cm). All correlations were statistically significant ($p < 0.01$ unless otherwise stated). Multivariable regression explained approximately 51% of the temperature variability at 70 cm (Adj. $R^2 = 0.51$), indicating weak coupling between shallow and deep soil layers.

Active layer thickness at FB ranged from 49 to 97 cm, with maximum thaw depths observed in March 2015 and March 2016.

At Telefon Bay (TB), mean air temperature averaged -1.4 °C during the 1453 days of continuous monitoring, with values ranging from -18.6 °C to 7.5 °C. Soil temperatures were consistently colder than those observed at FB across all depths. Annual mean temperatures ranged from -1.6 to -0.7 °C at 10 cm, -1.6 to -0.9 °C at 30 cm, -1.6 to -0.9 °C at 50 cm, and -1.6 to -0.9 °C at 65 cm (Table 1). In contrast to FB, thermal amplitudes at TB were

relatively uniform across the soil profile, varying between 3.6 and 4.5 °C.

Thawing days decreased with depth at TB, totaling 103 days at 10 cm, while no thawing days were recorded at either 50 or 65 cm. Freeze days dominated the soil profile, exceeding 600 days at 30, 50 and 65 cm. Isothermal days were comparatively rare, with a maximum of 127 days at 65 cm. Freeze-thaw days were frequent throughout the profile, with 742 days at 30 cm, 745 days at 50 cm and 719 days at 65 cm. Cumulative TDD declined from 867 °C·days at 10 cm to zero at 65 cm, whereas FDD remained high across all depths, ranging from -2284 to -1620 °C·days (Figures 4b, 5b).

Soil moisture at TB was generally higher than at FB, averaging between 8 and 12%, with summer peaks approaching 30% at all monitored depths. Temperature correlations were stronger than those observed at FB. Air-soil correlation decreased with depth ($r = 0.64$ at 10 cm and $r = 0.28$ at 65 cm), while internal consistency within the soil profile remained very high, particularly between 30 and 50 cm ($r = 0.95$) and between 50 and 65 cm ($r = 0.99$). All correlations were statistically significant ($p < 0.01$ unless otherwise stated). Regression models explained 98% of the temperature variability at 65 cm (Adj. $R^2 = 0.98$), indicating strong vertical coupling of energy flux.

Despite similar air temperature conditions during overlapping years (2010, 2013, 2015 and 2016), soil thermal regimes differed markedly

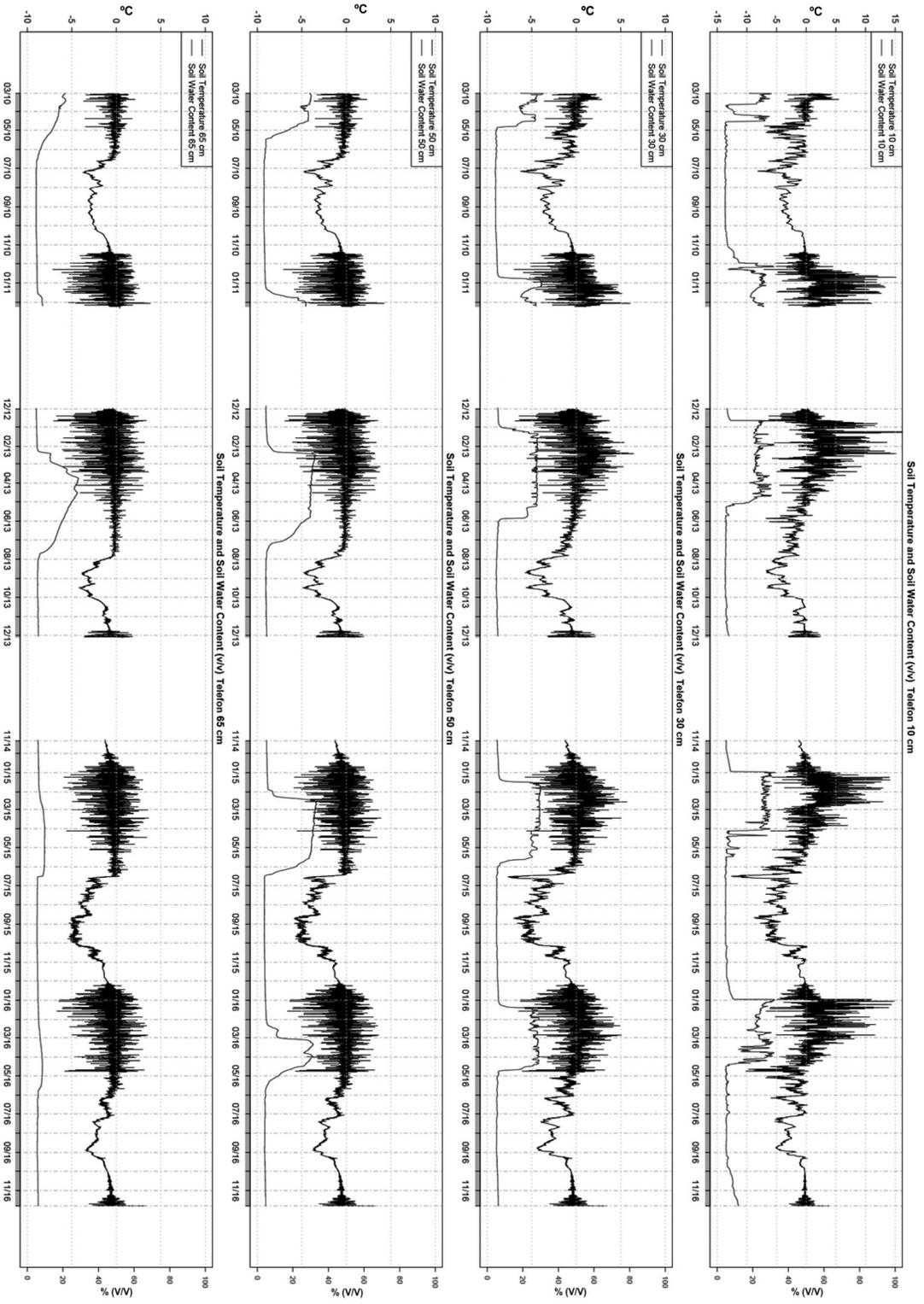


FIGURE 3 (cont.) – (b) Annual variation of soil temperature and moisture at Telefon Bay. The values shown are daily averages obtained from hourly records.

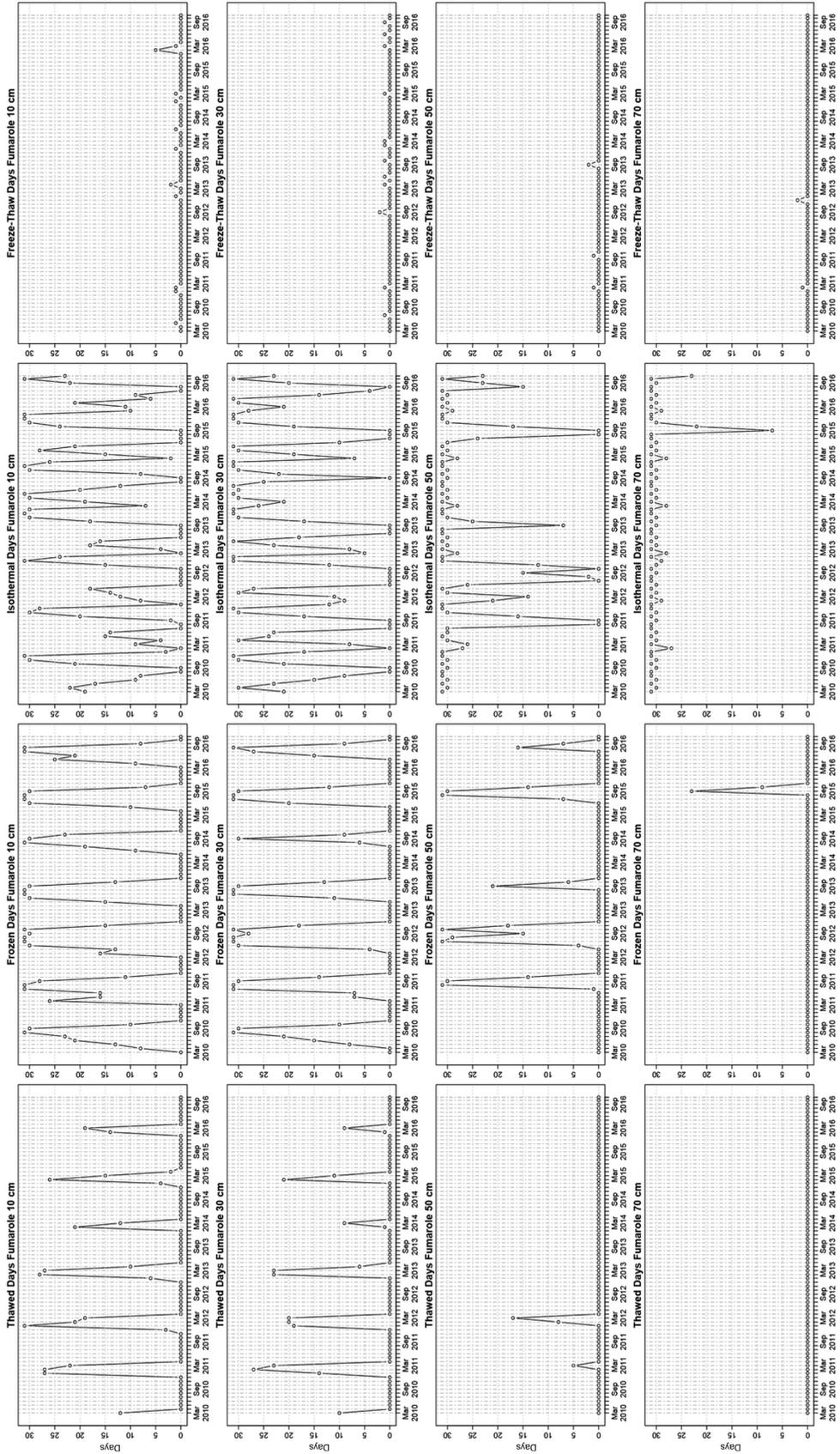


FIGURE 4 – (a) Classification of days as frozen, isothermal, thawed, and freeze–thaw cycles at Fumarole Bay.

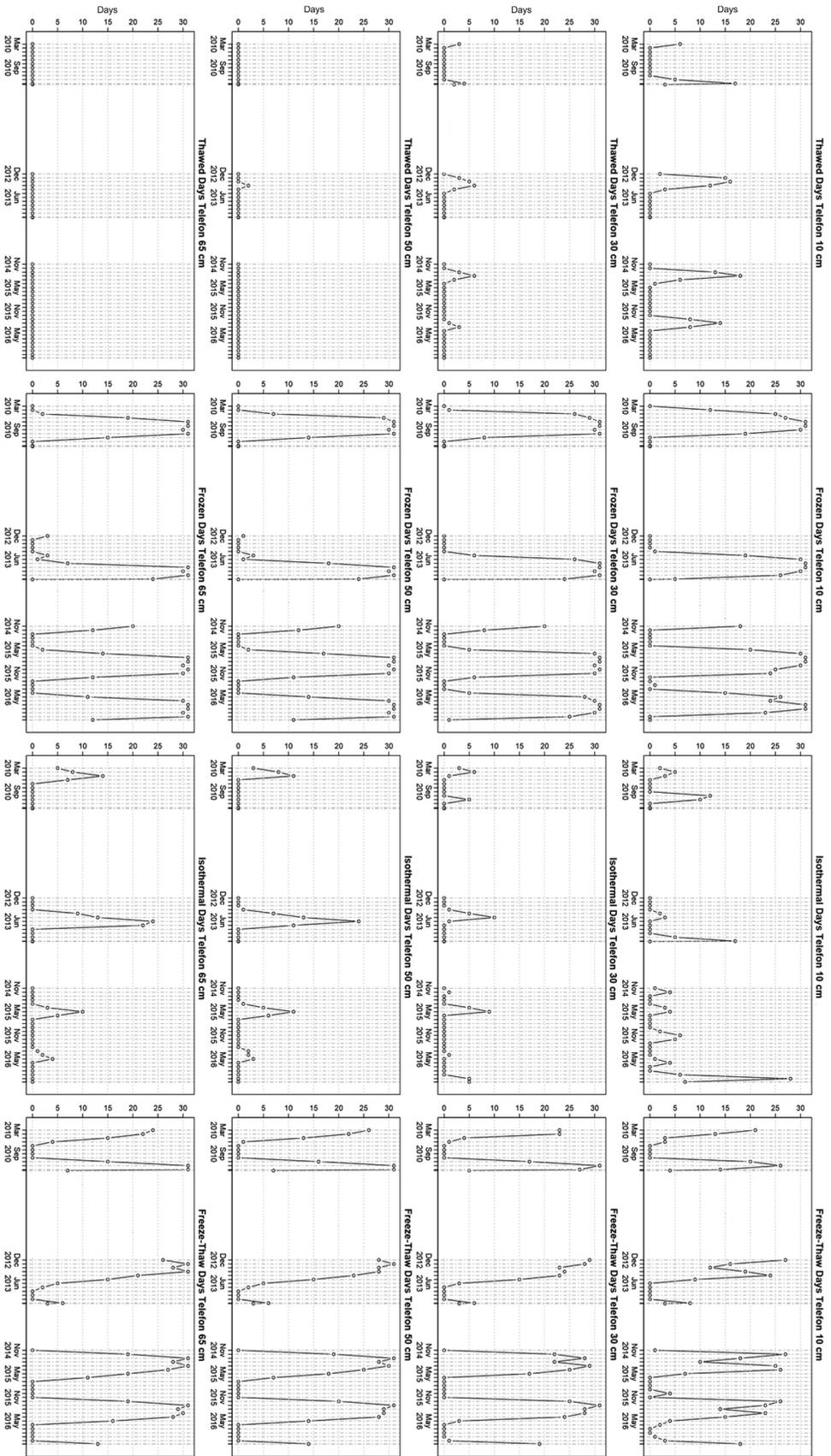


FIGURE 4 (cont.) – (b) Classification of days as frozen, isothermal, thawed, and freeze–thaw cycles at Telefon Bay.

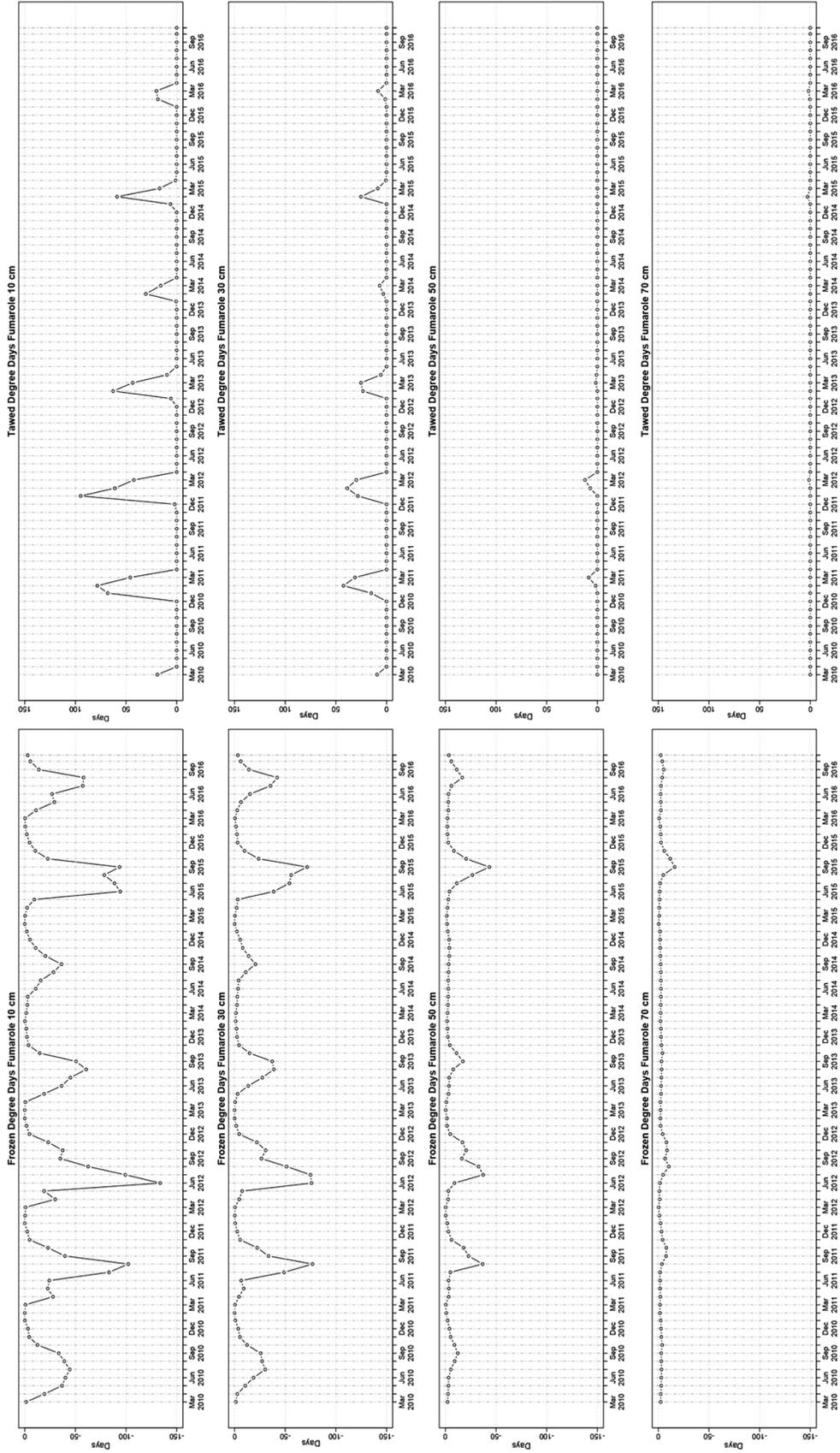


FIGURE 5 – (a) Cumulative thermal indices (Freezing Degree Days – FDD, Thawing Degree Days – TDD) at Fumarole Bay.

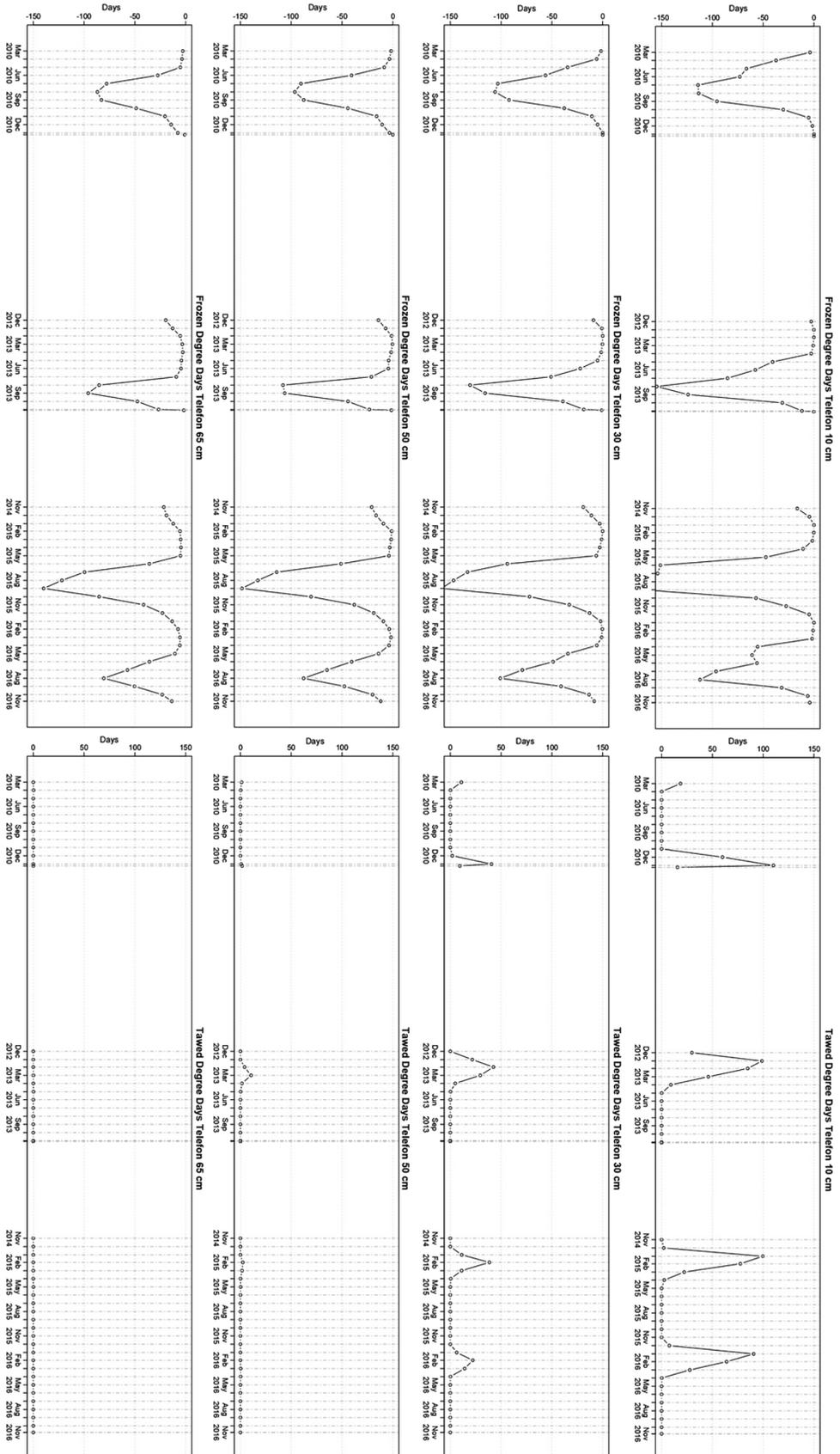


FIGURE 5 (cont.) – (b) Cumulative thermal indices (Freezing Degree Days – FDD, Thawing Degree Days – TDD) at Telefon Bay.

between sites. Telefon Bay consistently exhibited lower soil temperatures than Fumarole Bay at all monitored depths. At FB, temperatures converged toward near-isothermal conditions at 70 cm, whereas at TB negative temperatures persisted throughout the soil profile, reflecting stronger soil–air coupling and greater sensitivity of the permafrost system to atmospheric forcing. Multivariable regression models were applied to predict soil temperatures at the deepest sensor in both study sites (Table 2). The predictors included

air temperature, upper soil layer temperature, and moisture conditions. The models achieved a satisfactory performance, with estimated values closely matching the measured data (Figure 6). At Fumarole Bay, the regression model captured both the seasonal amplitude and the attenuation of temperature with depth, reflecting the buffering effect of the sedimentary deposits. At Telefon Bay, where soil–air coupling was stronger, the model reproduced the sharper fluctuations of soil temperature, although slight underestimations were observed during thawing peaks.

TABLE 2 – Correlation of temperature records along layers and multi-variable regression having bottom most layer as the dependent variable.

Fumarole Bay					
	10 cm	30 cm	50 cm	70 cm	Air
10 cm		0.91	0.58	0.33	0.62
30 cm	0.91		0.75	0.44	0.56
50 cm	0.58	0.75		0.70	0.37
70 cm	0.33	0.44	0.70		0.19
Air	0.62	0.56	0.37	0.19	

$T_{70cm} = -0.058 - 0.001(T_{Air}) + 0.013(T_{10cm}) - 0.044(T_{30cm}) + 0.026(T_{50cm})$
 Adjusted R-squared: 0.51/59034 degrees of freedom

Telefon Bay					
	10 cm	30 cm	50 cm	65 cm	Air
10 cm		0.81	0.68	0.62	0.64
30 cm	0.81		0.95	0.90	0.48
50 cm	0.68	0.95		0.99	0.36
65 cm	0.62	0.90	0.99		0.28
Air	0.64	0.48	0.36	0.28	

$T_{65cm} = -0.063 - 0.012(T_{Air}) + 0.008(T_{10cm}) - 0.213(T_{30cm}) + 1.136(T_{50cm})$
 Adjusted R-squared: 0.98/34883 degrees of freedom

4 DISCUSSION

The seven-year continuous monitoring of soil thermal and moisture regimes at Deception Island (DI) confirms the widespread presence of permafrost and reveals contrasting patterns of active layer dynamics controlled primarily by geomorphological setting and parent material. This represents the first continuous multi-year permafrost dataset from a volcanic island in Maritime Antarctica. Maximum thaw depths reached 86 cm at Fumarole Bay (FB) and 109 cm at Telefon Bay (TB), values that fall within the upper range reported for ice-free areas of the South Shetland Islands. Although air temperatures were comparable at both sites during overlapping years, soil thermal behavior diverged markedly, emphasizing the dominant role of subsurface characteristics in regulating permafrost stability.

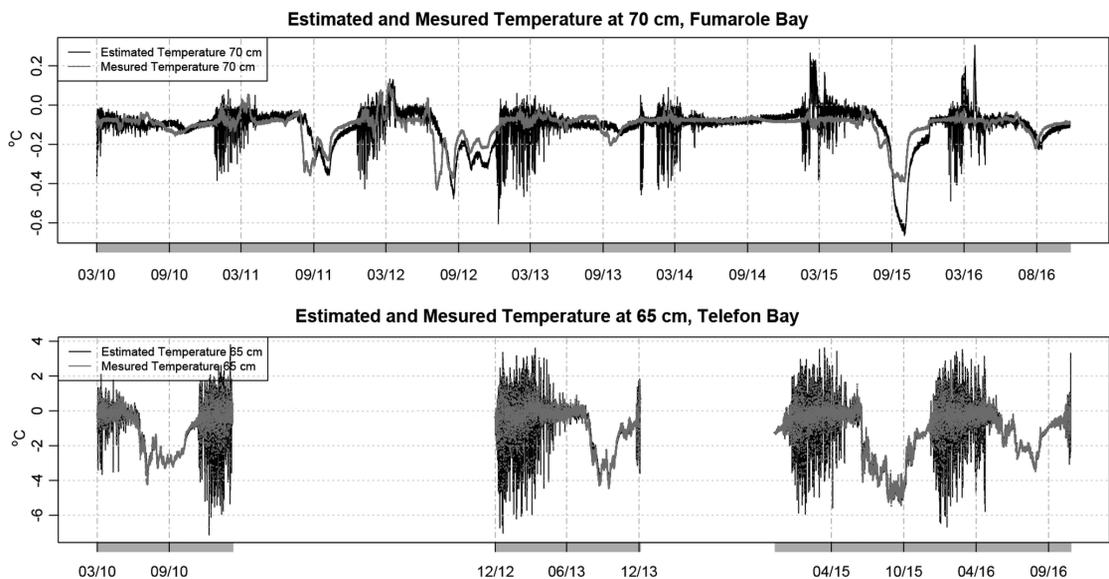


FIGURE 6 – Estimated and measured soil temperature at Fumarole Bay and Telefon Bay.

At Fumarole Bay, soil temperatures were strongly buffered with depth, and the deepest monitored layer (70 cm) remained close to isothermal conditions throughout most of the record. This thermal behavior is consistent with the presence of ice-rich horizons or buried ice lenses within reworked marine and paraglacial sediments, which reduce effective thermal conductivity and limit downward heat flux. The prevalence of isothermal days, combined with low cumulative freezing and thawing degree days at depth, supports the interpretation of a thermally dampened regime. Similar buffering effects associated with sedimentary discontinuities have been described in paraglacial environments elsewhere in Maritime Antarctica, where heterogeneous stratigraphy promotes sharp vertical contrasts in heat transfer (Goyanes et al., 2014; Ramos et al., 2012; Vieira et al., 2008).

In contrast, the soil profile at Telefon Bay, developed on relatively homogeneous pyroclastic deposits, exhibited strong vertical coupling, as evidenced by high correlations between soil layers and the performance of regression models at depth. Freeze–thaw cycles were frequent throughout the profile, and minimum temperatures at 65 cm reached -7.1 °C, indicating efficient propagation of surface thermal signals. Despite being colder on average, this configuration renders permafrost at TB more sensitive to atmospheric forcing, as warming at the surface can propagate downward with limited attenuation. Such behavior is consistent with studies highlighting the high porosity and permeability of volcanic materials, which facilitate rapid heat transfer despite low bulk density (e.g., Arenson et al., 2015; Delmelle et al., 2015).

The contrasting behavior between FB and TB highlights the importance of andic soil properties in shaping permafrost dynamics on volcanic islands. High porosity and low bulk density enhance water storage capacity, while simultaneously reducing thermal conductivity under frozen conditions. Seasonal variations in soil moisture further modulate thermal regimes through latent heat effects during phase changes, particularly during thaw periods. At TB, higher moisture contents combined with frequent freeze–thaw cycles likely contributed to the pronounced thermal variability observed across depths. Although TDR measurements under frozen conditions have known limitations, the moisture patterns observed here are consistent with previous monitoring efforts in Antarctic volcanic terrains

and provide valuable context for interpreting energy transfer processes.

Active layer thickness (ALT) varied substantially between sites and years, reflecting differences in geomorphic setting and subsurface structure. At FB, shallower and more variable ALT values are consistent with the presence of buried ice and stratigraphic discontinuities that constrain downward thaw. At TB, deeper ALT values indicate a more continuous and thermally connected soil profile, allowing seasonal thaw to penetrate further. These values are comparable to those reported for other Maritime Antarctic sites, such as Livingston Island, King George Island and Hope Bay, but contrast with shallower active layers observed in colder continental settings like Vega Island, underscoring the combined influence of climate and substrate on permafrost dynamics (Hrbáček et al., 2016; Michel et al., 2014; Schaefer et al., 2016).

The regression models applied in this study complement the descriptive analysis of soil thermal regimes and provide insight into site-specific controls on energy transfer. At FB, the models reproduced the attenuated thermal oscillations observed at depth, reflecting the buffering effect of sedimentary heterogeneity. At TB, stronger soil–air coupling resulted in sharper modeled fluctuations, in agreement with measured data. However, residual discrepancies during thaw peaks and zero-curtain periods highlight the limitations of linear regression approaches, as phase-change processes dominate energy exchange during these intervals. Similar constraints have been reported in permafrost modeling studies, emphasizing that regression-based methods should be interpreted cautiously and in conjunction with physical understanding of site conditions (Riseborough et al., 2008; Romanovsky et al., 2010).

From a broader perspective, these results underscore the sensitivity of Antarctic volcanic islands to climate variability and geomorphological controls. Volcanic deposits, characterized by high porosity and permeability, promote efficient thermal coupling with the atmosphere, whereas paraglacial and reworked sediments introduce discontinuities that buffer permafrost against surface warming. The absence of detectable geothermal anomalies during the monitoring period suggests that, at the studied sites, volcanic heat flux did not directly influence shallow permafrost dynamics. Instead, geomorphological context and sedimentary architecture emerged as the primary

controls on active layer thickness and permafrost resilience, reinforcing the need for long-term, site-specific monitoring across heterogeneous Antarctic landscapes.

5 CONCLUSIONS

This study provides the first continuous multi-year dataset of active layer thermal and moisture dynamics on Deception Island. Despite similar atmospheric conditions, the two monitored sites exhibited contrasting soil thermal regimes, driven primarily by geomorphology and sedimentary context. At Fumarole Bay, marine deposits and sedimentary discontinuities buffered permafrost, whereas at Telefon Bay the homogeneous volcanic matrix allowed greater energy transfer, making permafrost more sensitive to atmospheric forcing.

These findings highlight that permafrost vulnerability on volcanic islands of Maritime Antarctica is not solely determined by regional climate trends but is strongly modulated by local geomorphic and lithological settings. Understanding these contrasts is essential for predicting future permafrost trajectories under continued warming. This work therefore contributes to Antarctic permafrost monitoring initiatives and provides new insights into the cryosphere–landscape interactions shaping Maritime Antarctica.

Beyond site-specific interpretations, the results have direct implications for regional permafrost monitoring networks such as ANTPAS and GTN-P. The contrasting thermal responses observed at Deception Island emphasize the need to incorporate geomorphological context and substrate properties into network design, data interpretation and model calibration. Long-term ground temperature records from volcanic and paraglacial environments, such as those presented here, provide critical benchmarks for improving the representation of active layer processes in permafrost models and for reducing uncertainty in projections of permafrost response to climate change across Maritime Antarctica.

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